FROM WASTE TO INVENTORY

PHOSPHOGYPSUM — THE BUSINESS CASE

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PHOSPHOGYPSUM THE BUSINESS CASE

Foreword

In one social media post in late 2023 the global phosphogypsum (PG) narrative was irreversibly changed. After thirty or more years of scepticism and rejection of PG as a hazardous waste of no value, the conversation on top of a phosphogypsum mound in Uberaba Brazil was about the profitable Mosaic Fertilizantes phosphogypsum business.

Alzbeta Klein, President and CEO of IFA, was visiting Corinne Ricard, then CEO of Mosaic Fertilizantes, and her team. And where better than on the PG stack itself for Corinne to capture for Alzbeta in just four words the night-to-day nature of the change in PG's fortunes — from waste to inventory, from liability to asset, from sunk cost to sustainable profitability — a fairy-tale reversal and a hard-won struggle rolled into one.

The New Narrative – Welcome Back PG

The global phosphate industry now recognises that phosphogypsum management has had to be fundamentally rethought and that the rethink was — is — worth it creatively, environmentally, socially and financially. PG is a high revenue-potential secondary raw material business complement to phosphoric acid and the phosphate industry staple fertilisers, mono-ammonium and di-ammonium phosphate.

It is at the same time an exhilarating, technically demanding, environmental, social and communications challenge on a vast scale to be resolved and a commercial opportunity of great and enduring value, to be grasped for now and for long into the future.

What is definitively understood in Brazil as now progressively in more and more markets, is that phosphogypsum is not, as it has for too long been caricatured, an intractable, one-dimensional, waste disposal problem which reaches its mandatory end point incarcerated in landfill. Disposal simply moves the challenge, it does not meet and solve it. Disposal as a solution has effectively failed, most clearly because as a solution for a circular economy it is wholly value — destructive — which it need not be. Disposal also to land severely breaches the principle of intergenerational justice at the heart of sustainable development.

Against that background, "From Waste to Inventory" resets PG as a multi-use resource future generations will be pleased to inherit and put to good, safe use.

The Suite of PG Solutions

As the PG3 report shows, there are many solutions for valorising and using PG, increasingly diverse in nature, increasingly profitable, and available now. You will profit from reading case studies from around the world, including the four main global PG production centres: Brazil, China, Morocco and Saud Arabia, speak eloquently for themselves, where they are coming from, what stage of the PG business journey they are now on and what creative effort and depth of investment it has taken to develop the business to that point.

The case studies have in common that while they have ample financial, technical, policy and regulatory content, they are all set in the same context, as part of the composite global PG business case. Each one is different according to local needs and priorities but with key business drivers in common.

To that end, PG3 prefaces the collection of case studies with an outline of the novel circular economic and green investment principles now being applied by public and private sector banks and investors to facilitate a profitable transition from waste to inventory using key circular economy policy anchors. These are no longer stories of island solutions to one-off waste disposal problems. They are based on a common understanding that PG and P are both anchored at the base of new value chains, the full social, environmental and commercial potential of which is now emerging out of the fog of bad policy and flawed science.

The Policy Anchors

The policy anchors which underpin the necessary transformative investments at systemic scale, are blunt in their demands: "stacks" must turn into "stocks", wastes to inventories, to feedstock repositories offering "treasure" to fuel a rapidly expanding range of PG products and services. To ensure public, regulatory and investor confidence and transparent governance a solid platform of long-term opportunities has to be constructed and then scaled worldwide, including — as it is now doing already — using PG to remedy some of the highest causes of current stress to the world, food insecurity, water stress, soil salination, climate change and cancer.

Likewise at a time when irreversible land loss to urban development is increasingly stressing land resources worldwide, especially in countries whose populations are already large or growing fast or both, and for whom security and climate stress are hence top priorities, it is no longer defensible to see indefinite disposal of PG to land close to, or even in the midst of, these over-crowded places as a socially or environmentally responsible solution.

In fact, not using PG as a feedstock to face or mitigate these issues — which it demonstrably can — runs already counter to the principles of sustainability to optimise value creation from any resource. To compound this avoidable loss of opportunity by another caused by disposal of these resources unused to sequestered landfills is doubly wasteful.

The only outcome has been to reinforce PG's unmerited status as a negative externality — a high cost to future generations imposed on them without their consent — when that externality can actually be fully internalised. The sadness this evokes is that the root cause of this loss is not the inherent hazard of the material it is still alleged by some to have, it is in reality a questionable construct of our own making and wholly avoidable.

Meanwhile, as shown in this report, the intangible value of PG — fuelled by the creativity of those now producing and managing it — is growing at an astonishing speed. Driven by advances in PG valorisation and use, a reversal in stakeholder acceptance — waste to inventory — is well under way, bringing with it the tangible evidence of what can be done with it to benefit society and the environment with PG. Combat desertification, remediate soil salinity, conserve water in climate stressed agriculture and forestry, sequester carbon in trees and root matter in soils, off-set lost land to urbanisation and radically enhance resource use efficiency, all these uses bring societal appreciation and sustainable business.

Folding in AI, Driving Intangible Value

The sources of new intangible value are the science, technology and the instinctive creativity of the global PG community itself. Adoption of the circular economic process of double materiality analysis which sees as much financial value in virtual as in physical assets — often more — is now compounded by folding AI into the PG business case. Where might this lead?

It was the defining insight of the 2024 Nobel Prize for Chemistry that it should be awarded to two leading scientists, Demis Hassabis and John Jumper, who are simultaneously and indivisibly chemists and AI specialists. For them, AI operates as an innovation engine for powering their profession, chemistry.

AI is now inseparably "folded in" to chemistry. He Guangliang, Chairman of Guizhou Phosphate Chemicals Group, rightly points out in closing this report that these 2024 laureates belong to a different but closely-related branch of the same diverse tribe as the PG team — phosphate geologists, mineralogists, miners, chemists, engineers, processors, agronomists, farmers, climate scientists, specialty chemists in a vast range of new product developments — … and all have native ingenuity and use of AI in their DNA. They share a common vision and find inspiration from each other in terms of how the reimagined conduct of P and PG chemistry works.

The utility that promises to unite them with all other branches of chemistry and beyond is a new "Janus" currency that AI, in tandem with blockchain (Distributed Ledger Technologies), is minting, a fusion of monies and molecules. The double-faced coinage that this currency generates has molecules on one face, molecules on the other creating a new Janus-like financial instrument uniting the tangible and intangible values in resources essentials to life, such as food and energy, to both of which the phosphate industry now belongs.

For those of you who are already starting to enjoy first mover advantage by applying these principles to the PG narrative and business case and have disclosed the essence of your actual business plans and practices in this report, thank you for sharing some of your wisdom and experience on the frontline with us.

Now it is time with your collective help to normalise and standardise these experiences for both the public and the private good.

The ugly PG duckling has turned into a swan. The long-incubated PG business case has hatched.

Julian Hilton,
General Editor

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Seven Highlights

Volker Andresen and Malika Moussaid

1 **From Waste to Value** – Reclassifying PG from toxic waste to a valuable co-product transforms waste management costs into revenue opportunities and marks a major win for sustainability in the phosphate industry.

2 **Driving Circularity** – PG plays a crucial role in making phosphate fertiliser production more sustainable, acting as a key secondary raw material for a resilient, circular economy.

3 **Scaling Success** – Global case studies demonstrate that PG valorisation is becoming a profitable, mainstream, and scalable business model.

4 **Collaboration for Progress** – The PG 3 Report highlights industry leadership, smart regulation, public-private partnerships, and market adoption as essential drivers of success.

5 **Unlocking Potential** – Recognising PG's true potential reduces environmental harm while enabling scientific innovation, regulatory progress, and new economic opportunities.

6 **China's Model for Success** – China's local financing approach ensures accountability and supports its national PG utilisation policy, setting an example for effective governance.

7 **Revitalising Landscapes** – PG contributes to mine rehabilitation, promoting long-term environmental sustainability and benefiting surrounding communities.

Phosphogypsum - What's in a Name?

Phosphogypsum (PG) consists of some 85-90% of calcium sulphate, ($CaSO_4.2H_2O$). Why then phosphogypsum? The name phosphogypsum could be held to be misleading because its relative phosphate content is very low.

But PG is one of a number of commonly produced industrial gypsums, such as flue-gas desulphurised gypsum (FGD) and fluorogypsum, each of which adopts a suffix from the name of the industry which produces them. According to that naming convention, as the phosphate industry produces a unique gypsum type that gypsum must be called phosphogypsum however much phosphate content is in it.

If it comes from the phosphate fertiliser industry and its content is overwhelmingly calcium sulphate it is chemically gypsum. So, Phosphate-Gypsum — Phosphogypsum — it is.

The Wet Process

In the "wet process" extraction of phosphoric acid from fine-ground, phosphate rock concentrate is acidulated in strong sulphuric acid to make phosphoric acid (PA) and phosphogypsum. In the course of the reaction the trace quantities of other elements in the source rock partition, some staying with the acid and hence being included in the fertiliser fraction, some staying with the PG.

According to whether strong or weak PA is being manufactured, two forms of PG may be produced. These are di-hydrate for the weak acid and hemi-hydrate for the strong. Until quite recently, the phosphate industry was dominated by a commoditised market model with only two bulk products, di-ammonium phosphate (DAP) and mono-ammonium phosphate (MAP), so the question of which of two acid production options should be taken was a largely operational question for the PA business.

From Waste to Industry

But with the growing realisation that the attention of the industry in regard to PG is now increasingly on its role as revenue-generating feedstock or secondary raw material (SRM)[1] in its own right - the transition from waste to inventory - PG is now being considered from a very innovative perspective of a business case for use in its own right.

This is bringing with it not one but two financial value streams. On the one hand, the range of commercially viable PG products and engineering applications available is growing rapidly in range, quality and type. But on the other, every tonne used removes a cost against the balance sheet meaning both CAPEX and OPEX savings. At a capital investment level every new PG disposal facility — often referred to as a "stack" — entails high cost both in land acquisition or long-term lease outlay; but in that the land can no longer then be used for revenue generating purposes — the loss in terms of on-going outlay is potentially indefinite. This position alters dramatically as soon as revenue of any significance is generated, because not only does the "waste" become "inventory", the PG itself — the feedstock — moves to the asset side of the balance sheet, even at a purely nominal value per tonne.

In practice, as all phosphogypsum types are different, the nature and location have a significant bearing on the uses they may be suited for, so access to market can be targeted to meeting precise needs for that market. This is a potentially flexible circular economic value proposition.

Tonnages of PG and PA

Seen from a tonnes-produced perspective it is the PG not the PA that is the real product of the wet process. An average 5.4 tonnes of PG is produced for every tonne of phosphoric acid (PA); but the figure can vary quite significantly depending on the quality of the source rock, from 4.5 to 7 tonnes of PG per tonne of acid, or (rarely) even higher.

The typical P content remaining with the PG is 0.5%, effectively the industry standard for a well-run PA plant. But depending on the nature and quality of the phosphate source rock the phosphate content can edge higher, even above 1%; and also depending on the source rock the other trace elements each PG contains can vary widely, if subtly.

The outcome is that the annual PG output of IFA members is in the range ~225-245 million tonnes, while phosphoric acid — the primary traded product — is logged more precisely, with a corresponding annual PG output by these same companies of ~44.4 million tonnes[2].

Natural Variability

The natural variability of the content of sedimentary phosphate rock from which most phosphoric acid is made inevitably poses a range of challenges during and after production, some of which carry across to the PG itself. As one very distinguished America phosphate engineer once quipped, "phosphate rock may contain almost the entire Periodic Table so don't be surprised what you find".

Rock deposits rich in phosphate content generate less PG

1 Investigating Europe's secondary raw material markets, EEA Report 12/2022 https://www.eea.europa.eu/en/analysis/publications/investigating-europes-secondary-raw-material#:~:text=Secondary%20raw%20material%20(SRM)%20markets,SRM%20markets%20in%20the%20EU.

2 Worldwide 2023 Phosphoric Acid production data from IFA Market Intelligence Service.

per tonne of acid than lower quality sources; the lower the quality of rock, the higher the ratio of PG to phosphoric acid. As the global trend is towards mining lower quality resources because the higher grades have already been mined, proportionately the ratio of PG to PA produced has slightly increased.

Typically, trace quantities of a) Naturally Occurring Radioactive Materials (NORM), in particular radium salts, and b) some heavy metals (HMs) such as cadmium. In general, the quantities of both NORM and HM are very low, measured in parts per million (ppm) and parts per billion (ppb) sometimes testing even the limits of detection; but the quantities of these trace elements are kept under continuous observation and may result in regulatory restrictions for some uses under a widely applied proportionate regulatory system called the "graded approach".

Because of the very high volumes of PG produced in the early years of wet process production it was common practice to discharge the PG to water bodies, notably rivers and seas. From the 1980s the practice was discouraged or disallowed by regulatory authorities worldwide, and in 1989 the then lead producing country, the United States, mandated that all PG should be stored in "stacks". The mandate rested on the assessment that the NORM level in PG is sufficiently hazardous in nature that PG should be classified as a radioactive waste. At the time the United States was the centre of gravity of global phosphoric acid production, so as the phosphate industry started to develop a global presence, the influence of this US classification of PG as radioactive waste with highly restricted use took a wide hold.

Since the early 2000s, however, this negative approach has come under increasingly sceptical scientific scrutiny; but natural and understandable apprehensiveness about using any materials classed as radioactive has made the task of rebalancing attitudes to valorisation and use of PG from an evidence-based perspective very challenging. The impact of this tussle of attitudes has concentrated on how to correctly classify the material and how significant is its radioactive content.

How to Classify PG as a Secondary Raw Material

Since 1989, phosphogypsum, has been classified worldwide variously as a hazardous waste (United States) [1], a "high volume, low effect" waste but authorised for use (India) [2] as an anthropogenic resource (UNECE Geneva) [3], a by-product (European Union) [4] and a co-product (IAEA and Brazil) [5] [6] of the phosphate fertiliser industry.

In the past five years since the second IFA PG report was published the gradual shift away from an effective ban on use has accelerated to the point where, as part of a global trend towards adopting circular economy standards and policies, there has been extensive investment in rethinking and re-engineering how to manage materials such as PG, how to eliminate the avoidable waste [7] [8]. This in practical terms means establishing pathways for safe valorisation and beneficial use of PG rather than permanent disposal to landfill as waste, or "negative externalities".

Happily, that very approach was the clear one recommended in the landmark Phosphate Industry Safety Report published in 2013 by the International Atomic Energy Agency [6]. Now the vision of ending negative externalities is being adopted as industry good practice, and at considerable speed as is well illustrated across the body of this report. Progress is even such that the investment community is now investing in projects being undertaken by the phosphate industry in a range of countries to develop the appropriate technologies and know-how to transform PG from costly waste to precious, responsibly profitable feedstock.

Comprehensive Utilisation

This transformation is not being driven by ignoring the challenges that "comprehensive utilisation" of PG inherently brings with it. There are challenges such as from the NORM and heavy metal content which must be dealt with. But the approach is to use innovation and investment to find the way to do this safely and profitably, and if pretreatment is required as a step in the valorisation and use process, it is of course being used.

A number of remarkable "break out", safe and profitable uses of PG are described in this report – whether to combat soil salinity, enhance water use efficiency in climate stressed agriculture, develop biodegradable packaging or create cancer treatments from the NORM content. Together they yield social, environmental, and economic benefits, with significant return on investment to investors. Hence the title of this report "From Waste to Inventory".

In that context PG is rapidly taking its place among the circular economic class of "secondary raw materials'. As a result, the conclusion presented at the end of this report is that there are two unifying aspects to the PG business case, profitability and optimum resource use efficiency from PG as feedstock.

SECTION A

BANKING AND INVESTMENT IN PHOSPHOGYPSUM FOR THE CIRCULAR ECONOMY TRANSITION

1

CHAPTER ONE

A BANKER'S VIEW ON PHOSPHOGYPSUM

Author: Alzbeta Klein, Chief Executive Officer, IFA

1. Context

As an investment banker who worked for the International Finance Corporation before joining IFA, I naturally focus on the case for investing in phosphogypsum valorisation and reuse. Its evident potential for material recycling within a circular economic framework offers a promising avenue for investment into sustainable development.

2. Understanding Phosphogypsum and its Challenges

Phosphogypsum is produced during the wet process of phosphoric acid production, where phosphate rock is combined with sulphuric acid. For every tonne of phosphoric acid, five or more tonnes of phosphogypsum are generated, leading to substantial materials management challenges, not least very high capital and operating expenditures. Until 2000, Florida was the centre of gravity of global phosphate fertiliser production. As required by the US Phosphogypsum Rule. since 1989 phosphogypsum was managed in the United States as a waste, to be stored on land in ever larger “stacks”. These stacks not only occupy a significant and ever-growing land area but also require costly lifetime management in both their operational and post-operational states. This practice of stacking on land was initially closely followed elsewhere in the world as the phosphate industry developed outside the United States.

But for the past fifteen years new approaches have been increasingly explored which have led to a significant change of direction, a pivot from disposal to use. This has brought with it the need for strategic investment in innovation driven by policy anchors from the global trend towards adopting circular economic values, most notably in China.

From 2000 onwards, the centre of global phosphoric acid production passed progressively to China, such that by 2010 China had reached its current level of annual production of some 80 million tonnes, more than double the output of the United States. It now has the de facto leadership role in how the future of global PG production is being defined. This future is to be in use, not disposal; what China calls “comprehensive utilisation”.

3. Potential for Reuse and Circular Economy

As a result, the focus on safe, beneficial reuse of phosphogypsum as first recommended by the International Atomic Energy Agency (IAEA) in 2013 [6] is gaining traction globally. Bulk applications of PG are increasingly common in construction materials such as cement, in soil amendments, and road construction. Combinations of these options are now being used routinely in many countries. Other emerging uses, such as combating desertification, pharmaceuticals, packaging materials and paints are now beginning to enter the market. In construction, phosphogypsum can be used as a bulk feedstock for wallboard for affordable housing; as mine backfill, its natural cementitious properties enhance the utilisation efficiency and structural strength of the material for rehabilitating mined out mineral deposits. Its significant sulphur content can now be recovered and reused. And there is now attention being paid to very low volume but very high value uses, as a source of critical raw materials such as Rare Earth Elements for renewable energy and electric vehicles and of Radium salts for cancer therapies.

This new high value-added, quality-driven approach aligns with the principles of a circular economy, where waste products are transformed into valuable resources, reducing the need for virgin materials and minimising environmental impact [4].

4. Financing the Reuse of Phosphogypsum

From a financial perspective, the reuse of phosphogypsum presents an opportunity to shift from waste management costs to revenue-generating activities. The economic benefits of transforming phosphogypsum into saleable products can offset the expenses associated with traditional disposal methods, such as stacking. However, financing these initiatives requires a structured approach to mitigate risks and ensure profitability.

4.1 Structuring Financial Models - Public-Private Partnerships

Collaborations between government entities and private companies, Public-Private Partnerships (PPPs) can facilitate the development of phosphogypsum reuse projects. Governments can provide regulatory support and incentives, while private companies bring expertise and capital investment.

In such PPPs, it would be essential:

- to establish partnerships between government entities, private companies, and research institutions.
- for governments to provide regulatory support and incentives, while private companies bring expertise and capital investment.
- for research institutions to support innovation and technology development.

4.2 Commercial Financing through Green Bonds/Loans and Sustainable Bonds/Loans

Issuing green bonds can attract investors interested in sustainable projects. These bonds can finance the development of infrastructure for phosphogypsum processing and conversion into building materials or other applications.

For these types of instruments, an issuer would have to consider a number of aspects. Some but not all are listed below.

- Use of Proceeds: Clearly define the use of proceeds for specific phosphogypsum reuse projects, such as:
  - Infrastructure for processing phosphogypsum
  - Equipment for converting phosphogypsum into usable materials (e.g. construction materials, soil amendments)
  - Research and development of new reuse technologies.
- Project Evaluation and Selection: Establish clear criteria for selecting eligible phosphogypsum reuse projects, considering environmental impact, technical feasibility, and economic viability.
- Management of Proceeds: Implement a system to track and report on the use of loan funds for approved projects.
- Reporting: Commit to regular reporting on the environmental impact and progress of the funded projects.
- Risk Mitigation:
  - Include provisions for environmental liability insurance to protect against potential contamination risks
  - Require borrowers to meet specific environmental and safety standards in their phosphogypsum handling and processing.
- Performance-Based Pricing: Consider incorporating sustainability-linked features, where the interest rate is tied to achieving specific environmental targets or milestones in phosphogypsum reuse.
- Public-Private Partnership (PPP) Structure: Design the loan to support PPP models, where government entities provide regulatory support, and private companies bring expertise and capital (per point 1 above).
- Technical Assistance: Include provisions for technical assistance or capacity building to support the development of phosphogypsum reuse technologies and best practices.
- Long-Term Perspective: Structure the loan with longer tenors to account for the time needed to develop and implement phosphogypsum reuse solutions.
- Regulatory Compliance: Ensure the loan structure accounts for compliance with relevant environmental regulations and standards for phosphogypsum handling and reuse.
- Stakeholder Engagement: Include requirements for borrowers to engage with local communities and environmental groups to address concerns and build support for phosphogypsum reuse projects.

By incorporating these elements, a sustainable loan can be structured to support the financing of phosphogypsum reuse while addressing environmental concerns and promoting circular economy principles.

4.3 Multilateral Funding through the Green Climate Fund, Climate Investment Funds and other Donor-based Investment Vehicles

The Green Climate Fund (GCF)[3] and other climate funds have the potential to play a significant role in financing initiatives related to phosphogypsum, particularly those that promote circularity and sustainable resource management. The GCF, with its focus on supporting projects that contribute to low-emission and climate-resilient development pathways, could be well-positioned to fund initiatives that transform phosphogypsum from a waste product into a valuable resource.

4.3.1 Safe, Efficient Recycling of Phosphogypsum

One key area where climate funds could provide financing is in the development and implementation of technologies that enable the safe and efficient recycling of phosphogypsum. This could include funding for research and pilot projects aimed at extracting valuable elements like rare earth elements from phosphogypsum or developing new applications for its use in construction materials or soil amendments. The GCF's emphasis on innovative and transformative projects aligns well with such circular economy approaches.

4.3.2 Climate Funds

Furthermore, climate funds could support the integration of phosphogypsum recycling into broader sustainable agriculture and resource management strategies. This could involve financing projects that combine phosphogypsum utilisation with other circular economy practices in the agricultural sector, such as improved nutrient management and waste reduction. By focusing on the potential of phosphogypsum to contribute to multiple Sustainable Development Goals, including those related to climate action, responsible consumption and production, and sustainable agriculture, projects could align closely with the objectives of climate funds and increase their chances of securing financing.

3 For the Green Climate Fund see https://www.greenclimate.fund/

4.4. Working with such Multilateral Funds

Working with such multilateral funds of this type would require several assessments – which include, among others:

- **Rigorous environmental and social safeguards**: The GCF and others would apply an Environmental and Social Safeguards framework.
- **Stakeholder engagement**: The GCF and others would require meaningful consultation with local communities and stakeholders throughout project design and implementation.
- **Monitoring and evaluation**: Robust monitoring systems should be put in place at the project level to track environmental and health impacts throughout project lifecycles.

4 4.1 Research and Development Grants

Funding from research institutions and environmental agencies can support the innovation of new technologies for phosphogypsum reuse. Grants can reduce the financial burden on companies and encourage the exploration of novel applications.

4.4.2 Risk Mitigation Strategies

Given the novel approach to financing PG reuse, investors would seek insurance to offset potential risks. Insurance products and hedging strategies can protect investors from potential environmental liabilities associated with phosphogypsum reuse. These financial instruments can enhance investor confidence and attract more capital.

5. Insurance

When structuring insurance for phosphogypsum reuse projects, it is important to consider:

- Comprehensive coverage that addresses both sudden and gradual pollution events
- Policies that cover historical liabilities, as phosphogypsum reuse may involve legacy contamination issues
- Coverage for clean-up costs, third-party claims, and regulatory compliance
- Inclusion of legal defence costs and expert support for incident response.

By incorporating these insurance products into the project financing structure, stakeholders can better manage and mitigate the environmental risks associated with phosphogypsum reuse initiatives.

6. Conclusions

The extensive reuse of phosphogypsum offers a pathway towards a more sustainable and circular economy. By transforming a waste product into a valuable resource, the industry can reduce its environmental impact and create economic opportunities. As a banker, structuring financing models that support these initiatives is crucial. By leveraging public-private partnerships, sustainable financing, and innovative risk mitigation strategies, the financial sector can play a pivotal role in advancing the reuse of phosphogypsum and contributing to a more sustainable future.

CHAPTER TWO

PHOSPHOGYPSUM: A VALUABLE RESOURCE WITHIN THE CIRCULAR ECONOMY

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1. Repurposing Phosphogypsum as a Secondary Raw Material

The European Bank for Reconstruction and Development (EBRD)[4] recognises the substantial potential of phosphogypsum, a by-product of phosphate fertiliser production, as a valuable resource within the circular economy. In the EBRD regions of operation, particularly in phosphate-rich countries such as Morocco, Tunisia, Egypt, and Jordan, phosphogypsum is generated in large quantities as a by-product of phosphoric acid production, essential in fertiliser manufacturing. With increasing global fertiliser demand, the scale of phosphogypsum production has grown significantly, presenting both environmental challenges and potential economic opportunities. Repurposing phosphogypsum as a secondary raw material could enable waste minimisation, enhance resource security, and support innovation and competitiveness in sectors such as agriculture, construction, and manufacturing.

Table 1. *Key Phosphoric Acid producers in EBRD countries of operation*

Phosphoric Acid Producing Companies in EBRD Countries of Operation	
Country	**Company(ies)**
Bulgaria	Agropolychim
Egypt	Abu Zaabal Fertilizer & Chemical Co. El Nasr Co. For Intermediate Chemicals (NCIC)
Jordan	Jordan Phosphate Mines Company (JPMC) Jordan India Fertilizer Company (JIFCO) Indo-Jordan Chemicals Co.
Kazakhstan	Kazphosphate
Lithuania	Lifosa
Morocco	OCP Group
Poland	Grupa Azoty
Serbia	Elixir
Tunisia	Groupe Chimique Tunisien (GCT)
Turkiye	Eti Bakir TOROS (Agri)
Uzbekistan	Ammofos Maxam Indorama Kokand[4] Samarkandchimyo

4 For the European Bank of Reconstruction and Development see https://www.ebrd.com/home

5 Indorama Kokand imports phosphoric acid to blend with sulphuric acid for superphosphate fertilisers.

2. What is a Circular Economy?

The EBRD defines a circular economy as one where the inherent value of resources is retained and extended across multiple product life cycles. For phosphogypsum, this means transforming it from a waste product to a resource, allowing for recycling and repurposing within various industrial processes. This approach aligns with the European Commission's Circular Economy Action Plan[6][9] and the categorisation system developed by the Directorate-General for Research and Innovation, which provides guidance on activities that qualify as circular economy investments [10]. As a participant in the creation of this categorisation system, the EBRD integrates these principles into its Green Economy Transition (GET)[7] [11] approach, providing its personnel with tools to assess projects' circularity and environmental benefits (see Figure 1).

> The EU Categorization System for the Circular Economy aims to establish a shared language and understanding among stakeholders, promoting circular design, supporting procurement decisions, highlighting circular products in the market, fostering innovation, aiding policymakers and integrating circularity across supply chains. It seeks to provide criteria and definitions to advance the transition to a circular economy by encouraging sustainable practices and guiding various sectors towards circularity.

Box 1. *EBRD application of CE Categorisation System*

3. Green Investments

Since 2014, the EBRD has invested over EUR 2 billion in projects that foster circularity in industrial processes, with a growing focus on by-products and secondary resource streams such as phosphogypsum.

3.1 Advancing Circular Economies in EBRD's Countries of Operation

Through direct investments and indirect financing via Green Economy Financing Facilities (GEFFs)[8], the EBRD supports a broad spectrum of circular economy applica-

6 EU Circular Economy Action Plan see https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en

7 Green Economy Transition see https://www.ebrd.com/what-we-do/get.html

8 Green Economy Financing Facilities https://ebrdgeff.com/

Fig. 1. *EBRD's approach to Green Investments and Policy Dialogue*

tions. With over 200 financial institution partners in GEFF, the EBRD enables local businesses and households to access funds for green investments, including those that align with circular economy principles, such as reusing industrial by-products.

In addition, the EBRD's Green Trade Facilitation Program (Green TFP)[9] extends financing to support the trade and distribution of technologies and materials that promote circularity. Numerous projects within Green TFP's portfolio have focused on improving resource efficiency in manufacturing, reducing waste, and advancing sustainable construction materials. Phosphogypsum reuse aligns well with these policy anchor[10] objectives, as it addresses waste minimisation, enhances material recovery, and creates economic opportunities from industrial by-products.

EBRD recently carried out and successfully completed a Near Zero Waste (NØW)/circular economy pilot in Turkey, which provides an important baseline for the proposed Project. This pilot project in Turkey aimed to support state-of-the-art waste minimisation, resource efficiency technologies and processes with:

a. Financing for waste minimisation and resource efficiency projects, combining EBRD funds with concessional finance, to support early movers in replicable investments currently hindered by market failures.
b. Technical assistance support for project developers.
c. Policy dialogue to enable and mainstream the concept of waste minimisation in different economic sectors.

With the lessons learned from NØW programme, the Bank has launched the Circular Economy Regional Initiative (CERI)[11] in partnership with the Global Environment Facility (GEF)[12]. GEF aims to bolster investments in innovative resource-efficient technologies, circular processes, and business models in Turkiye, Albania, Bosnia-Herzegovina, Montenegro, North Macedonia, and Serbia by enhancing raw material management across product lifecycles, so diverting waste from landfills and marine environments.

3.2 Circular Economy Policy Anchors

- Battery-grade manganese is listed as a strategic raw material by the European Critical Raw Material Act.

9 For the Green Trade Facilitation Program (Green TFP) see https://www.ebrd.com/work-with-us/trade-facilitation-programme.html

10 As an example of the role of policy anchors in financial management and related investments see paper for Bank for International Settlements, Paul Masson, Anchors for Monetary Policy, https://www.bis.org/events/cbcd06g.pdf

11 For the CERI initiative see https://www.ebrd.com/home/work-with-us/projects/tcpsd/14440.html

12 For the Global Environment Facility (GEF) see https://www.thegef.org/

Euro Manganese,[13] a Canadian mineral development company, plans to conduct a feasibility study on the viability of processing mining waste in the Chvaletice Manganese Project in Czechia and to eventually build a demonstration plant that will process mining waste, such as crushed rocks and mineral leftovers. The EBRD is supporting the project with a CAD 8.5 million investment, made possible through the purchase of 17.8 million common shares in Euro Manganese in December 2021. Manganese is primarily used in the manufacturing of iron and stainless steel, but this is evolving. At Chvaletice, the process will recover high-purity manganese, an essential raw material needed by the growing electric vehicle and lithium-ion battery markets.

Fig. 2. *Legacy Chvaletice mining waste — Source: Euro Manganese, Inc*

Box 2. *Reference project type — Manganese*

- The EU circular economy action plan calls for the efficient use and recycling of critical raw materials, notably for non-ferrous metals such as manganese.
- The circular economy framework created in the country, Circular Czechia 2040[13], (see Figure 2) recognises the importance of waste reduction, increasing Europe's autonomy in raw materials and the use of raw materials from secondary sources [12].

3.3 Key Features

- Recovering material from waste to prepare it for reuse, turning that waste into critical secondary raw materials.
- Reprocessing old mining waste into high-purity manganese products that can be used for electric vehicles and energy storage.
- Helping to meet EU and national material recovery targets.
- Collaborating with other companies to increase the quality of recovered materials as long as it is technically feasible and economically viable.

3.4 Impact

- The demonstration plant will convert 750 kg of old mining waste into 100 kg of high-purity manganese daily, providing a valuable raw material.

4. Scaling Investments

The EBRD is committed to scaling investments and capacity-building efforts to help both public and private sector clients identify and implement circular economy solutions. As demand for resources rises, harnessing phosphogypsum and other industrial by-products will be central to advancing the transition toward a resilient and circular economy in phosphate fertiliser producing countries.

13 For Circular Czechia 2040, see https://www.oecd.org/en/publications/towards-a-national-strategic-framework-for-the-circular-economy-in-the-czech-republic_5d33734d-en.html

14 For Euro Manganese see https://www.mn25.ca/chvaletice-manganese-project

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CHAPTER THREE

WHAT IS A PHOSPHOGYPSUM BUSINESS CASE IN A CIRCULAR ECONOMY?

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1. Context – Phosphogypsum in Transition

The transition to a circular economy is transforming the nature of a "business case" to be much more policy-sensitive than before, but basic financial questions still have their role. Why spend money when one can make money instead? Why manage the risks of a PG liability or its costs as negative externality when it can be put to good, profitable use an asset? How does conducting a double materiality assessment of PG as secondary raw material potentially change the game, including regulatory compliance and ESG-compatible financing and reporting? How does reassessing the role of PG as a feedstock fit with the status now in many countries of phosphate as a "critical" or "strategic" raw material, or both? These are increasingly typical questions addressed at boardroom level. PG is suddenly a priority topic on the boardroom agenda, whether because of the rapidly escalating cost of storing it, or because PG management policies are more and more focused on minimum use targets or even 100% use, or because PG can actually turn out to be a profitable resource. Whether driven by regulations, national policies or company policy, the global trend is clear: phosphogypsum is transitioning from a waste, discharged or stored, into an inventory of valuable raw material(s).

1.1 An Industry in Transition

In the past, things were simple and common sense: fertiliser plants were of a relatively small size, serving mainly a local market, customers benefiting from the local agricultural extension services whether provided by universities and colleges or the manufacturers themselves. When phosphogypsum was produced, in many cases it found its way in meeting local and specific needs, from road construction to soil amendments for saline soils. Phosphogypsum was, by default, a resource to be used opportunistically, driven by opportunity rather than policy. It was not a waste but because it was produced in a much higher volume than phosphoric acid it was often discharged to water bodies rivers, seas and oceans, rather than being stored on land – producers being defeated by the sheer volume of material to be used.

With a scale up of fertiliser facilities in the 1970s after the intervention of the oil and gas industries into the fertiliser markets, large plants producing a small range of high volume commodities including MAP and DAP, serving an international market of fertiliser blenders and distributors, started producing high volumes of PG every year. But whether for reasons of its sheer quantity or because of restrictive or prohibitive regulations, including prohibition of the practice of marine or river discharge, very little PG was used. The volumes produced were so large that in countries moving fast up the industrial and social development scale, PG was unknown to the general public as a resource. And if it was known, it was commonly demonised as radioactive. For an increasingly commoditised industry, it was a high volume nuisance because its value as an unusual calcium sulphate - gypsum - was less than the cost of moving it to markets where it might have attracted customers. Meanwhile, small phosphate fertiliser plants were closed down as inefficient and large producing plants grew quickly used to the convenience of disposing PG as waste to huge stacks.

In a society with a sense of unlimited resources and a mantra of prioritising "core business", phosphogypsum turned into a waste and was managed accordingly: disposed of in stacks with no, or very limited, opportunity for use. The almost universal practice of disposal to land entrenched the perception of phosphogypsum as a waste, which actually suited a commoditised business process because it proved a convenient bona fide for doing nothing of value with PG. Then in the USA in 1989, the Environmental Protection Agency (EPA) brought in a de facto near ban on PG use, the PG "Rule" [1] declaring "stacking" of PG to be mandatory, and classifying the materials to be hazardous, radioactive and a waste – despite the fact that in some states (such as California) it was already in regular commerce, costing typically $50/ton to the farmer including delivery. As the then global leader of P fertiliser production, the USEPA set the benchmark for the majority of producing countries, regulations which were not challenged scientifically to any degree until the 2000s.

Now, twenty-five years into the 21st century, sustainable development has largely displaced the unlimited growth paradigm of the second half of the 20th century. Development is still part of the equation and remains urgently important for a large part of the world population. But unrestricted development with no attention to the environment and no recognition of planetary limits is now understood to be unsustainable. If unchanged, the consequence would be no or lower development in precisely those countries which need it most, with a high risk of degrading living conditions in already well-developed countries as well.

2. Sustainable Development

Sustainable development has become a fundamental driver of thought and action, embedded in the UN Sustainable Development Goals shared by all countries but also now axiomatic in the boardroom. Sustainable Development is therefore underlying many national "anchor" policies, intergovernmental frameworks, and is translating into a new and different set of expectations toward business. These expectations are expressed either in regulations to be complied with – including more stringent environmental and waste management regulations – or complemented by stringent financial reporting standards and rules. In parallel, in some markets but not all, a radical change of perception of the role of fertiliser plants took place from a purely commoditised product or service provider and profit maker to an enterprise that uses "triple bottom line" values as key performance indicators. The success with which an enterprise can address and contribute to holistic societal needs with equal emphasis on delivering social, environmental and financial benefits became the new gold standard. Boardrooms of public and private sector companies took note of the shift and adapted to the new policy environment.

3. The Circular Economy

Along with the concept of sustainable development, several additional factors are further strengthening the case for considering the use instead of disposal of possible resources such as PG. Of these, the most significant is the circular economy. In an environmentally-conscious and resource-limited world, the circular economy (CE) is providing a framework for a radical overhaul of policy and for resultant changes in modes of action. The CE concept has been researched and expanded in the last decades from mere "recycling at the end of life" to a comprehensive approach aiming at avoiding, reducing, re-using or recycling any input at any stage of a product or service life, from design to operation to end of life. While theorisation is easy, implementation in national markets in our complex, global society is running into significant hurdles. These are more of an historical and cultural than scientific or technical nature, but are nonetheless very powerful. Where such hurdles are being overcome, the lead is coming from policy and decision-makers with supporting regulation and investment in technical innovation on business grounds rather than sustainability principles. What is encouraging in this report is that the case studies show that the same destination - beneficial use of PG - can be reached by more than one route, depending on local needs and priorities.

3.1 Decarbonisation and Scope Emissions Control

An increasingly significant policy consideration is decarbonisation as part of a comprehensive Scope emissions control and carbon footprint reduction policy. With decarbonisation targets being set and a price of carbon being progressively introduced, sourcing a secondary raw material with by definition a lower carbon footprint than a primary resource is becoming one of the leading procurement parameters. PG is one such secondary raw material, which when used as an anthrosol, has properties well suited to carbon sequestration goals through capture of CO_2 in forestation, root systems and in soil organic matter. These properties are described in the case studies in Section B of this report.

4. PG From Waste to Inventory

Driven by sustainability, environmental consciousness, security of supply and carbon footprint, boardrooms must consider or reconsider their management strategy and policy for PG. When a new regulation closes the door to disposal, an alternative path must be found. When stacks become not a solution but a significant negative externality and environmental concern, subject to more stringent regulations and more suspicion from stakeholders, alternative paths must be considered and assessed. And when successful examples of valorisation of phosphogypsum are emerging as a "new normal", business opportunities are there to be seized at scale.

The case studies in this report bring a lot of inspirational lessons learned to bear on setting new pathways to valorisation. They tell a story of leadership vision from the industry, constructive discussion with the regulatory bodies, public and private partnering to support new market access and acceptance. They show that PG valorisation makes a good business case, provided the boardroom addresses it for what it is: a business decision which will be successful if: 1) the usual set of core business processes, modified as needed for the CE, are followed; 2) significant investment is made in quality and technical R&D, market research, regulatory discussions, innovation when needed; serviced by 3) dedicated facilities to generate services; and products meeting market specifications and standards; and 4) fostering business development in new markets or in domains different from those frequented by the core business to date.

4.1 Fundamentals

To have a business case, one of the first requirements is that the product (or service) to be sold is safe. This is obvious, but phosphogypsum still suffers from its categorisation in many countries as a waste and/or as a hazardous material. It is therefore necessary to bring the science to the regulators and get recognition that phosphogypsum can be categorised as a resource (i.e. co-product, by-product, secondary raw material …) and used in a restricted or unrestricted manner depending on the use case.

5. Policy Anchors

In this respect, experts gathered by the International Atomic Energy Agency (IAEA) looked comprehensively at the available evidence. This led to an IAEA safety report [6] published in 2013 which clearly states:

> *'Future liabilities associated with the continued presence of large phosphogypsum stacks place a considerable burden on future generations. This, together with the increasing rate of phosphogypsum production, provides a very compelling reason for creating a regulatory environment that is conducive to identifying and promoting further ways of safely using phosphogypsum as a co-product of phosphoric acid production rather than having to manage it as waste.'*

And, looking into use cases, the same report states that:

> *'All evidence suggests that the doses received as a result of the use of phosphogypsum in agriculture, road construction, marine applications and in landfill facilities are sufficiently low that no restrictions on such uses are necessary. The uses of phosphogypsum in structural panels for the construction of a house could, in extreme circumstances, result in the occupant receiving an annual effective dose exceeding 1 mSv. Therefore, it would be prudent for the relevant authority to ensure that an appropriate situation specific risk assessment be carried out in order to determine whether any restrictions on this particular use of phosphogypsum are needed. For all other uses of phosphogypsum in home construction, including its use in cement, bricks, plasterboard and tiles, the annual effective dose received by the occupant is unlikely to exceed 1 mSv and restrictions on such use would appear to be unnecessary.'*

Once the safety issue has been addressed, the next step is to do business! While valorisation of phosphogypsum may be driven by regulations or policy framework at national level, ESG commitment, innovation and company policies at industry level can make the difference between valorisation as "part of the cost of the business" and valorisation "making business sense".

6. Success Factors

Some contributing factors that are likely to be included in developing a successful PG business case can be identified from the case studies included in this report.

6.1 Country-level Policy Anchors

When circular economy and secondary resources are seen as national policy anchors, such a framework brings more certainty for business and investment decisions. In addition, in many cases such policies are complemented by incentives such as access to financing, fiscal support, or review of regulations to facilitate market entry of products and services using such secondary raw material.

6.2 Trust between Regulator and Operator

An open and trusting relationship between the operator and the regulator will enable the regulator to draw on local and international knowledge and experience and determine first whether phosphogypsum can no longer be considered a waste and then whether it can be used with or without restrictions.

Because phosphogypsum has long been considered as a waste and because the use of phosphogypsum in many countries is new, such technical discussion between the regulator and the industry is essential. Constructive technical discussion with the regulator will also be key when groundbreaking or innovative applications are considered. While the regulator will make its independent decision, the regulator, the producers and as the case may be the users must have a similar level of knowledge. Academia can play a role in bringing science in a neutral way. Such a constructive and transparent regulatory process will bring high certainty to the business decision makers and offer a higher level of confidence to the end user. Industry and regulators can support the development of product standards, which would further enhance users' confidence and widen the market.

6.3 Market Research and Development

Depending on the use of the end product containing phosphogypsum, market research is needed to understand what the needs of the users are, whether there are already a set of specifications to be met, and at what price a product can be sold. Investment in R&D may be needed to develop an industrial process to produce a product meeting market need, or a feasibility study to adopt a refining process already in use. R&D can also lead to innovation, developing a phosphogypsum-based product which can beat the market by offering value-additional advantages such as a premium fertiliser or a stronger road building material, or bringing to market a new application such as packaging. Investing in and maintaining a flow of market intelligence is also essential to identify new market opportunities such as radium salts, now in demand in new pharmaceuticals for oncology, or rare earth elements whose demand is growing to feed the renewable energy transition, electric vehicles (EVs) or the digitalisation of the world.

6.4 New Products in New Markets

Being a new entrant in a new market is never easy, and overcoming existing negative perceptions may be another hurdle. A national policy drive for circular economy and valorisation of co-product, along with financial or tax incentives, will help with entering or creating a market. The industry must dedicate specific human and financial resources to develop these new market opportunities. Other business options are to enter a strategic partnership with potential users or an agreement with distributors in a market too far from the core business of a fertiliser company, or to create a dedicated subsidiary to develop a new business line.

6.5 Additional Circular Economy Related Factors

As well illustrated in the EU's "Green Deal" CE[15] Plan a growing range of additional factors may be taken into account when developing and assessing a business plan.

6.5.1 Choice Between Storage / Disposal and Valorisation

When there is still a choice between storage/disposal and valorisation, valorisation will avoid the cost of managing a waste inventory, including storage and final disposal in a landfill. This could tilt the financial equation when the return on investment to entering a new market is not yet well established. Besides, there could be a reputational issue to keep stacks of phosphogypsum and possible financial liabilities in case of more stringent regulations or an environmental incident: valorisation appropriately managed in compliance with ESG values will address these problems.

6.5.2 The Carbon Equation

The carbon equation could be an added benefit. In many use-cases phosphogypsum can substitute other materials at a much lower carbon content, still providing a similar or higher level of quality. Such a lower carbon footprint could be a selling point for market access, strengthening the marketing business case. And where carbon has a price, the avoidance of carbon can bring extra financial income. The recent international agreement on a voluntary carbon emission market may create additional opportunities in this respect.

6.5.3 Shortening Supply Chains

The local supply of material derived from phosphogypsum for local use can add to the economic and environmental benefits for local stakeholders and contribute to the security of supply at the region or the country level.

7. Conclusion

Entering the second quarter of the 21st century with the premise of sustainable development, environmental stewardship and circular economy, the case of considering phosphogypsum as an inventory is compelling. And as for any asset, business common sense dictates that use must be grounded in a robust business case. The case studies in this report present good, functioning examples of how to succeed: research and development, constructive dialogue with the regulator(s), adaptation of process and flow sheet to produce a marketable product, push to enter or create a market, and the incentive (in so far as possible) of a supportive national policy. As a result, there is a stronger case for making a business out of phosphogypsum and offering a positive impact to society instead of spending money on managing stacks or disposal in landfills.

Sustainable development and awareness of the physical limitation of natural resources is driving a new approach to the Circular Economy. PG – which was a local resource and then became a waste in many places – is once again becoming a resource: reclassified by policy as "secondary raw material". The volume of PG produced has grown, in line with a more global fertiliser market. Besides, regulations are becoming more and more stringent on storage and disposal, and in some countries, regulations are mandating circularity. In this context, the sheer size of the inventory and of the future accumulations of PG creates a business opportunity which may extend from local to global. In addition to the well-established use of PG, innovation is opening new paths and new markets. There is today a clear policy-anchored business case to invest in PG valorisation, transforming a potential liability into an asset and offering a positive return on investment (ROI). Looking to the future, an alignment of regulations between countries and the emergence of global standards for products using PG would be welcome developments to strengthen the business case of PG valorisation locally and in global markets.

15 For the European Green Deal see https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en#:~:text=1%20of%201-,The%20European%20Green%20Deal,European%20Green%20Deal%20visual%20story

CHAPTER FOUR

IFA'S ROLE IN THE EVOLUTION OF PHOSPHOGYPSUM MANAGEMENT

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1. Formation and Evolution of IFA

The International Fertilizer Association (IFA) was founded in 1927 in the UK by predominantly phosphate fertiliser producers, only one year after the 1926 International Conference on Superphosphate Manufacturing[16] in which scientists from Rothamsted Research UK, played a leading role. As IFA membership subsequently extended first to the nitrogen and potash industries – bringing the manufacture of the major nutrients N, P and K under one association – so the fertiliser industry as a whole became increasingly dominated by the five major global commodities: ammonia, urea, monoammonium phosphate (MAP), diammonium phosphate (DAP) and muriate of potassium (MOP).

In tandem, there was significant concentration among fertiliser producers with a strong emphasis on food production at agri-business scale, but with much less regard for environmental or social factors. Now of course, the trend is in the opposite direction, towards reducing or eliminating negative environmental impacts, protecting and restoring biodiversity and reprioritising fertiliser use for food security in the context of climate action and precision agriculture (the 4 Rs[17]). This is reflected in the rise of a much diversified and differentiated range of specialty products.

2. The Phosphogypsum Rule and its Impact

In 1989, the U.S. Environmental Protection Agency (USEPA) decided to promulgate the Phosphogypsum Rule in what was by far the major centre of global P fertiliser production, the United States. The Rule made it mandatory to stack PG on land. The US state most severely impacted was Florida with major production facilities grouped in Central Florida close to the major phosphate deposits, and a smaller production base in the north of the state. In practice this all but banned PG use despite decades of its beneficial application in agriculture and road building. In practice, in Florida – with land plentiful and inexpensive and rainfall also plentiful – the requirements of the Rule did not prove insurmountably difficult for the big commodity producers of MAP and DAP to accept, despite the fact that producing these fertilisers generated five times as much PG as phosphoric acid. The financial margins could absorb the cost.

16 Keen, B. A. 1926. The history and development of the use of superphosphate. International conference on superphosphate manufacturing.

17 The "4Rs" in fertiliser management refers to the principles of Right Source, Right Rate, Right Time, and Right Place, which are key to efficient and sustainable fertiliser use. See https://www.fertilizer.org/key-priorities/fertilizer-use/4rs-and-fertilizer-best-management-practices/#:~:text=08 Nov 2016-,Nutrient Management Handbook,Privacy and Terms and Conditions

Though widely but informally used before 1989, notably where supply chains were short, such as in California and Florida, PG had never been core business for a global phosphate fertiliser market served by bulk high value ammonium phosphate fertiliser shipments by sea, notably from Tampa.

During the 1970s and 1980s, the post-war localised phosphate industry and its highly skilled science and agricultural extension service-based value chain, was transformed from within as nitrogen producers were first taken over largely by oil and gas industry commodity business models. These new oil and gas based practices brought with them the sulphur essential for wet process production of phosphoric acid, expertise in managing high volume supply-chains and the ammonia required for MAP and DAP. Even well-established markets for agricultural PG use, notably California, were simply no match for the overwhelming opinion of the industry at the time to follow the Rule and "stack".

2.1 The Decline of Phosphogypsum Utilisation in the 1990s

Up to 1989, PG was used in a significant range of applications – not just as soil amendment – including extensively in northern and eastern Europe. PG for roads, parking lots, embankments, railway track sleepers, landfill cover, and construction materials was taken up by local markets such as Belgium and northeastern France, with short haul distances due to the low cost and readily available phosphoric acid (PA) as a byproduct. Some markets such as Japan in the 1960s and '70s integrated the PA production process into the cement industry conveying the by-product PG to a cement making unit with the PA plant. This was in retrospect an almost perfect circular economic production model with close to zero waste. In the two decades after the 1989 USEPA rule, resistance grew in the US to PG use in response to public concerns about the potential health and environmental risks associated with the radioactive and heavy metal elements contained in the material. As other PG-producing countries started to introduce regulatory controls the natural tendency was to follow the practice and rule set of USEPA. This had two consequences. In countries where land availability was good and prices low, on-land stacking became the standard. Whereas in Europe land was expensive and PG discharge to sea banned, PA production simply died out. By then, millions of tonnes of PG – by default deemed waste – had accumulated in high volume on land in stacks.

Because the US PA industry by the turn of the century had a near monopoly on global supplies, the only regulator with any authority was effectively the US. When regulators in other markets, especially those new to PA production, started to look for regulatory guidance, the source was commonly the US EPA not least because so much of the PA production technology also came from the US. This meant that disposal stacking had become normalised worldwide.

3. Turning the Tide: Global Shifts in Phosphogypsum Use and Regulation

With the rise of the BRICS economies, led by China, from the early 2000s a series of independent evidence-based scientific reviews began, led by national regulators such as in India and Brazil. These ran in parallel with a joint initiative of the IAEA and the Florida Institute of Phosphate Research[18] (FIPR) from 2005-2011.[19] This initiative aimed to conduct an independent, global evidence-based review into the role of PG as a potential beneficial resource, as part of the Phosphate Industries Safety Report being undertaken by the IAEA across a range of industries associated with naturally-occurring radioactive materials (NORM) [6].

By 2008, Indian regulatory bodies, the Atomic Energy Commission and the Pollution Control Board, had both completed their review and under the graded approach, released PG for use either unrestricted in agriculture or cement, or with varying degrees of restriction when used in buildings according to whether they were commercial or residential. A similar review had been completed by the Brazilian regulator CNEN, which opened the pathways to similar high-volume uses (agriculture and cement) with some 80% going to agriculture and 20% cement use being largely determined by the cost of transportation.

Despite this, it took until 2013 at a global level, when the highest authority in radioactivity matters, the IAEA issued its peer-reviewed Safety Report no. 78 on Radiation Protection and Management of NORM Residues in the Phosphate Industry [6] that three principles in the EPA PG Rule were challenged by four from IAEA:

- PG should be classified as a "co-product", not as a "de jure" hazardous waste
- There are no scientific reasons to support radiological barriers to PG usage
- Utilising PG under the graded approach is in many cases a more socially and environmentally sustainable solution than either indefinite storage on land or discharge to sea
- Regulators should encourage producers to foster safe, beneficial uses in preference to disposal as "waste".

Historically more than 50 countries have at some time produced PG; but now most smaller producers have closed down and production is heavily focused on a much smaller range of countries producing around 230 million tonnes (mt) of PG annually. By 2020, of this roughly 80.5mt was already being used, with an organic Compound Annual Groth Rate (CAGR) of 4-6%. Despite these advancements, legacy PG stacks continue to grow, with current estimates reaching approximately 4.5 billion tonnes, i.e. accumulating still at more than100 million tonnes per year on land. This highlights both the progress in PG use and the ongoing challenge of managing its large-scale (though proportionately shrinking) accumulation rate.

3.1 The Rise of Sustainability as Accelerator of Change

In 2015, the 17 Sustainable Development Goals (SDGs) were adopted by all 193 UN member states to address pressing global challenges such as poverty, inequality, climate change, and environmental degradation. The SDGs aim to foster a more sustainable, equitable, and prosperous future by 2030, encouraging global cooperation, guiding policy and investment, and promoting accountability to improve health, education, economic growth, and environmental protection.

Since then, global sustainability regulations have increasingly focused on promoting a circular economy, shifting from a "take-make-waste" model to one that emphasises reducing waste, reusing materials, and recycling. Key developments include:

3.1.1 Stricter Waste Management Laws

Governments worldwide have implemented tougher regulations on waste disposal and recycling, encouraging industries to minimise waste.

3.1.2 Circular Economy Action Plans

The European Union, for example, has introduced a Circular Economy Action Plan that mandates resource efficiency, product longevity, and waste reduction across various sectors.

3.1.3 Sustainability Reporting

Corporations are now required to disclose their sustainability efforts and resource use, integrating circular economy principles into their business models.

4. Changing the IFA Values and Working Culture from Within

In 2018, IFA announced the outcomes of its 'IFA2030 scenarios,' which explored plausible futures for the fertiliser industry.

18 FIPR was renamed FIPRI in the course of being absorbed into the Florida Polytechnic University.

19 The Stack Free by '53 Project, 2005-2011 PI Julian Hilton, an evidence-based approach to the risks and benefits of PG use worldwide, was funded by the Florida Institute of Phosphate Research.

These scenarios were developed through extensive consultations with IFA members and external experts over two years, mapping out potential opportunities and challenges for plant nutrition up to 2030 and beyond. The aim was to guide strategic planning both for the fertiliser sector as a whole and for individual companies. Key takeaways for IFA emphasised the need for the organisation to become more outward-looking, science-focused, and sustainability-driven, to provide maximum value to its 500 members from 80 countries[20].

The IFA's Technical Committee, created half a century ago, initially focused on increasing fertiliser production. Twenty years ago, it began benchmarking IFA members on employee safety, production emissions, and energy efficiency. A decade later, it introduced an externally audited product stewardship certification, Protect & Sustain, which has since become the de facto standard for the fertiliser industry. Five years ago, the Technical Committee increased its focus on decarbonisation, publishing low-carbon pathways for ammonia production [14] in collaboration with the International Energy Agency and analysing emissions from fertiliser use with sustainability consultants from Systemiq [15]. In 2021, the Technical Committee was transformed into the new Sustainability Committee, which now combines responsible production and use of fertilisers. One of its most impactful initiatives has been the launch of IFA's Sustainable Fertilizer Academy[19], which offers around 50 online courses taught by subject matter experts.

4.1 The IFA's Pivotal Role in Developing Phosphogypsum Valorisation

IFA has been crucial in guiding the sustainable management and use of PG. As the only global association dedicated to the fertiliser industry, it serves as the central hub for addressing issues related to PG. Its NORM Working Group, the largest of its kind within IFA, was established in 2012 at the Association's Technical Symposium held in Toshkent, Uzbekistan. That meeting was also attended by an IAEA official, who presented the review draft of the IAEA Phosphate Industry Safety Report [6]. Since then, it has steadily grown and comprises over 140 experts globally. This group, which has members from industry, academia and regulatory bodies played a key role in developing and promoting best practices for the sustainable management and use of PG as well as promoting innovation and investment in the diversification of uses of PG as what is now classed within a circular economy framework as a secondary raw material.

20 For IFA see https://www.fertilizer.org

4.2 Phosphogypsum Milestones along the Way

4.2.1 Foundations and Early Developments (2012-2014)

2012 – Founding Meeting of the IFA NORM Working Group, Toshkent, May – The inaugural gathering sets the stage for ongoing discussions and strategies in sustainable management of phosphogypsum.

2013 – Publication of the IAEA Phosphate Safety Report, Vienna, March – This pivotal report highlights the safety and sustainability considerations in phosphate use, providing essential guidelines.

2013 – Second Meeting of the IFA NORM Working Group, Istanbul, September – This meeting advances the agenda for phosphogypsum management, engaging key stakeholders.

2014 – Keynote Speech by Esin Mete, AFA Forum, Sharm El Sheikh, February – Esin Mete, CEO of Toros, addresses the intersection of phosphogypsum and Sustainable Development Goals, emphasising their importance.

4.2.2 Establishing Goals and Reports (2015-2016)

2015 – IFA commissions Phosphogypsum – Sustainable Management and Use (PG Report 1)– A comprehensive guide launched to outline best practices for phosphogypsum utilisation.

– IFA NORM Working Group reports to IFA's Technical Committee, Vancouver, March - The Working Group submits significant PG findings to the Technical Committee, reinforcing its commitment to sustainable practices.

– UN Sustainable Development Goals released, New York, December – These goals provide a framework for sustainable practices across industries, including fertilisers.

2016 – IFA NORM Working Group Annual Meeting, New Delhi, March – The release of the PG1 report marks a significant step in independent, peer reviewed research into the real rather than supposed risks from using PG and the balancing of the societal, environmental and economic benefits of use.

4.2.3 Expansion and Global Engagement (2018-2020)

2018 – IFA NORM Working Group Annual Meeting, Madrid, March – The PG2 report project kicks off with industry case studies, fostering collaboration and peer review.

2019 – IFA NORM Working Group Annual Meeting, New Orleans, March – A preliminary review of PG2 emphasises the importance of ongoing research and development.

– Annual IFA-China Consultative Group (CCG) Meeting, Beijing, August – The top priority of "Comprehensive Utilisation" for the local fertiliser industry is established, reflecting a global commitment to innovation.

2020 – IFA NORM Working Group Annual Meeting at Global Sustainability Conference, New York, February; COVID – Amid the COVID-19 pandemic, the PG2 report sub-titled **Core Principles Of Management and Use of Phosphogypsum: Leadership, Innovation, Partnership** is released.
– Adoption of Hybrid Meetings – IFA PG/NORM Working Group transitions to biannual hybrid meetings, maintaining engagement despite global disruptions.

4.2.4 Anniversary and New Initiatives (2021-2024)

2021 – Virtual Meetings amid COVID-19 – The PG Working Group meets online twice, adapting to challenges while ensuring continuity in discussions.
– IFA launches Sustainability Committee – The NORM Working Group becomes part of this strategic business unit.
2022 –10th Anniversary Meeting of IFA NORM Working Group, Prague, May –IFA CEO Alzbeta Klein challenges the NORM Working Group to develop a compelling business case for phosphogypsum use, paving the way for future initiatives.
– IFA launches Sustainable Fertilizer Academy[21] – the curriculum of this online training includes a class on the sustainable production and use of phosphogypsum.
2023 – Title Announcement for PG3 – The project is dubbed "From Waste to Inventory," emphasising a transformative approach to phosphogypsum.
2024 – Editorial Consultation Meeting at IFA's GSC Conference, Amsterdam, March – The NORM Working Group discusses the outline of the PG3 report.
– IFA NORM Working Group Annual Meeting, Singapore, May – Update on PG3 report and keynote speech from Li Guang, Secretary General of the CPFIA.

5. The Journey from PG1 to PG3

This IFA report, "From Waste to Inventory" (also referred to as PG3), is the latest publication from the NORM Working Group, following two earlier reports:

PG1: Published in 2016, the report, Phosphogypsum Sustainable Management and Use [16], was initiated by then IFA Chair, Esin Mete. It was conceived as an industry response to the IAEA study on NORM residue management, highlighting PG as a valuable co-product of phosphoric acid production. It followed a precedent set by the oil and gas industry which responded to the publication of IAEA safety report on oil and gas [13] with a complementary industry report outlining how the IAEA recommendations had been acted on in regard to managing NORM issues, especially occupational and environmental health and safety.

PG2: Building on the success of PG1, the second IFA PG report, "Core Principles Of Management and Use of Phosphogypsum: Leadership, Innovation, Partnership" [17], published in 2020, included case studies of successful collaborations between industry, academia, and government agencies in PG applications worldwide.

To further disseminate information on sustainable PG management and use, the IFA regularly dedicates conference sessions, conducts public webinars, runs social media campaigns, produces infographics, and includes PG in its Sustainable Fertilizer Academy curriculum.

The IFA also collaborates with stakeholders globally, including as government representatives in China, where it signed an agreement with the China Petroleum and Chemical Industry Federation (CPCIF) in 2024 to exchange sustainability best practices and enhance PG use from currently 55% to 65% by 2026, and to develop a plan by 2027 to utilise all byproduct in the following decade.

6. Breaking Out: Packaging Materials and Pharmaceuticals

In this category, the main thinking is based on one of the leading members of CPCIF, Guizhou Phosphate Chemical Group (GPCG) which has solved the problem of how to convert the phosphogypsum-based anhydrous gypsum to other polymer materials (30 to 85% of gypsum according to usage), and to make a variety of packaging boxes, shopping bags, paints, coatings and protective clothing. Compared with conventional paper packaging materials, the gypsum packaging offers superior moisture and freeze resistance, as well as ease of recycling use. This makes it easier to identify niche markets with competitive advantages for specific polymer products, and for PG as feedstock for polymers, a large potential market worldwide. GPCG has now built an anhydrous gypsum production line with 300kta capacity, as well as several demonstration lines for packaging material production. GPCG is currently engaging in-depth discussion and collaboration with various market stakeholders to scale up its market presence in this new domain.

7. Conclusion

The evolution of phosphogypsum management over the past decade represents a significant stride towards global sustainability. The IFA, through its NORM Working Group and various initiatives, has been pivotal in driving indus-

21 For the IFA Sustainable Fertilizer Academy see https://ifa-sfa.org/

try-wide change, transforming PG from a waste product to a valuable resource. By integrating best practices and fostering innovation, IFA has helped mitigate environmental challenges and align the industry with key UN Sustainable Development Goals, notably SDG 9 (industry, innovation, and infrastructure) and SDG 12 (responsible consumption and production).

Looking ahead, the path to a fully circular economy will require relentless innovation, stronger international partnerships, and proactive regulatory engagement. IFA's ongoing collaborations, such as the landmark agreement with the China Petroleum and Chemical Industry Federation, underscore its commitment to reaching ambitious goals, such as utilising 100% of PG by 2037. To secure a sustainable future, it will be crucial for industry, government, and academia to continue working together, ensuring that phosphogypsum valorisation becomes a model of environmental and economic success worldwide.

5

CHAPTER FIVE

LOOKING BACK AND LOOKING AHEAD: TRANSFORMATION OF PHOSPHOGYPSUM FROM WASTE TO RESOURCE

Author: Esin Mete, Former President, IFA, President Mt. Agri Consulting

1. Context – Looking Back

In early 2014, under my Presidency, the International Fertilizer Association (IFA) made a pivotal decision to confront an issue that had long been overlooked in the fertiliser industry: the management and utilisation of phosphogypsum (PG). For decades, PG, a by-product of phosphoric acid production, had been considered waste and largely ignored. Against the background of the publication by the International Atomic Energy Agency (IAEA) some nine months earlier of Safety Report 78 on the phosphate industry, in which it classified PG as a coproduct of phosphoric acid [6], recognising the environmental and economic opportunities it presented whether classified as co- or by-product, the IFA formed a PG working group dedicated to investigating how PG could be transformed from a waste into a valuable secondary raw material.

The progress made by the PG Working Group, which now in addition to industry, includes representatives from academia, regulators and UN agencies, has far exceeded expectations. Initially, PG's potential seemed limited, and the challenge of changing the industry's negative perception of it appeared daunting. However, today, PG is no longer regarded as waste. It has evolved into a resource with a wide range of applications that were once unimaginable. PG is now being used in areas as diverse as cancer treatment and biodegradable packaging, as well as a high volume soil amendment and feedstock for cement, marking a significant shift in its valuation. These achievements are not only a testament to the innovative efforts of the PG Working Group but also a point of pride for the entire fertiliser industry.

2. Milestone Pivots

One of the pivotal milestones on this journey from waste to inventory was, and still is, convincing regulators around the world to change their classification of PG. For PG to be seen as a valuable by-product instead of waste, regulatory frameworks had to adapt. Through continuous dialogue and evidence-based advocacy, the working group has succeeded in changing these classifications, and the concomitant regulations, in many countries. As a result, PG is no longer universally categorised as waste but is now recognised for its value as feedstock. Given that this pivot in classification and regulation has already been accomplished in several key regions, releasing a recent surge in creativity among producers as to what uses can safely and profitable made of PG, I am confident that other countries yet to make the transition will soon follow, further unlocking PG's global potential.

3. Looking Ahead

Ten years on from IFA's decision to fully investigate how to make best use of the opportunity for change created by the IAEA Safety Report, it is clear that PG is not waste, but a source of wealth. PG contains valuable components that can be converted into a variety of useful products. Beyond use in fertilisers and soil amendment where the combined calcium and sulphur content is of great benefit to many soil types, PG's potential now extends into industries such as packaging and even healthcare, where it is being explored for use in cancer treatment. The possibilities for PG are vast and its welcome transformation from waste to inventory represents a significant victory for sustainable practices within the industry.

3.1 Tradeable Products

However, the challenge we now face if 100% use is our collective goal is that the production of PG is concentrated in just a few countries, the annual quantities being produced are enormous, not to mention the legacy to which the policy of stacking it without permitting use significantly contributed. In many — perhaps all — of these countries, the local demand cannot absorb all the PG produced. As such, the next logical step is to focus on converting PG into tradeable products that can be exported to countries where there is demand, for example to combat the very severe global problem of salinity in soil for which PG is an excellent remedial amendment.

3.2 International Standards for PG Products and Services

To achieve this, it is essential that these products are manufactured to meet strict international standards in conformity with the same technical and scientific standards expected of all tradeable secondary raw materials, together with best available practices for production, management and valorisation. Consistency in quality and adherence to production standards will be crucial for ensuring that PG-derived products can successfully enter global markets and be integrated into existing supply chains.

4. Innovation, Collaboration and Regulatory Reform

The evolution of PG from waste to a resource demonstrates the power of innovation, collaboration, and regulatory reform. These are the “Double Materiality” attributes which were recognised in the second IFA PG report published in 2020 and which are visibly powering the transition from PG as waste to inventory. As the opening contributions to this report eloquently show, these attributes are now shaping the policy anchors which are framing investment decision makers in institutions such as the European Bank for Reconstruction and Development to consider PG as a "valuable resource within the circular economy". By recognising its true potential, we have not only reduced the environmental burden associated with its disposal but also unlocked new economic opportunities. As the global fertiliser industry continues to evolve, PG stands as a prime example of how once-overlooked materials can become valuable contributors to sustainable growth and development.

CHAPTER SIX

VISIONING THE FUTURE: THE COURSE AND THINKING OF THE COMPREHENSIVE UTILISATION OF PHOSPHOGYPSUM

Author: He, Guangliang (Gordon), Secretary of the Party Committee, Chairman, Guizhou Phosphate Chemical Group


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1. Introduction

In the 1990s, with loans from the World Bank and from the Overseas Economic Cooperation Fund (OECF) of Japan, wet-process phosphoric acid technology was first imported from Japan into China. The national phosphate industry thereafter experienced very rapid growth and consolidation, becoming the major production centre for phosphoric acid (PA) worldwide, concentrated in four provinces, Guizhou, Yunnan, Hubei and Sichuan. Annual PA production expressed as P_2O_5 is more than 20 million tonnes.

1.1 Phosphogypsum

Due to lack of experience and lower environmental standards at the time the wet process was introduced, application of specialised stacking and management techniques and associated custom-built storage facilities for the phosphogypsum was not taken into consideration. Instead, the general Chinese national standard for tailings storage was applied. In the early 2000s, upon completion of the first generation of PA production facilities in China, it became apparent that the PG stacking facilities as constructed could not meet the demands of "seepage-proofing", as pore water drainage points were discovered close to the stacks in active use, causing significant pollution to the ground water.

1.2 Cooperation between Wengfu Group and Ardaman

In 2006, Wengfu Group, now a subsidiary company of Guizhou Phosphate Chemical Group (GPCG), started cooperation with Aardman[22] company from USA by introducing its pore water containment system for phosphogypsum stacks. The initial remediation step was to line the surface of the existing gypsum stack as which at the outset seemed to have obviously alleviated the risk of pollution to the surrounding ground water. But through time the surface lining approach proved insufficient on its own to solve the pore water leaching and further measures were required. Fortunately, for the second generation of PG stacks implemented, constructed in strict accordance with new Ardaman standard [18], the pore water drainage system was fully successful.

1.3 Social and Environmental Consequences and Responses of Wengfu Group and Kailin Group

By the time the second generation stacking technology was in place, the negative impacts of PG on the environment had raised a high level of concern both at government and societal levels and this was a source of mounting pressure on the industry through time. This led Wengfu Group to introduce an innovative strategy which refocused attention on PG use rather than storage. Since the real estate construction boom in China was then in full swing, Wengfu Group (now a subsidiary of GPCG) started a new industrial scale business in PG-based construction materials. It introduced a technology to convert the dihydrate (DH) phosphogypsum it generated as coproduct to the PA into hemi-hydrated (HH) gypsum as a feedstock for producing gypsum blocks, gypsum wallboards and similar materials by casting. At the same time, the company cooperated with several scientific research institutes to develop technology to decompose phosphogypsum (calcium sulphate) to recover sulphuric acid from it and simultaneously to produce cement.

In parallel, Kailin Group, now another subsidiary company of GPCG, invested heavily in research into producing commercial scale gypsum-based building-blocks, while also developing a system founded on a comprehensive set of environmental standards to backfill underground phosphate mining pits. With the exception of underground mine backfilling, which remains a dependable way to consume a considerable tonnage of PG annually, all the above mentioned alternative routes did not fully succeed commercially for a variety of reasons. These included a lack of mature technology, the lack of a complete understanding of the properties of phosphogypsum, and the low value of the construction materials generated from the PG, which make them unprofitable because of transportation and distribution costs, despite their inherent suitability for use in building construction.

1.4 Increasing Regulatory Pressure after 2012

After 2012, the year of the 18th National Congress of the Communist Party of China, the regulatory requirements for the protection of the environment and its eco-systems were further increased significantly. In Guizhou Province, where GPC is located, a new production policy Coupling Phosphoric Acid Production Capacity to Phosphogypsum Consumption Capacity was introduced – the first of its kind in China. This entailed a complementary policy that no new phosphogypsum stacks would be permitted, posing a more demanding challenge for the phosphate enterprises in Guizhou to handle since in effect it made high-volume consumption of their PG compulsory. This new approach spread out from Guizhou province to the major producing centres in other provinces. So, enterprises all came under tough dual pressures, facing both tight cost controls and rigorous environmental protection assessments. The bare facts are that it costs GPC about 200 million USD per year to handle and utilise its phosphogypsum. So, Guizhou and the other phosphate companies in China have but no choice but to tackle the gypsum problem or effectively go out of business.

22 For Ardaman & Associates Inc. see https://ardaman.com/

1.5 Pathway Options

In summary, there were two basic pathways to solve the dilemma of handling and utilisation of phosphogypsum: one was to find certain affordable consumption methods by providing subsidies and incentives (the non-industrialisation, unsustainable pathway); the other, to utilise the phosphogypsum as a resource through creativity and technological innovation (the industrialisation sustainable pathway).

Considering the non-industrialisation pathway, GPC mainly found the available options unsatisfactory: these involved backfilling the underground mine pits, filling open mining pits, using PG as cement retarder, repurposing PG as reclamation or ecological restoration soil, or for road construction close to the gypsum stacks. These methods not only entail a lot of work to meet environmental standards but also depend on substantial economic subsidies. These could be at best short-term expedients, rather than long-term solution. Therefore, commercial logic dictated that a significantly greater effort should be invested in the industrialisation pathway, even though this path is certainly arduous and tortuous.

2. The Three Pathways

Up to now, the industrial pathways of phosphogypsum used by GPC can be summarised in three categories as follows.

2.1 First, Building Materials

In the first category, building materials, the main thinking is based on valorising the inherent properties of phosphogypsum, such as fireproofing, thermal insulation, in environmentally-friendly, low carbon ways, but developing a high and continuous consumption capacity. As a kind of air hardening cementitious material, whether hemi-hydrate or anhydrous, utilising PG to produce building materials has to rise to the challenge of making it both fully hydrated while also preserving its free-moisture content to the extent possible. This entails mastering frustrating requirements during application, especially demanding when these operational demands are combined with the intrinsically cost-sensitive nature of the end users. Facing these tough problems and after years of trial and error, a series of relatively mature market-ready products have now finally been researched and developed by GPCG. These include high-precision, interlocking blocks for rapid construction of building walls, self-levelling anhydrous gypsum for flooring, plastering mortar, alternative walling construction using gypsum spray, high-performance kerbstones, and similar. All these and other products may now be expected to be mass produced to meet market demands as they evolve in the next stage.

2.2 Secondly, Anhydrous Gypsum as Cementing Material

Using phosphogypsum as raw material, it is calcined at high temperature to produce anhydrous gypsum, which has excellent performance as a cementing material or polymer filling material. This is highly innovative and potentially a major breakthrough in what can be done with PG. Greater technical detail is given later in the case study in this report on the **Comprehensive utilisation of phosphogypsum in China.**

2.3 Thirdly, Project 1468 - Sulphuric Acid Recovery and Cement Co-production

The core concept in this category, sulphuric acid recovery and cement co-production based on phosphogypsum decomposition, is not new to the industry but it is attracting new levels of interest and investment. Relatively small-scale industrial facilities had been built decades ago and Wengfu itself accomplished a plot plant nearly 20 years ago, with the key problem being that commercial scale production was not feasible due to the lack of a major breakthrough in the technology.

In 2023, GPCG took a significant risk by building an industrial plant with a combined capacity of 2 trains *700kta, internally called Project "1468". This entails consuming 1.4 million tonnes of phosphogypsum annually, 1. to recover 650,000 tonnes of sulphuric acid, and 2. to co-produce 800,000 tonnes of cement. After one year of optimisation operation, the facilities have reached design quality standard and production capacity, but the economic side is still challenging. Helped, however, by painstaking efforts on adjusting the operation of plant through a combination of practical exploration at factory-level, and cooperation with some specialist R&D institutes, various technical transformations and upgrading modifications have been introduced. These have made it feasible in the course of the next year to reduce the unit cost of production. The plant is now expected to achieve break-even in 1 to 2 years (see Section C 4 of this report).

3. Conclusion

It is now foreseeable that, by using all the above mentioned pathways of industrialisation, the goal of comprehensive utilisation in a sustainable, environmentally friendly and profitable manner, can be realised. So, we hope we can together meet the expectation to solve the phosphogypsum problem that haunted us long enough and to bring great constructive impact to the whole industry.

We also hope that, through further cooperation, wisdom sharing, and concerted efforts, may the global phosphate chemical industry finally solve this world-wide problem of phosphogypsum as soon as possible!

SECTION B

SO, PHOSPHOGYPSUM IS OUR BUSINESS...

If there is a single objective that connects the many and varied case studies in this section of the report, it is to transform phosphogypsum seen from an economic perspective from negative externality to positive internality – another way of saying from waste to inventory. When PG2 was compiled in 2019 this was a dream, as was 100% use. But five years on, both goals are palpably close. If that much is common ground, the business cases behind the newly-forming consensus that the phosphate fertiliser industry is in the phosphogypsum business after all are different by country, company and application. Some of these are so unexpected and novel as to what the actual value proposition is that they propose, they have a frisson of alchemy about them.

Business Drivers

While the offerings are very diverse, the business drivers have a number of common features – features that sit much more comfortably in a circular economic framework than a commodity market. These include.

- **Policy** – eg 100% use; Circular Economic Transition; (Double) Materiality compliance; Holistic approach
- **Values/Social Responsibility** – eg zero waste, primary resource conservation; resource use efficiency including water, land, energy
- **Innovation** – e.g. solving major technical problems restricting use / performance – engineering gypsum, polymer chemistry, pharmaceuticals
- **Profit** – new revenues from PG-based products and services, overall revenue and margin enhancement through cost saving (CAPEX and OPEX) forming a secondary raw materials market – PG alone or as component of mixes; new product development for specialty chemicals
- **Environment** – phase out disposal; use as a soil amendment or anthrosol resource for combating soil salinity, yield loss, desertification, significantly enhancing water and nutrient use efficiency.

The Rise of Secondary Raw Materials

One trend that has advanced rapidly during the eleven months since the compilation of this report began, is the emergence of a new class of feedstock, secondary raw materials. This is certainly a consequence of circular economy thinking, but the uptake of that term has been rapid and very influential – the new name fits well.


1

C H A P T E R O N E

THE CIRCULAR ECONOMY: GYPSUM VALORISATION AT PRAYON, ENGIS, BELGIUM

Authors: Tibaut Theys, Corine Petry, Prayon

Introduction

Prayon[23] is a prominent producer of phosphate-based products, including fertilisers, operating from its site in Engis. The production process yields phosphoric acid and gypsum as a by-product. As it is in Prayon's DNA to have a fully integrated process to reduce by-product emissions, the company's approach to phosphogypsum (PG) has always been based on circular economy principles (see Figure 4) and green investment.

Fig. 3. *The Prayon phosphogypsum plant, Engis, Belgium just opposite the construction materials facility*

For more than 45 years, a significant portion of the gypsum the company produces has been valorised mainly for construction purposes in various forms such as plaster, cement additives (see Figure 3). But agricultural applications of PG as a soil amendment have been popular with local farmers for just as long, welcoming both the moisture retention properties PG as a soil amendment brings to the soils but also the beneficial side effects this property of PG has on biodiversity in the Meuse valley. For Prayon, its gypsum is a byproduct with a real and lasting market value not a high-risk liability on the balance sheet.

1. Valorisation and Use – Contributing Factors

The valorisation and use of gypsum has been made possible due to several factors. Prayon has invested in technical advancements to optimise gypsum utilisation. Tailored solutions such as the Central Prayon and Dihydrate Attack-Hemihydrate Filtration (DA-HF) [19] processes ensure the production of dry gypsum, significantly reducing its drying cost. The company maintains a dedicated research team continuously exploring novel approaches to gypsum valorisation. Strong, long-term relationships between Prayon and both national and international independent academics, scientists, and authorities contribute to public confidence in the company's values and good governance. This allows the company to promote gypsum as a by-product, facilitating its utilisation and wider social acceptance.

Commercially, Prayon has fostered a strong partnership with a major plaster-producing company (see Figure 4) and as a feedstock Prayon's gypsum competes favourably with natural gypsum, yielding a double win in terms of conservation of primary resources of natural gypsum and profitability. With the expected decrease in availability of gypsum from coal plant flue gas desulphurisation (FGD) in the coming years, Prayon's market position is poised to further strengthen.

1.1 The "Environment-Competitiveness" Relationship

Over the longer term the company's experience has proven that environmental, legal and technical constraints actually favour a strategic and market commitment to combining innovation, environmental responsibility and company profitability. This is in line with the hypothesis of Porter and Linde [20] that regulations are potential stimuli to innovation and competitivity provided that the local ecosystem allows time to implement such a company double materiality culture.

This requires a synthesis of new technical and scientific capabilities, complementary technologies and access to financial instruments which enable the necessary capital investments to be made, where and when required and on realistic terms. It took a decade from the crystallisation of the first idea, to the development, maturation and pilot testing of the technology and finally the implementation of the first Central-Prayon industrial unit and the eventual addition of the DA-HF process.

1.2 Prayon's Commitment to Circular Economy and EU Initiatives

Prayon's approach to managing phosphogypsum (PG) is also naturally aligned with the principles of the circular economy (see Figure 4), the EU's strategic initiatives such as the Action Plan, Green Deal and the Critical Raw Materials Act (CRM Act)[24] [21] without the need for any major modifications, either of attitude or technology (see Figure 5).

By integrating PG into its production processes some forty years ago and viewing it commercially as a valuable resource rather than waste, Prayon anticipated the need to meet stringent environmental regulations and contribute to the EU's

23 For Prayon SA see https://www.prayon.com/en/

24 The CRM Act came into legal force in the European Union May 24 2024

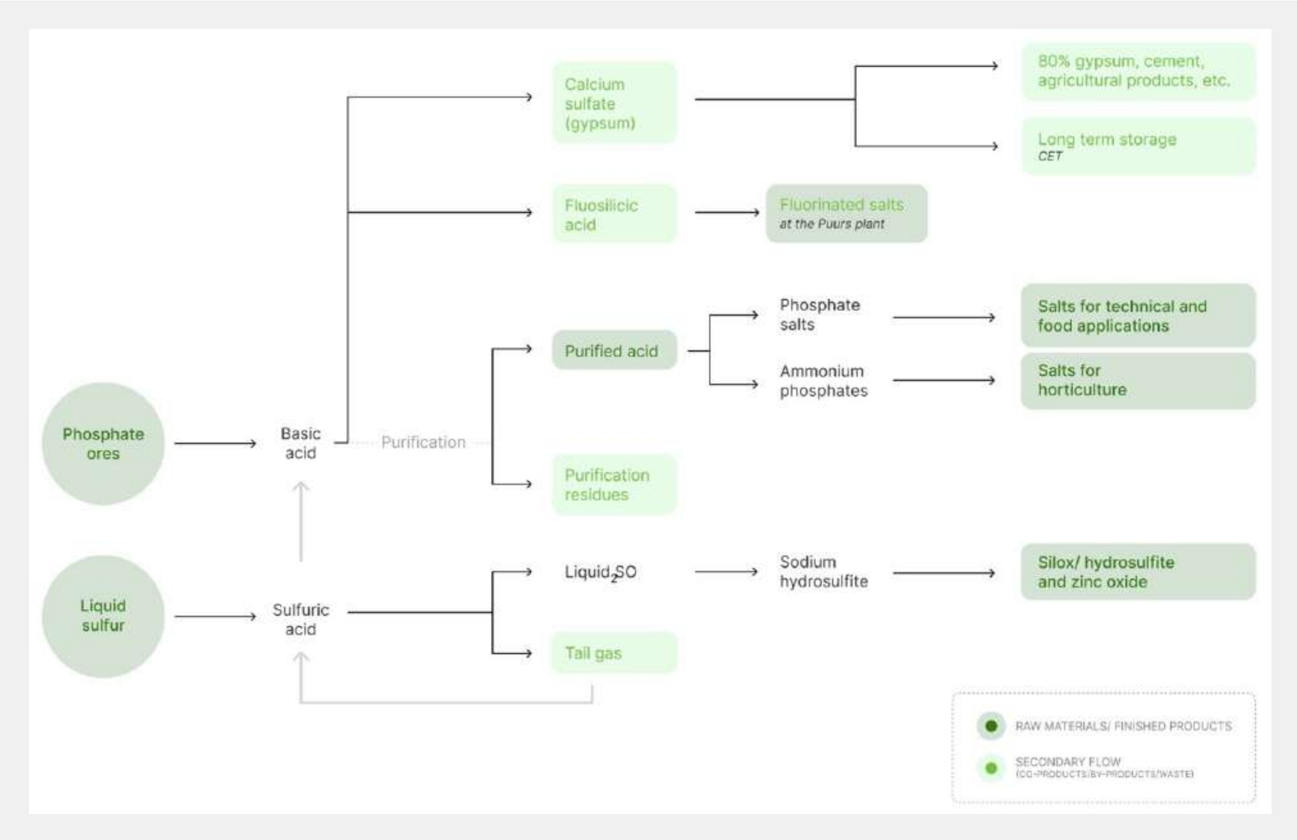


Fig. 4. *Prayon's production of PG according to circular economic principles*

sustainability goals before these were adopted as the defining principles of contemporary policy and regulatory goals.

1.3 Partnership – Close Working Relationship with the Local Regulatory Authority

Since the start of its new co-product PG strategy to protect the environment, Prayon has enjoyed two long-term partnerships: first, continuous close cooperation with the local regulatory authority and secondly, an intermittent but high-value collaboration with an independent technical-scientific centre of excellence, the nearby University of Liège. Prayon has continuously fostered very close collaboration with the local authorities, based on trust, mutual respect, and a sustained effort to protect and improve the environment in which the plant operates.

This relationship is partially reflected in a public environmental report available through a dedicated website[25] which shows the present condition, and the efforts made to mitigate any negative operational impact. Partnering with the local regulator under tightly determined rules of engagement allows Prayon to work together with regulatory services in a constructive, on-going sustainability partnership, fostering in the process the development of science and evidence-based solutions to protect the environment. Sometimes intermittent collaboration with the University resulted in a double win; a biodiversity plus for nature and a major cost saving for Prayon.

In 2014, the company was unexpectedly advised by the University not to fully cover the gypsum pile deposited annually on the ground with a soil cap, contrary to previous practice. The policy change was designed to ensure the re-colonisation of the lower levels of the Meuse valley by rare plants. A University study appeared to confirm that these plants were at risk due to climate change of being lost to the biodiversity range of the area, but that if the favourable attributes of PG as a growing medium (anthrosol), including its significant moisture-retaining capabilities were introduced into the local eco-system, it would likely recover. Ten years on, the eco-system recovery has indeed happened with the return of the at-risk flora and fauna.

25 See Prayon Sustainability Report https://sustainabilityreport.prayon.com

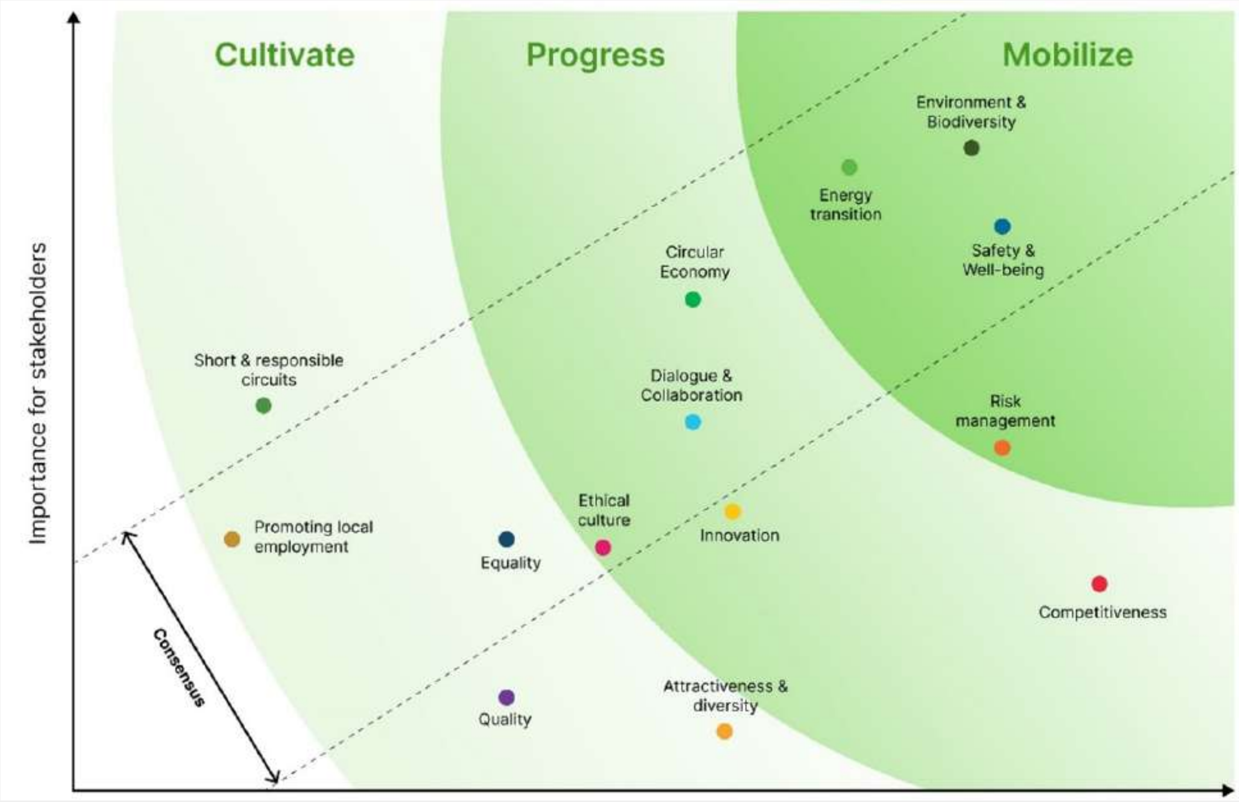


Fig. 5. *The Prayon Materiality Matrix (2021)*

Currently some 85% of the nearly 800,000 t of gypsum produced annually at Engis is sold. The remainder is stored on the ground near the plant where, in the opinion of both independent academia and the regulator, the stability and purity of the production process enable this residual fraction of the PG output to be safely kept available for potential future use without the need for a liner. The first formal permit to store unused PG close to the Engis production facility was issued in 2001, with an initial expiry date of 2015. Not least because of the biodiversity gain discovered in 2014 from leaving some of the stored PG uncapped by soil, the permit was renewed on expiry until 2035.

2. Materiality Gains through Partnership

Partnerships with all stakeholders, regulators, academia and most significantly the local community residing near to the Engis production plant are fundamental to Prayon's approach to defining its materiality values. These can be articulated and schematised by reference to the company's materiality matrix (Figure 5)[26].

26 See in particular the Prayon Materiality Matrix, Prayon 2030 Strategic Vision, p.11 https://sustainabilityreport.prayon.com/wp-content/uploads/2024/07/GSR-PRAYON-EN-2024.pdf

The results of compiling the Materiality Matrix (Figure 5) demonstrate that the Corporate Social Responsibility (CSR) philosophy adopted by Prayon in 2021 is in line with its stakeholders' expectations and its three declared priorities Environment and Biodiversity, the Energy Transition and Safety and Well-being. Prayon sees these as primary challenges shared in equal measure by partners.

2.1 Direct and Indirect Alignment by Zone

The Materiality Matrix is used as a tool to implement and monitor how the materiality values are applied both within the company and its innovative business and technical cultures, but also how that reaches outside the company into the local and regional communities. This is shown on the matrix by "zone", above and below the "consensus" line, where company and community think and act as one.

Above but very close to the consensus zone, Prayon has already paid close attention to the "Short & Responsible Circuits" pillar, as the monitoring indicator for this pillar is higher than the set target.

- **Cultivate** = initiatives aimed at generating a continuous progress dynamic and remaining within the average range for companies within its sector
- **Develop** = major initiatives aimed at achieving significant progress towards implementing the best practices in its sector
- **Mobilise** = the Group's priorities aimed at positioning Prayon as a leader within its sector.

Below the consensus zone, pillars can be observed that are more closely linked to Prayon's internal operations and are therefore of less direct interest for its stakeholders. As the quality pillar was rated highly by all the relevant parties, it must be cultivated as part of a continuous progress dynamic. Risk management and competitiveness are key to the company's long-term future and continue to represent strategic priorities for Prayon.

This Materiality continuum is reflected in the way PG is valorised and used. The direct commercial value of the gypsum contributes tangibly to the profitability of the company through product sales, but also through the continuous savings linked to the elimination of the greater part of the storage cost. The indirect value of Prayon's long-term collaborations with independent academics, scientists, and regulatory bodies contributes intangibly to its long-term, sustainable success as a whole, not just in finding a suitable PG storage management solution. The link is innovation.

2.2 Innovation Serving the Industry – The Central Prayon Technology

Until the 1980s, the Engis plant was producing phosphoric acid using a DH process that did not support the ability to valorise and use the gypsum produced. This situation was clearly not sustainable in the long term, and large quantities of unused PG accumulated every year. Prayon was faced with a harsh but clear choice: to either stop production and start producing in a location with lower environmental constraints, or come up with a radically innovative solution that produced a gypsum that could be valorised and sold. The chosen solution was to completely reengineer the phosphoric acid production process to yield a phosphogypsum (PG) that could be sold long-term, primarily into the local and regional market for construction materials.

3. Process Description

The plant at the Prayon headquarters in Engis, Belgium (Figure 6), operates a unique dihydrate-hemihydrate (DH-HH) manufacturing system known as the Central-Prayon Process.

Fig. 6. *Prayon manufacturing hub, Engis*

In the 1960s, Prayon in Belgium and Central Glass of Japan independently developed their own two-stage DH-HH processes. Upon discovering the close similarities between their methods, they decided to join forces. This collaboration led to the development of the unified, optimised, two-stage "Central-Prayon Process" (Figure 7).

3.1 Technology Features

The aim of the two-stage process is 1. to optimise the parameters in Stage 1 to produce high-quality phosphoric acid, and 2. to select different parameters in Stage 2 to produce high-quality "Alpha" Hemi-hydrate gypsum (α-HH). In the dihydrate I(DH) stage (Stage 1), the P_2O_5 concentration is maintained at about 32-35%, while (Stage 2) the calcium sulphate ($CaSO_4$ -gypsum) leaving the filter in the hemihydrate form contains less than 0.5% P_2O_5.

The $CaSO_4$ produced is fed to a curing area where the α-HH is stored temporarily, naturally converting to DH over some 28 days, absorbing the majority of free water during the "self-drying" process. The DH is then reclaimed, crushed in a roller crusher and fed to the downstream Stucco Plaster plant which may be located on the same site or shipped to one of a variety of third-party customers such as a cement company or fertiliser producer.

4. Future Trends

4.1 Volume Aspects

Currently, the main competitor to the gypsum produced by Prayon is Flue Gas Desulfurisation (FGD) gypsum. FGD is a byproduct of washing the flue gases released by coal-fired electricity plants. Within a 500 km radius of the Engis plant, approximately 1.6 million tonnes of FGD gypsum are produced annually. Due however, to Germany's commitment to "Carbon Zero" ie substantially reducing its national CO^2 emissions to

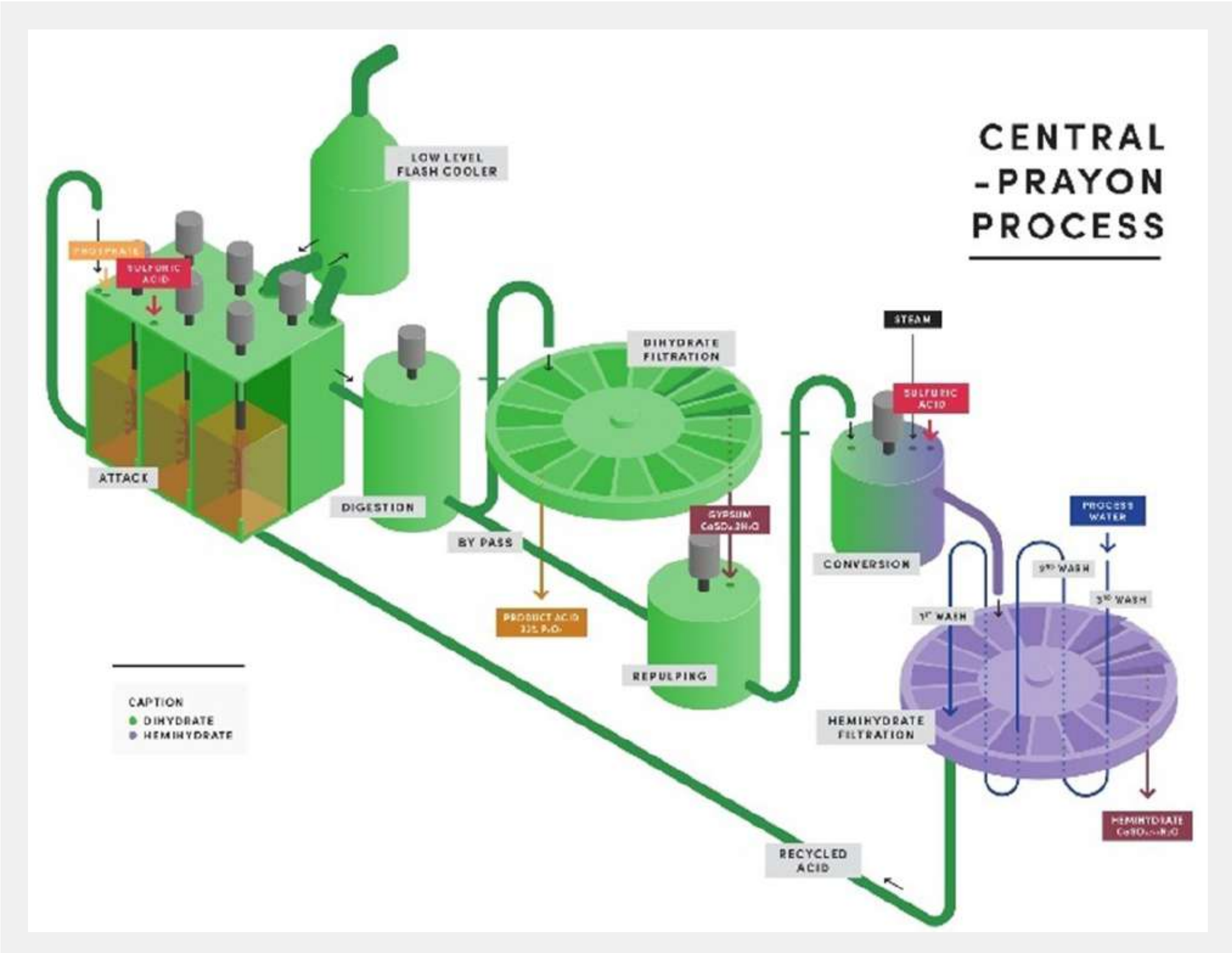


Fig. 7. *Central Prayon Process*

meet climate action goals, this FGD capacity is expected to decrease by some 50% to 840,000 tonnes by 2030. Given that FGD gypsum is predominantly used as a feedstock in the plaster industry, significant quantities of alternative sources of gypsum will be needed by the industry to make up missing feedstock. In the pursuit of CE solutions to this challenge the goal is to used secondary raw materials (SRMs) in preference to virgin natural gypsum.

4.2 Quality Aspects

In addition to PG's obvious merits as a SRM substitute for natural gypsum, the gypsum produced during the phosphoric acid production process also contains materials such as rare earth elements (REEs), which may in the future become recoverable at commercially viable scale.

These observations lead Prayon to anticipate that the "secondary" gypsum inventory that the company produces year on year could open up new sources of revenue for the company fully in line with the long-standing company commitment to innovation, UN SDG 9.

5. Conclusion

Prayon's strategic approach to gypsum valorisation exemplifies a commitment to sustainable practices and innovation within the framework of the circular economy. By leveraging advances in technology, such as the Central Prayon process, and fostering strong partnerships with the authorities and academic institutions, Prayon has transformed phosphogypsum from a by-product into a valuable resource with new applications emerging on the horizon.

The company's proactive stance has enabled it to contribute to EU and UN sustainability goals[27] dating back to even before the concepts of sustainability and markets for secondary raw materials had taken such a dominant place in the mineral resource economy. As the availability of FGD gypsum declines due to environmental policies, Prayon's gypsum stands to gain a competitive edge, particularly with its high quality and potential for future reuse. The company's ongoing research and innovative applications for its gypsum further underscores its forward-thinking approach and potential for continued growth.

Prayon's experience highlights how environmental and regulatory challenges can drive innovation, ultimately enhancing profitability and reinforcing the hypothesis that reasoned and well-timed regulations which take into account best available practices can be a source of competitive advantage. Moving forward, Prayon's dedication to sustainability and efficiency will likely position it favourably on the global scene.

27 See Prayon Sustainability Report https://sustainabilityreport.prayon.com

CHAPTER TWO

COMPREHENSIVE UTILISATION OF PHOSPHOGYPSUM IN CHINA

Authors: China Phosphate and Compound Fertilizer Industry Association, Secretariat Experts and Member Company Leading Representatives


2

1. Overview and Context

As the world's population grows, so global demand for food continues to increase. In parallel, a series of agricultural policies introduced by China have also progressively promoted demand for phosphate fertilisers. According to statistical monitoring by the China Phosphate and Compound Fertilizer Industry Association (CPFIA)[28], by 2023 China's total phosphate fertiliser production capacity had stopped falling and started to rebound. So ended the downward trend of phosphate fertiliser production capacity since 2016, by the end of 2023 recovering to reach an annualised output of 21.7 million tonnes of P_2O_5, a year-on-year increase of 2.3%. From 2015, Phosphoric acid (PA) output likewise followed an overall downward trend for several years until 2020, but since then, affected by patterns of both international trade and domestic demand, PA output has fluctuated slightly.

At the end of 2023 annualised output reached 16.151 million tonnes of P_2O_5, a year-on-year increase of 6.1%. Corresponding PG production climbed to 81 million tonnes, a year-on-year increase of 5.2%. Total PG utilisation in 2023 reached 45 million tonnes, an increase in use of 6.2 million tonnes from the previous year. This equates to a 16.0% rise in the annual comprehensive utilisation (CU) rate in 2023 to 55.6% of annual PG production reflecting a significant success for the China national comprehensive utilisation policy and putting the industry well on track for reaching the CU rate target of 65% by the end of 2026.

2. PG Comprehensive Utilisation Policies by Province

2.1 The Benchmark 2019 - Yangtze River Economic Zone

While the policy of comprehensive utilisation of PG is overseen at national level, the implementation of that policy is managed on a provincial basis and by company (see section 3 below). And while technological approaches to pre-treating all PG to produce “harmless” (purified) PG to facilitate eventual 100% use differ by province the strategic objectives are identical.

The Yangtze River Economic Zone (YREZ) is the main area for phosphate fertiliser production in China and is therefore simultaneously the main producer of phosphogypsum. To protect the green ecology of the Yangtze River, in 2019 the Ministry of Ecology and Environment issued the **Implementation Plan for the Special Characterisation and Remediation of "Triple Phosphorus" Levels in the Yangtze River**. The primary objectives were to:

1. solve the problem of excessive phosphorus in some water bodies and wetlands in the Yangtze River Economic Zone
2. standardise the management of phosphorus-related enterprises
3. eliminate excess phosphorus from the YREZ ecosystem at source.

Regarding the hidden dangers to the water environment caused by gypsum, seven provinces (cities) including Hubei have been guided to carry out:

- comprehensive investigation and rectification
- long-term monitoring of groundwater in phosphogypsum process water reservoirs
- effective collection of leachate, safe treatment, and discharge in compliance with standards
- increased protection of phosphogypsum stockpiles
- promotion of phosphogypsum stockpiles.

2.2 Comprehensive Utilisation of Gypsum

To ensure the implementation of the plan, the **Technical Guidelines for the Special Investigation and Remediation of "Three Phosphorus" in the Yangtze River** were issued, and similarly **Guidelines for the investigation of problem enterprises and key points for rectification** were formulated around the "Three Phosphorus" enterprises to ensure regulatory compliance by all of them.

2.3 Ecological Environment

In 2020, the Ministry of Agriculture issued the **Notice on Effectively Conducting Environmental Impact Assessment and Pollution Emission Permit Management of "Three Phosphorus" Construction Projects**, which clarified that phosphate fertiliser construction projects should implement a policy of "use-based production". That is, the permitted wet process production capacity would be determined by a reciprocal commitment to comprehensive utilisation of the phosphogypsum that resulted from the phosphoric acid production. This was the first time that the policy of “determining production as reciprocal of consumption” had been proposed in a national document.

During this period, in order to reduce the burden on enterprises, the Ministry of Finance and the State Administration of Taxation issued tax policies to support the comprehensive

28 For background information on China Phosphate and Compound Fertilizer Industry Association see https://www.echemi.com/cms/1762749.html

utilisation of phosphogypsum - the **Announcement on Value-Added Tax Policies for Comprehensive Utilisation of Resources** - stipulating that taxpayers selling locally produced products derived from feedstock drawing on designated phosphogypsum resource comprehensive utilisation products could enjoy a 70% VAT refund upon finished product collection.

Entering the **14th Five-year Plan** in March 2021, the National Development and Reform Commission, the Ministry of Science and Technology, the Ministry of Industry and Information Technology and other ministries and commissions jointly issued the **Guiding Opinions on the Comprehensive Utilisation of Bulk Solid Waste during the 14th Five-Year Plan**. This proposed to broaden the comprehensive utilisation of PG by increasing the promotion of its use in two complementary ways: first, by the application of PG in the production of cement and new building materials; and secondly, on the premise of meeting environmental requirements, by testing the use of PG in different mixes, both as a soil amendment and in roadbed. At the same time, the processing of bulk solid residues for using phosphogypsum in "green" buildings is encouraged.

This might take the form of innovative wall panels, decorative plasters and ceramics, or deploying new walling materials to construct rural public infrastructure such as community buildings. The **14th Five-Year Plan** "Circular Economy Development" clearly states that the channels for utilisation of bulk solid waste (secondary raw materials) such as PG should be favoured, especially to expand the scope of use in ecological restoration using "green building materials". Other "green projects" should also be fostered, substituting primary resources with reusable secondary materials, in the process conserving precious primary resources for use by future generations.

2.4 Double Carbon Goal

The establishment of the "double carbon" climate action goal marks China's more active role in global climate governance and reflects China's important sense of national responsibility and public determination in mitigating climate change. In 2021, the State Council issued the Carbon Peak Action Plan before 2030, proposing to strengthen the comprehensive utilisation of bulk solid waste, focusing in particular on resources such as by-product gypsum. Supporting and promoting large-volume, large-scale, and high-value utilisation, encourages the use of phosphogypsum to replace primary non-metallic minerals, sand and gravel and other resources. It also stimulates the application of phosphogypsum in soil improvement, structural fill, roadbed construction, and similar while ensuring public safety and environmental protection.

In 2022, six Ministries including the Ministry of Industry and Information Technology issued the **Guiding Opinions on Promoting High-Quality Development of the Petrochemical and Chemical Industry during the "14th Five-Year Plan"**, to promote the coupled development of complementary industries, improve the efficiency of resource recycling, and proportionately increase the use of industrial by-products such as phosphogypsum as part of a policy of CU of all solid waste. This was designed in general to strengthen resource value-chains, strengthen the supply security of raw material resources, maintain the safety and stability of the industrial chain and supply chain. More specifically it was intended to put in place multiple measures to promote production efficiency, resource utilisation and harmlessness of phosphogypsum, and steadily promote the "determination of production based on maintaining balance with demand" in the phosphorus chemical industry.

2.4.1 Accelerating the Comprehensive Utilisation of Industrial Resources

The Implementation Plan on **Accelerating the Comprehensive Utilisation of Industrial Resources** clearly points out that the comprehensive utilisation of phosphogypsum will be promoted to increase both quantity and efficiency, and phosphate fertiliser production enterprises will be encouraged to strengthen process management to improve the resource-recyclability phosphogypsum from the filter or the stockpile. This policy led to a breakthrough in promoting the purification pretreatment of PG – the traditional bottleneck of PG valorisation and use has been resolved by adapting PGuses to meet local needs and market conditions, and by formulating harmless treatment methods and technologies for phosphogypsum use based on local priorities. One major consequence was to recover sulphur from PG resources and use sulphuric acid in the co-production of cement and alkaline fertilisers, the production of high-strength alpha gypsum powder and its derivatives.

In the interest of ensuring occupational, public and environmental protection, another major consequence was to explore the use of phosphogypsum in high-volume mine backfill, and road materials. In the Provinces of Hubei, Sichuan, Guizhou, Yunnan and other smaller markets, PG was used in the construction of large-scale and efficient utilisation PG demonstration projects to stimulate major projects counterbalancing "island" non-scalable, case by case solutions.

2.4.2 Work Plan for Steady Growth of the Building Materials Industry

The **Work Plan for Steady Growth of the Building Materials Industry** pointed out the need to promote coupled industrial growth construction materials. These include the general policy to combine the comprehensive utilisation of regional waste with the technological transformation of cement kilns and tunnel kilns for wall materials. The result was the construction of new wall materials, synthetic sand and gravel projects. On the premise of ensuring product quality and ecological safety, enterprises were encouraged to improve their ability to absorb industrial waste in products such as cement, concrete, wall materials, ready-mixed mortar, solid waste ceramics, lightweight aggregate, and synthetic sand and gravel. Gradually the range of secondary raw materials that could be valorised grew to significant proportions.

2.5 April 2024 – A Major Milestone

In April 2024, seven Ministries including the Ministry of Industry and Information Technology (MIIT) jointly issued the **Action Plan for Comprehensive Utilisation of Phosphogypsum** establishing that by 2026, the comprehensive utilisation rate of phosphogypsum would reach 65%. Likewise, the comprehensive consumption volume (including comprehensive utilisation volume and purified PG) would achieve a dynamic balance between chemical harmless pre-treatment capacity and production volume. In response a set of demonstration projects for comprehensive utilisation of phosphogypsum was implemented by the leading professional enterprises, building 10 industrial scale PG purification plants for deployment in Yunnan, Guizhou, Sichuan, Hubei, Anhui and in smaller production centres. The outcome is that since April industrial chain resilience has been significantly enhanced, and an integrated sustainable development template procedure has been formed with coordinated efforts from upstream and downstream operating units and coordinated utilisation across industries and regions.

3. Main policies issued by provinces and cities in key phosphate fertiliser producing areas

3.1 Guizhou Province

Since the **Opinions of the Provincial People's Government on Accelerating the Comprehensive Utilisation of Phosphogypsum Resources** was issued in 2018, requiring the full implementation of "consumption-based production" of phosphogypsum, a series of relevant supporting policies have been formulated to guide and encourage the use of phosphogypsum. The **Work Plan for the Promotion and Application of Phosphogypsum Building Materials in Guizhou Province** and the **Notice on Increasing Efforts to Promote the Application of Phosphogypsum Building Materials** mandated the promotion of phosphogypsum building materials and the large-scale promotion and application of phosphogypsum building materials, making the construction industry an important player in the consumption of phosphogypsum.

As a result, in 2023 the **Guizhou Provincial Department of Industry and Information Technology** released the **Guizhou Province Industrial Sector Carbon Peaking Implementation Plan** and the **Guizhou Province Building Materials Industry Carbon Peaking Implementation Plan**, clearly requiring the promotion of alternative utilisation of low-carbon raw materials and gradually reducing carbon emissions. As a result, the use of acid salts was reduced and inter-industry coupling was strengthened, accelerating the substitution of non-carbonate raw materials in the cement industry. This led to higher substitution of calcium-containing resources such as calcium carbide slag, phosphogypsum, fluorogypsum, manganese slag, red mud, and steel slag while at the same time ensuring the quality of cement products was maintained or enhanced.

This resulted in:

- limestone use in more balanced proportions
- lower carbon dioxide emissions in the cement production process
- development of a green building materials product system
- using industrial by-products such as gypsum, gangue, fly ash and other solid waste to produce wall materials
- technical equipment development, and
- new product development.

While policies support the comprehensive utilisation of phosphogypsum, Guizhou Province has also included the comprehensive utilisation of phosphogypsum and other renewable resources into provincial-level special financial projects, providing certain financial support to promote green and low-carbon recycling development. In addition, Guizhou Province pays attention to pollution prevention and control during the comprehensive utilisation of phosphogypsum.

In July 2024, the Guizhou Provincial Department of Ecology and Environment issued the **Guizhou Province Technical Specifications for Harmless Treatment, Comprehensive Utilisation and Temporary Storage Pollution Control of Phosphogypsum (Trial)**, formulating the overall requirements for the purification treatment, comprehensive utilisation and temporary storage of phosphogypsum, within comprehensive utilisation control guidelines.

Precise specifications such as comprehensive utilisation control indicators, temporary storage of phosphogypsum resources, and environmental and pollutant monitoring are aimed at further strengthening the prevention and control of phosphogypsum pollution in Guizhou Province, standardising the environmental management of purification treatment, comprehensive utilisation and temporary storage of phosphogypsum, while promoting phosphorus green development of chemical industry.

3.2 Yunnan Province

The **Three-Year Action Plan for Resolutely Fighting against Industrial and Communication Pollution Prevention and Control** released in 2018 initiated building a number of comprehensive utilisation facilities for industrial resources, vigorously promoting the comprehensive utilisation of industrial solid waste such as phosphogypsum, smelting slag, and tailings in the Yangtze River Economic Zone. To standardise the application of phosphogypsum in the field of building materials, in 2022 the Yunnan Provincial Department of Housing and Urban-Rural Development issued the **Technical Guidelines for the Application of Phosphogypsum Building Materials in Yunnan Province**.

In July 2022, with the joint efforts of Yuntianhua Co., Ltd., China Phosphate and Compound Fertilizer Industry Association and other parties, the General Office of the Ministry of Ecology and Environment issued the **Reply Letter on Matters Concerning the Use of Phosphogypsum in Mine Ecological Restoration Projects after Being Harmless** to encourage Local authorities to formulate purification treatment plants for phosphogypsum based on local conditions. The parameters were to expand resource utilisation in multiple fields, channels, and methods, and require work on backfill feasibility assessment, strengthening phosphogypsum quality indicator control, and implementing the main responsibilities of pollution prevention and control.

Against this background, Kunming City actively carried out the formulation of local standards for modified phosphogypsum for ecological restoration in mines in August 2022 and issued three local standards in 2023. In December 2023, the Yunnan Provincial Department of Industry and Information Technology released the **Work Plan for Comprehensive Promotion of Comprehensive Utilisation of Phosphogypsum in Yunnan Province**, proposing that by 2025 the comprehensive utilisation of phosphogypsum in the province would be effectively expanded, the level of comprehensive utilisation would be significantly enhanced, and the comprehensive utilisation rate would reach the target of 75% that year.

In the same year, the Kunming Municipal People's Government Office issued the **Kunming City Three-Year Action Plan to Comprehensively Strengthen the Comprehensive Utilisation of Phosphogypsum (2023-2025)**, which also proposed to "strictly control increments, consume stocks", and based on the principle of "dynamic balance", was designed to lift the comprehensive utilisation rate of phosphogypsum in Kunming to 52% in 2023, 64% in 2024, at a minimum reach 73% by 2025 while striving to reach 75%.

In August 2023, the **Yunnan Provincial Department of Industry and Information Technology and three other departments released the Yunnan Provincial Industrial Sector Carbon Peak Implementation Plan**, which was designed to: 1. achieve a significant rate of substitution of secondary raw materials for primary, 2. increase the proportion of phosphogypsum used as substitute for primary materials, and 3. reduce the use of calcium-based limestone raw materials in cement production – in sum, where technically feasible, reliase the comprehensive utilisation of phosphogypsum.

Enhanced specifications such as comprehensive utilisation control indicators, temporary storage of PG resources, and environmental and pollutant monitoring are aimed at further strengthening measures for both prevention and control of PG pollution in Guizhou Province. The planned outcomes are 1. standardisation of purification treatment measures for PG environmental control; 2. transforming PG disposal stacks into temporary storage facilities pending eventual comprehensive utilisation; and 3. promoting "green" phosphorus production methods in the fast-changing chemical industry.

3.3 Hubei Province

The development strategy of the Yangtze River Economic Belt "jointly focuses on large-scale **protection** and does not engage in large-scale **development**". the development focus is on **high quality**. In 2018, as an important phosphorus chemical province in the Yangtze River Basin, the General Office of the Hubei Provincial People's Government issued the **Supporting the Provincial People's Government along the Yangtze River: Implementation Options on the Transformation and Upgrading of the Chemical Industry.**

It required accelerating the comprehensive utilisation of phosphogypsum resources, formulating policies and measures to encourage the comprehensive utilisation of phosphogypsum resources, providing technical support and fiscal and taxation policy support for the comprehensive utilisation of phosphogypsum resources, while supporting the addition of phosphogypsum comprehensive utilisation projects.

According to the National Resource Comprehensive Utilisation Value-Added Tax Preferential Catalogue, enterprises that use more than 70% of their product raw materials to produce bricks (tiles), bricklaying, wallboard products, gypsum products, and commercial fly ash with waste residues such as phosphogypsum are subject to reduced tax rates, of which 90% is included in total income. In 2022, the Hubei Provincial Development and Reform Commission issued the **Notice on Accelerating the Construction of Demonstration Construction of Comprehensive Utilisation of Bulk Solid Waste**. This requires that by 2025 the comprehensive utilisation rate of bulk solid waste in national demonstration bases should reach more than 75%.

In the same year, the Hubei Provincial Department of Finance **took the Decision to Incorporate Phosphogypsum into the Scope of "Other Solid Wastes" in the Environmental Protection Tax Items** to include phosphogypsum in scope of "Other Solid Waste". Subsequently, that May the **Environmental Protection Tax Items and Amounts** were attached to the **Environmental Protection Tax Law of the People's Republic of China**, Hubei. The province promulgated the **Hubei Province Phosphogypsum Pollution Prevention and Control Regulations**, the first local regulation in the country to focus specifically on the prevention and control of pollution from phosphogypsum.

In May 2023, the Hubei Provincial Department of Ecology and Environment released the **Three-Year Action Plan for the Construction of a "Waste-Free City" in Hubei Province**, which pointed out that it was necessary to strengthen source control, promote the balance between phosphogypsum production and consumption, promote green advanced technology, and reduce the production of phosphogypsum — in sum, comprehensively promote the harmless treatment of phosphogypsum.

In terms of deadline, by 2025, 100% of the newly generated phosphogypsum in the province is to be pretreated, and the comprehensive utilisation rate is required to meet the requirements of national and provincial regulations. Financial support will be advanced to producers, and special funds will be coordinated at the provincial level. These funds are to be provided from local finances in support of the comprehensive utilisation policy, but in a manner directly accountable at local level.

In October 2023, the General Office of the Hubei Provincial People's Government issued the **Implementation Plan for the Transformation and Upgrading of the Chemical Industry in Hubei Province** (2023-2025), requiring that by 2025, the comprehensive utilisation of phosphogypsum should exceed 65%. All newly-generated phosphogypsum has to be pretreated, promoting the coordinated and clustered development of the upstream and downstream phosphorus chemical industry value-chains. "Small, scattered and polluting" enterprises with poor governance capabilities are to be closed down completely and decommissioned, eliminating any phosphogypsum derivative product generated without the applicable mining and processing permits, of mid-to-low-end quality and value, high emissions. At the same time, the consolidated production capacity of the top five phosphate fertiliser enterprises in the province must exceed 70% of the province's total output, thereby forming a group of industry-leading producers capable of competing at the international level. Safety procedures and environmental supervision of phosphogypsum warehouses are to be strengthened, promoting the "one warehouse, one policy" management of phosphogypsum to strictly prevent safety and environmental risks caused by leakage from or spillage of individual phosphogypsum piles.

3.4 Sichuan Province

In 2022, the Provincial Department of Economy and Information Technology issued the **Sichuan Province's "14th Five-Year Plan" Industrial Green Development Plan**, to maintain the "balance between production and consumption" of regional phosphogypsum, while broadening the utilisation channels of phosphogypsum, and continuing to promote the use of phosphogypsum in the production of cement and new types of phosphogypsum. Utilisation of building materials and other fields, for the purpose of ensuring environmental safety, were prescribed to explore the application of phosphogypsum in soil improvement, mine back-filling, roadbed materials and other fields. This would demonstrate and promote the effective resource utilisation technology of phosphogypsum and other industrial waste residues and improve resource utilisation efficiency.

In October of the same year, seven departments, including the **Sichuan Provincial Development and Reform Commission** jointly issued the **Sichuan Province's "14th Five-Year Plan" Solid Waste Classification Disposal and Resource Utilisation Plan** to promote the use of phosphogypsum in building materials and roadbed materials, and to modify phosphogypsum to be environmentally suitable for use for "in-ground" applications such as promotion and application as soil amendment or remediation agent and other in-ground uses, such as roadbed.

In October 2023, the Sichuan Provincial Department of Economics and Information Technology released the **Work Plan for Further Promoting the Comprehensive Utilisation of Industrial Resources in Sichuan Province (2023-2025)**, which clearly requires that by 2025 the comprehensive utilisation capacity of industrial resources will be significantly improved, striving to comprehensively integrate bulk industrial solid waste. The utilisation rate must increase continuously by an average of 1% per year until phosphogypsum is fully consumed (including comprehensive utilisation and safe disposal). Waste production and waste enterprises are encouraged to add purification processes for by-product gypsum to reduce alkali metal salts and soluble phosphorus in by-product gypsum, soluble fluorine, organic matter and other harmful impurities.

3.4.1 Green Building Materials

In counter-balance, the emphasis shifts to a focus on promoting the application of industrial by-product gypsum in green building materials and prefabricated wall materials, encouraging the development of mixed-phase type II anhydrous gypsum, gypsum hollow blocks, thermal insulation and sound insulation materials and other high quality materials. The value-added material product system actively promotes the application of industrial by-product gypsum in roadbed materials, ecological restoration, mine pit filling, soil improvement and other fields for the purpose of ensuring the safety of eco-systems and the environment.

4. Standards Aspects

China's standards system consists of national standards, industry standards, local standards and group standards from top to bottom.

4.1 National Standards

4.1.1. Phosphogypsum GB/T 23456 - Product Standard

According to the content of calcium sulphate dihydrate, phosphogypsum is divided into first, second and third grades. The specific indicator requirements are shown in Table 3.

4.1.2. Specifications for the Treatment and Disposal of Phosphogypsum and Specifications for the Treatment and Reprocessing of Phosphogypsum to Sulphuric Acid

GB/T 32124 specifies the quality requirements, main equipment and operating steps of raw and auxiliary materials in the production process, including the quality requirements for phosphogypsum (See Table 2). The two standards respectively focus on the application of building materials and the decomposition of phosphogypsum to produce sulphuric acid. They lack extensive guidance. The two national standards are currently being revised.

Table 2. *GB/T 23456 indicator requirements*

Project	Indicator		
	Level 1	**Level 2**	**Level 3**
Bound water (wet basis)/%	≤15	≤20	≤25
Calcium sulphate dihydrate (dry basis)/%	≥90	≥80	≥65
Water-soluble phosphorus pentoxide (dry basis)/%	≤0.20	≤0.30	≤0.50
Water-soluble fluoride ion (dry basis)/%	≤0.10	≤0.20	≤0.30
Water-soluble magnesium oxide (dry basis)/%	≤0.10	≤0.30	—
Water-soluble sodium oxide (dry basis)/%	≤0.06	≤0.10	—
Chloride ion (dry basis)/%	≤0.02	≤0.04	—
Radionuclide limit	IRa≤1.0 Ir≤1.3		
pH	As agreed by both parties		

Table 3. *GB/T 32124 indicator requirements*

Project Indicator	
Sulfur trioxide	/% 40
Silica	/% 8.0
Phosphorus pentoxide	/% 1.5
Fluorine	/% 0.35

Table 4. *Industry standard index requirements related to phosphogypsum*

Standard	**Project**	**Indicators**	
NY/T 1060	/	**Level 1**	**Level 2**
	Calcium sulphate dihydrate/%	≥85	≥75
	Bound water/%	≤8.0	
	Phosphorus pentoxide/% ≤1.5	≤1.5	
	Bound water (wet basis)/%	≤15	
	Calcium sulphate dihydrate (dry basis)/%	≥90	
	Water-soluble phosphorus pentoxide (dry basis)/%	≤0.30	
JC/T 2391	Water-soluble fluoride ion (dry basis)/%	≤0.10	
	Water-soluble magnesium oxide (dry basis)/%	≤0.10	
	Water-soluble sodium oxide (dry basis)/%	≤0.06	
	Chloride ion (dry basis)/%	≤0.02	
HG/T 4219 (requirements for products)	Calcium (dry basis)/%	≥17.0	
	Sulfur (dry basis)/%	≥14.0	
	pH	3.0-6.5	
	Free water/%	≤25	
	Water-soluble fluorine	≤0.3	

4.1.3 General Industrial Solid Waste Storage and Landfill Pollution Control Standards GB 18599-2020

GB 18599-2020 stipulates the site selection, construction, operation, closure, land reclamation and other processes of general industrial solid waste storage sites and landfills such as phosphogypsum. It covers environmental protection requirements for PG, for general industrial solid waste filling and backfill utilisation that replace storage and landfill disposal, as well as monitoring requirements, implementation and supervision, etc.

4.1.4 Phosphogypsum Classified as Category II Solid Waste

PG belongs to Category II solid waste. When being disposed of at Category II sites, the organic matter content must be less than 5% and the total water-soluble salt content must be less than 5%.

At the same time, Category II sites should use a single artificial composite liner as the anti-seepage membrane and meet the following technical requirements:

a. Artificial synthetic materials should use high-density polyethylene film, with a thickness of not less than 1.5 mm. If other synthetic materials are used, its anti-seepage performance is at least equivalent to that of 1.5 mm high-density polyethylene film.
b. The thickness of the clay lining should not be less than 0.75 m, and the saturated permeability coefficient after compaction, artificial modification and other measures should not be greater than 1.0×10-7 cm/s.

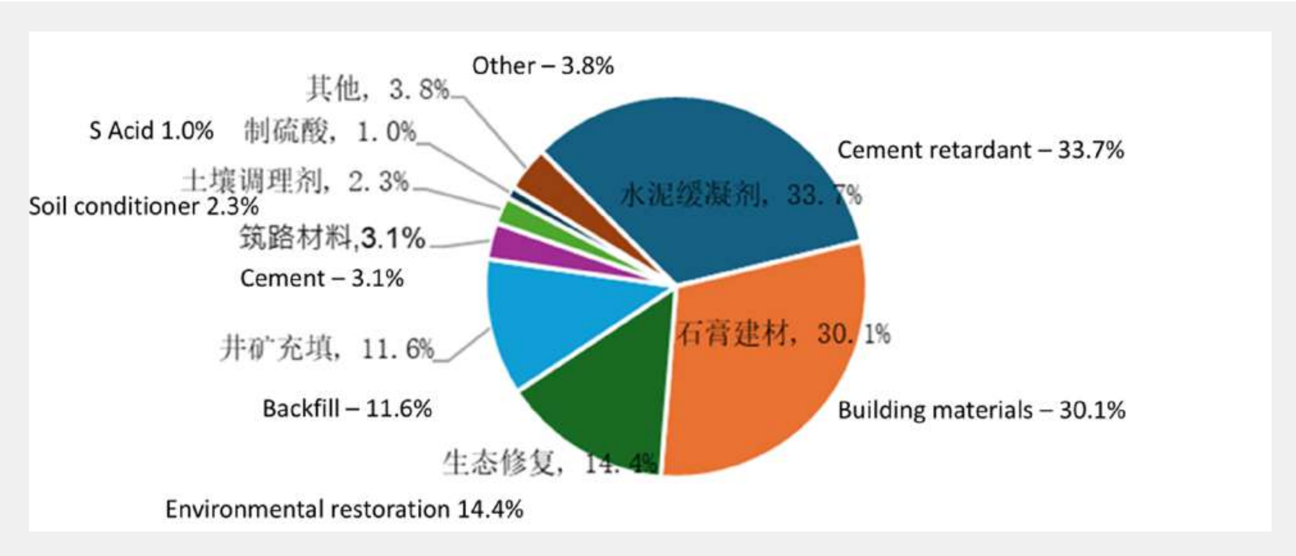


Fig. 8. *Distribution of comprehensive utilisation pathways of phosphogypsum in China in 2023*

c. When using other clay-based anti-seepage lining materials, they should have an equal or higher water-proofing effect.
d. The surface of the foundation layer of Category II sites should be kept at least 1.5 m away from the annual highest groundwater level.
e. When the distance between the surface of the base layer in the site and the annual maximum groundwater level is less than 1.5 m, a groundwater drainage system should be constructed. The groundwater drainage system should ensure that the groundwater level of a Class II site is kept no higher than 1.5 m below the surface of the base layer during operational periods.

4.2 Industry Standards

There are in total seven industry standards at national level, two in the field of building materials, one in the agricultural field, three in the safety field, covering testing methods and two others and one standard in the environmental/ HSE protection field (under development, to be released this year):

1. "Phosphogypsum for cement production" NY/T 1060
2. "Perthion Raw Phosphogypsum Cement Concrete for Products" JC/T 2391
3. "Phosphogypsum Soil Conditioner" HG/T 4219
4. "Safety Technical Regulations for Phosphogypsum Storage" AQ 2059
5. "Method for determination of phosphorus and fluorine in phosphogypsum" JC/T 2073
6. "Double-Turn Phosphogypsum Wet Residue Filtrate Machine" HG/T 4753
7. An HSE/ environmental standard is being prepared (late 2024). See Table 3 for relevant indicator requirements.

4.3 Local Standards

In addition to national standards a total of 20 local standards have been registered, including:

6 in Guizhou Province
5 in Yunnan Province plus 1 in preparation
3 in Hubei Province
4 in Sichuan Province
1 in Inner Mongolia.

The standards cover issues as diverse as saline-alkali soil improvement, highway base, planting materials, ecological restoration, cement retarder, building materials products, comprehensive utilisation evaluation specifications, “harmless” treatment (pretreatment and purification), etc.

4.4 Group Standards

A total of 41 group standards have been registered.

4.4.1 Comprehensive Utilisation Approaches of Phosphogypsum in China

The comprehensive utilisation pathways of phosphogypsum in China are mainly cement retarder, gypsum building materials, ecological restoration and mine-backfilling (see Figure 8). By 2023, they accounted for approximately 33.7%, 30.1%, 14.4% and 11.6% of PG use respectively. Soil conditioners and road construction materials have achieved good early stage market uptake. In 2023, their utilisation accounted for 2.3% and 3.1% of total PG use respectively.

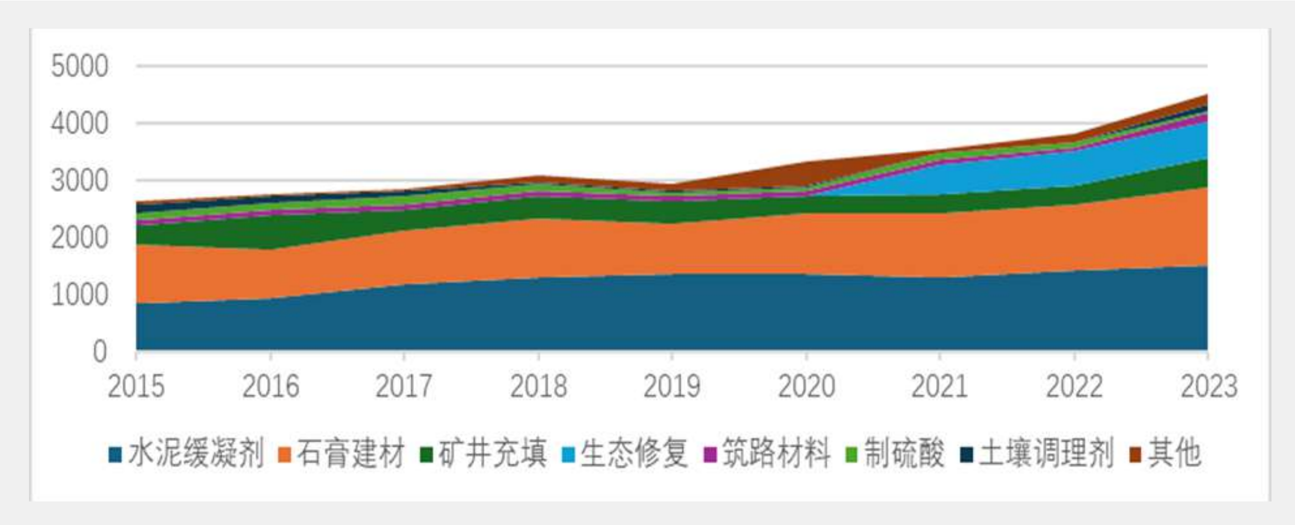


Fig. 9. *Changes in comprehensive utilisation pathways of phosphogypsum in China 2015-2023*

4.4.2 Other Methods

Other comprehensive utilisation methods, such as phosphogypsum decomposition to produce sulphuric acid, plant materials, and fertiliser conditioners etc., have also developed, reflecting China's increasingly diversified "quality-driven" strategy for reaching the comprehensive utilisation of phosphogypsum.

The pie chart shows (see Figure 8) the percentage breakdown of different applications of phosphogypsum in China.

In a clockwise direction starting from the top, the shares are:

- 33.7% for cement retarders
- 30.1% for building materials
- 14.4% for ecological restoration
- 11.6% for backfill in mines
- 3.1% for road construction materials
- 2.3% for soil conditioners
- 1.0% for sulphuric acid production combined with cement or clinker
- 3.8% for other uses.

4.4.3 Comparative Use Rates by Application Type

The consumption of phosphogypsum in the fields of cement retarder and gypsum building materials is large and shows a steady upward trend (Figure 9). In 2023, the consumption of phosphogypsum through the cement retarder channel reached 15.15 million tonnes, a year-on-year increase of 6.7%; the consumption through the gypsum building materials channel Phosphogypsum reached 13.53 million tonnes, a year-on-year increase of 17.1%.

Among them, gypsum board increased significantly, with consumption reaching 5.9 million tonnes by Year End 2023, a year-on-year increase of 28.3%. Gypsum powder consumption reached 5.6 million tonnes, a year-on-year increase of 14.3%.

4.4.4 Remediation Uses - Ecology

As an emerging comprehensive utilisation method of phosphogypsum, ecological restoration and repair materials have been implemented in successive provinces. The consumption volume in 2023 reached 6.5 million tonnes, a year-on-year increase of 10.9%; the application of phosphogypsum in the field of road construction materials gradually expanded, rom on-site pilot roads within the factory campus boundaries gradually to Municipal roads and highway sections, which then are extended. By year end 2023, consumption volume reached 1.38 million tonnes, nearly doubling the previous year-on-year increase.

4.4.5 Soil Conditioner and Sulphur Recovery

There was also significant progress in the field of soil conditioners, with the consumption volume reaching more than 1 million tonnes again in 2023, mainly based back orders from previous years. For reasons such as weakening demand, economic slowdown and exchange rate volatility and exchange rate volatility, the consumption of sulphuric acid produced by phosphogypsum decomposition dropped significantly, to only 430,000 tonnes in 2023, a year-on-year decrease of about 50%.

As shown in Figure 9 in ascending colour order from the x axis baseline, relative uses of PG are: cement retarders (dark blue), building materials (orange), environmental restoration (dark green), backfill (light blue), road construction materials (purple), sulphuric acid production combined with cement or clinker (navy blue), soil conditioners (light green), and other applications (dark red).

From the perspective of consumers, 66.4% of the PG produced in the industry is consumed by in-house enterprises or joint ventures established by the producers themselves, while 33.6% of the PG is sold downstream to comprehensive PG utilisation manufacturers for processing. In-house consumption mainly includes cement retarder, ecological restoration, gypsum building materials and mine backfilling, while third party sales part focus primarily on gypsum building materials and cement retardant.

4.5 Application Categories

A typology of application categories is set out below.

4.5.1. Pretreatment/ Purification: Overview

Responsible technical design units: Wuhan Engineering University, China Fifth Ring Engineering Co., Ltd.

4.5.1.1. Material Preparation/Modification Mechanism

Chemical methods are used to accelerate the dissolution of calcium sulphate dihydrate crystals and crystal lattice in phosphogypsum, release the entrained fluorine and eutectic phosphorus existing between crystals and within the crystal lattice, and transfer most of the phosphorus and fluorine impurities in phosphogypsum to the water body. Based on the mechanism of "co-precipitation-net capture", the remaining phosphorus and fluorine in the phosphogypsum after chemical washing are further fixed.

4.5.1.2. Processing Flowsheets

As shown in Figure 11: Mix phosphogypsum water, and chemicals in a certain proportion and beat; mechanically stir for 5 to 15 minutes → solid-liquid separation → add curing agent to the filter cake → mechanically stir for 5 to 15 minutes → solid-liquid separation → the resulting solid is harmless (purified) phosphogypsum.

4.5.2 Material Advantages

4.5.2.1. Resources and Technology

The “harmless” pretreatment of phosphogypsum can effectively reduce the content of impurities such as phosphorus and fluorine, improve the quality of phosphogypsum, and enhance its market competitiveness. While turning waste into treasure, it accelerates stock consumption, releases occupied land resources, and reduces the mining of natural gypsum. This technology is a significant improvement on the previous standard of traditional water washing and neutralisation. Detergents are introduced during the washing process to accelerate the transfer of pollutants in phosphogypsum to the water body, improve washing efficiency, reduce water consumption, and alleviate the water balance pressure of enterprises. The phosphorus and fluorine enriched in the wash water can be recycled as resources. The core lies in detergents, which can be achieved using traditional process equipment and requires little investment pressure on enterprises.

4.5.2.2. Environmental and Social Benefits

Phosphogypsum belongs to Class II general industrial solid waste and contains harmful impurities such as phosphates, fluorides, organic matter, heavy metals, etc. Its direct accumulation poses a significant threat to the surrounding atmosphere, soil, and water bodies. Phosphate ores in China are mainly distributed in the Yangtze River Basin, and phosphorus chemical companies are mostly built along the river. The Yangtze River Basin Economic Zone is a major national strategic development area, covering 11 provinces and cities, involving more than 40% of the country's population and GDP. Achieving harmless treatment of phosphogypsum is of great significance to the implementation of Yangtze River protection.

4.5.3 Pretreatment and Application Cases

Fig. 10. *Pilot plant, phosphogypsum purification project.*

Responsible units, Hubei Xiangyun (Group) Chemical Co., Ltd.: 5 million t/year PG purification project.

2024 Hubei Ezhong Ecological Engineering Co., Ltd.: Pilot plant, PG purification project (Figure 10.)

4.5.4 Application of Comprehensive Utilisation of Phosphogypsum in the Field of Ecological Restoration

Responsible application units: Yunnan Yuntianhua Environmental Protection Technology Co., Ltd., Yunnan Xiangfeng Fertilizer Co., Ltd.

4.5.4.1 Phosphogypsum-based Ecological Restoration

Phosphogypsum-based ecological restoration material is developed using phosphogypsum as the main raw material and stabilised by adding additives. This material can replace mining waste rock, building materials, soil, sand and other materials in applications. Mine ecological restoration projects are in progress.

4.5.4.2. Material Preparation/Modification Mechanism

The modification of phosphogypsum-based ecological materials is mainly aimed at stabilising the pollution vectors soluble phosphorus and fluorine. By adjusting the pH value and adding chemicals, it forms an insoluble fluorine-phosphorus double salt with the soluble phosphorus and fluorine and then solidifies to form an encapsulation coating consisting of Performance-stable particles. The environmental safety of phosphogypsum stabilised by modifiers is greatly improved (Figure 11).

4.5.5 Material Advantages

4.5.5.1. Resources and Technology

The developed phosphogypsum-based ecological restoration material has physical and mechanical advantages. Its mechanical index is higher than that of ordinary clay soil. It has high sliding force (kinetic friction) and high sliding resistance, which is beneficial to the stability of the slope after landform reconstruction. The phosphogypsum-based ecological restoration material is used for reverse pressure; backfill treatment can manually control the slope after treatment and the geological disaster control rate can reach 100%.

Because the secondary formation rate of complete geological disasters is extremely low, phosphogypsum-based ecological restoration materials have sufficient sources and can be reshaped according to the original topography.

Under restoration, 80% of the original topography can be restored and the damaged landscape is remediated 100%. Land is levelled and regraded resulting in a high land redevelopment rate. Ecologically suitable PG-based restoration materials for mine rehabilitating abandoned mines replace traditional backfill materials such as building rubble, soil, sand, fly ash and construction spoil. This solves two problems: first, where to source filling materials suitable for ecological restoration of abandoned mines and secondly, consumes safely and cost-effectively absorbs high volumes of phosphogypsum, serving the strategic purpose of comprehensive utilisation.

4.5.4.3 Material/Product Processing Flow

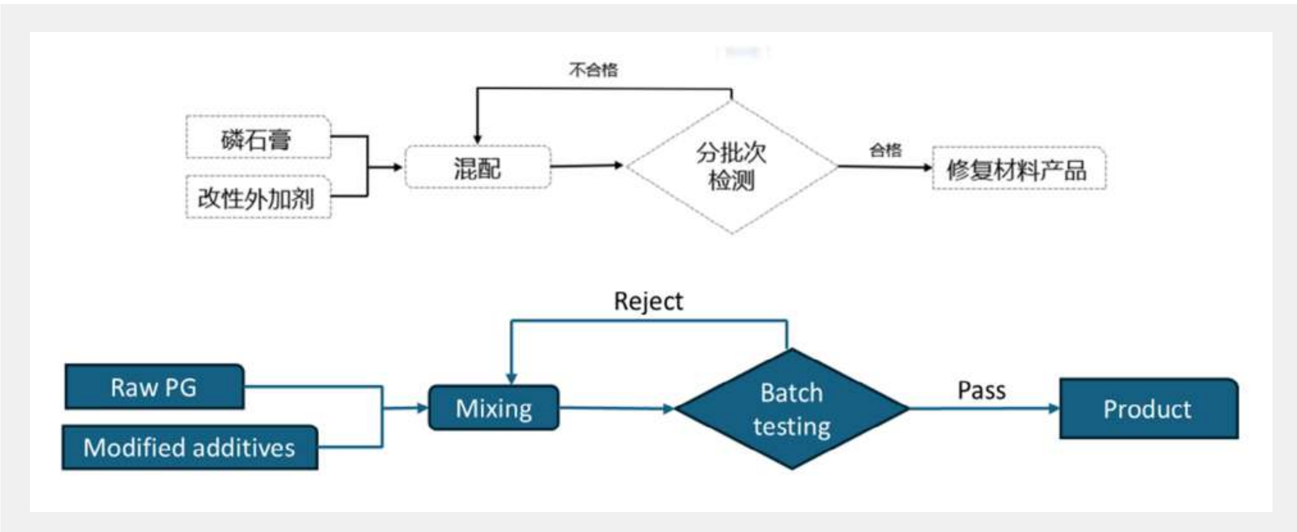


Fig. 11. *PG Mixing and Processing Product Flowsheet (original and translation)*

Fig. 12. *Yunlong Phosphate Mine Area Management Project - Figures 12 L and 12 R*

Fig. 13. *Shuangshao Phosphate Mine Area Management Project (Before)*

Fig. 14. *Shuangshao Phosphate Mine Area Management Project (After)*

Fig. 15. *Taoshu Phosphate Mine treatment and restoration (before)*

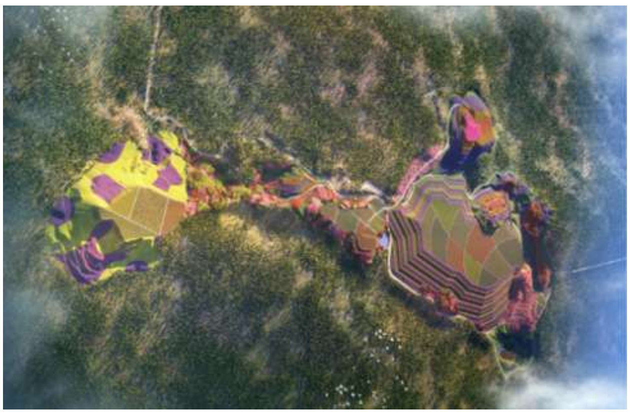


Fig. 16. *Taoshu Phosphate Mine treatment and restoration (after)*

4.5.5.2. Environmental and Social Benefits

Phosphogypsum-based ecological restoration materials are used for ecological restoration of mines, which greatly increases the vegetation area, reduces water and soil erosion, and improves soil fertility. It promotes the harmony and coordination of the entire regional natural ecosystem, and restores biodiversity; it also solves the remaining three phosphorus problems and source pollution problems: 1) to assist the transformation and upgrading of the phosphorus chemical industry; 2) to create the integration of mineralised slag (untreated PG); and 3) to extend it to land consolidation and development.

4.5.6 Application Cases

4.5.6.1. Yunlong Phosphate Mine Area Management Project

Features: Investment of 427 million Yuan. Restored land area is 1,026,627 square meters. 8.178 million cubic meters of phosphogypsum is comprehensively utilised (Figure 12).

4.5.6.2. Shuangshao Phosphate Mine Area Management Project

The Shuangshao total investment scale is approximately 769 million (Figure 13 (Before), Figure 14 (After Rehabilitation). Scheduled to be completed by the end of 2025, the total backfill volume of the project is 9.7415 million cubic meters, of which 8.724 million cubic meters are phosphogypsum-based ecological restoration materials.

The total investment scale of the project is approximately Renminbi ￥1.269 billion. The project is scheduled to be completed by the end of 2025. The total backfill volume of the project is 15.5691 million cubic meters, of which 12.423 million cubic meters are phosphogypsum-based ecological restoration materials.

4.5.6.3. Taoshu Phosphate Mine Area Management Project

According to the rehabilitation plan, the Taoshu Phosphate Mine treatment and restoration area (Figure 15) is 825,373 square meters (including 298,669 square meters of backfill area and 526,704 square meters of non-backfill area), and the restoration direction is dry land, garden land, woodland and grassland.

According to the remediation and rehabilitation plan, the Taoshu Phosphate Mine will be restored to an area of 480,503 square meters, with the restoration directions being dry land, garden land, woodland and grassland (Figure 16). To date, a total of approximately 1.18 million cubic meters of solid land have been backfilled; a total of 208 acres of non-backfill areas have been regreened.

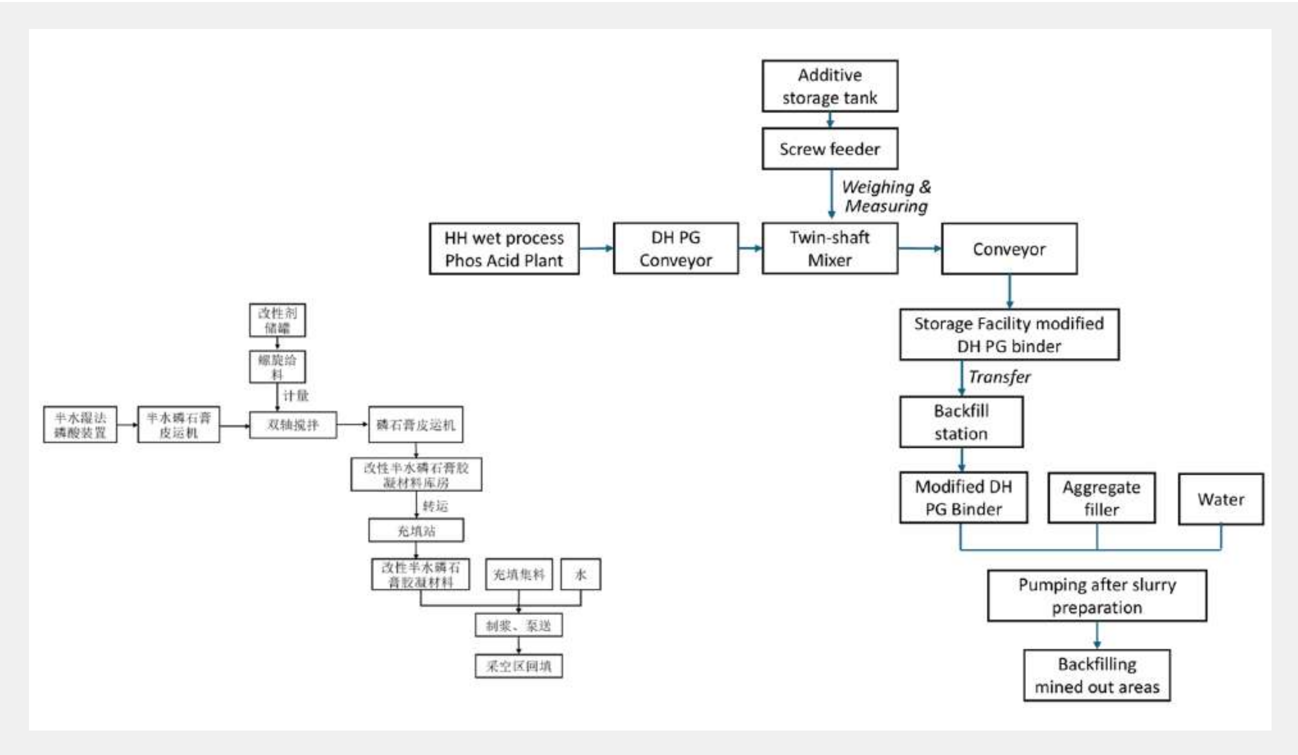


Fig. 17. *Preparation and filling application of semi-hydrated phosphogypsum cementitious material*

4.5.7. Mine Backfilling: Application of Hemi-hydrated PG-modified Cementitious Paste

Responsible units: Design and application representative unit: Guizhou Heng Chemical Co., Ltd.

4.5.7.1. Gelling Properties of Hemi-hydrated Phosphogypsum

The by-product of the semi-aqueous wet phosphoric acid process is hemihydrate phosphogypsum, similar in nature to α-hemihydrate phosphogypsum. The main phase, calcium sulphate hemihydrate, is in a metastable state. It dehydrates to form an anhydrous phase of calcium sulphate and then absorbs water to form a calcium sulphate dihydrate phase. Hemihydrate phosphogypsum condenses and hardens when exposed to water. The reaction process is as follows. It is used to trigger the hydration reaction. Calcium sulphate hemihydrate dissolves, crystallises and the crystals continue to grow. The crystals overlap each other to form a joint paste, which has good strength properties. Therefore, hemihydrate phosphogypsum has a gelling property and can be used as a cementitious material.

4.5.7.2. Modification Mechanism of Hemihydrate Phosphogypsum

The alkaline agent solidifies the harmful impurities of phosphorus and fluorine in the semi-aqueous phosphogypsum. The free phosphoric acid and the calcium ions in the alkaline agent form an insoluble substance called tricalcium phosphate. The free fluorine and the calcium ions in the alkaline agent form calcium fluoride-insoluble substances.

The hydration of HH phosphogypsum is generally considered to be the process of dissolution, crystallisation and crystal growth of calcium sulphate. The modifier adheres to the surface of calcium sulphate hemihydrate and inhibits the dissolution process of calcium sulphate, thus inhibiting the hydration process of hemihydrate phosphogypsum. Hemihydrate phosphogypsum can remain in a steady state for a long time.

4.5.7.3. Processing Flowsheet

The HH phosphogypsum from the HH wet phosphoric acid plant, carried by the DH conveyor, simultaneously with the introduction of a precise dose of modifier additive, applied by a screw feeder, enters the twin-shaft mixer (Figure 17).

The materials are mixed evenly during stirring to obtain a steady-state modified HH phosphogypsum which is then taken by conveyor to a facility for storing the resultant di-hydrate PG binder. Prior to application the modified binder is transferred to a backfill station where the binder and an aggregate filler are mixed with water, forming a slurry that is pumped into the mined out facility to restore it.

4.5.8 Advantages of Materials/ Products

4.5.8.1. Resources and Technology, etc.

Hemihydrate phosphogypsum (HHPG) is a plentiful industrial by-product with gelling properties and hence can be used as a gelling material. Compared with other gelling materials, HHPG is a low-cost alternative whose cementitious properties can transform it “from waste into treasure” and achieve remarkable performance and valorisation results in secondary resource utilisation.

Semi-aqueous HHPG exists in a metastable state, which condenses and hardens with water. In order to ensure its gelling properties during application, modifiers are added. The benefits of this process are on the one hand, that the potentially harmful impurities of phosphorus and fluorine in the phosphogypsum are solidified, meeting the requirements for “harmless” impact to the environment. On the other, HHPG can maintain its gelling property for a long time in a watery/humid environment. Compared with filling and drying methods, this technology has green, low-carbon, and other positive economic and environmental attributes.

4.5.8.2. Environmental and Social Benefits: Major CO_2 Emissions Reduction

It is estimated that when semi-hydrated phosphogypsum is used for mine back filling, the application can reduce CO_2 emissions by 96.1853 million kg per year compared with cement backfilling. This technology, by substituting a secondary raw material for cement, is also aligned with the national "carbon peak and carbon neutrality" strategic plan. This will have a significant and far-reaching impact on China's cement industry and its operation.

4.5.9 Applications

4.5.9.1. Ecological Restoration Technology of Gongjishan Open Pit

The Gongjishan open pit has been effectively repaired through the use of semi-hydrated phosphogypsum filling and ecological restoration technology (see Figure sequence 18 a-f). It is currently being promoted and applied in the open-pit pits of Daslope Trough.

18(a) *Before filling 2020.12*

18(b) *Filling 2020.12*

18(c) *2021.8*

18(d) *2021.8*

18(e) *2022.4*

18(f) *2022.10*

Fig. 18. *Image sequence a-f - The 2 year end-to-end process of ecological restoration of open pits. Images are dates year.month eg 2022.4 = April 2022.*


Fig. 19. *Sulphur recovery and recycling to sulphuric acid unit (L) and control room, (R) GPCG, Guizhou Province*

4.6. Decomposition of Phosphogypsum to Produce Sulphuric Acid

The responsible Application representative units are: Guizhou Phosphate (Group) Co., Ltd., Shandong Lubei Chemical Co., Ltd.

4.6.1 Overview

To improve the utilisation rate of phosphogypsum, Guizhou Phosphate Group fully integrates advanced design and production concepts in the chemical industry and building materials industry to build a large-scale phosphogypsum decomposition to produce sulphuric acid co-production cement clinker project, which can absorb 1.4 million tonnes of phosphogypsum (dry basis) and produce sulphuric acid. 650,000 tonnes and 600,000 tonnes of cement clinker (about 800,000 tonnes of cement). It is the world's largest phosphogypsum decomposition to sulphuric acid co-production cement process device and a "smart" project that has been completed and put into operation.

The sulphur extraction project uses phosphogypsum as a by-product in the phosphoric acid production process as raw material and adds auxiliary materials such as silicon and aluminum for batching. After preheating, decomposition, and calcination, the generated SO_2 flue gas is sent to the sulphuric acid plant to produce sulphuric acid and CaO after recovering the heat. It is mineralised with silicon, iron, aluminum, etc. to form cement clinker.

4.6.2 Project Advantages

4.6.2.1. Resource Technology

The phosphogypsum resource recycling economy project accounts for more than 90% of the raw materials of phosphogypsum, realising the recycling of "sulphur" resources and the resource utilisation of "calcium, silicon, aluminum and iron" resources, reducing dependence on imported sulphur and reducing limestone mining results from equal amounts of cement production. In addition, the resulting cement product has a low alkali content and high strength when fully cured.

4.6.2.2 Environmental and Social Benefits

Guizhou Phosphate Group is now able to process phosphogypsum in large quantities and produce sulphuric acid and cement at the same time. The sulphuric acid is returned to the phosphoric acid plant for use and the cement products are sold externally. This is another important measure to "squeeze out all the phosphate rock" and will play a role in extending the circular economic lifecycle of the wet-process phosphorus chemical industry. The sulphuric acid value chain then complements the cement value chain with good resultant ecological and social benefits and with demonstrable topographical and landscaping enhancements for the treated mines (see resultant effects in sequence, Figure 18 a-f).

4.6.3 Application Cases

The phosphogypsum resource recycling economy project (Figure 19) started construction in February 2023 in Machangping Industrial Park, Fuquan City, Qiannan Prefecture, Guizhou Province, and was completed and put into production in December of the same year.

The technology has achieved operational standards for production and in manufacturing a range of products. The technical and economic indicators are excellent.

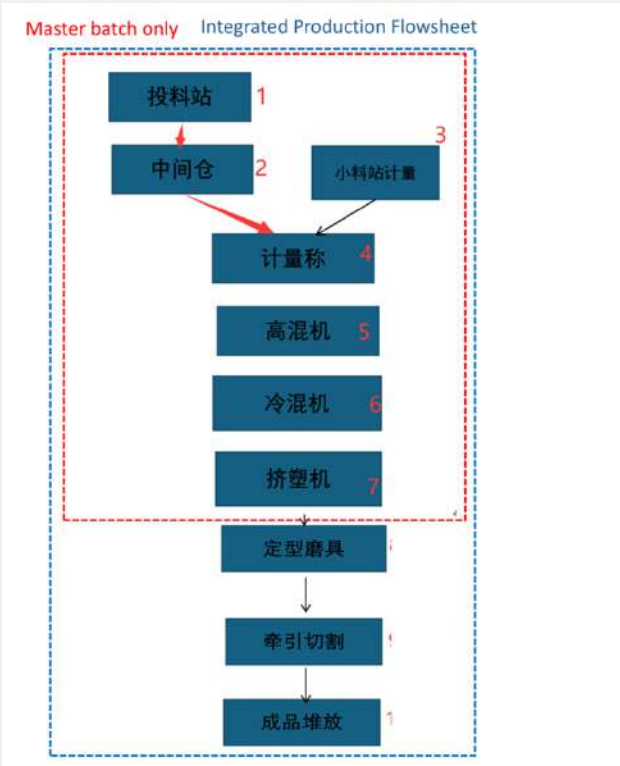


Fig. 20. *Finished masterbatch process flow chart*

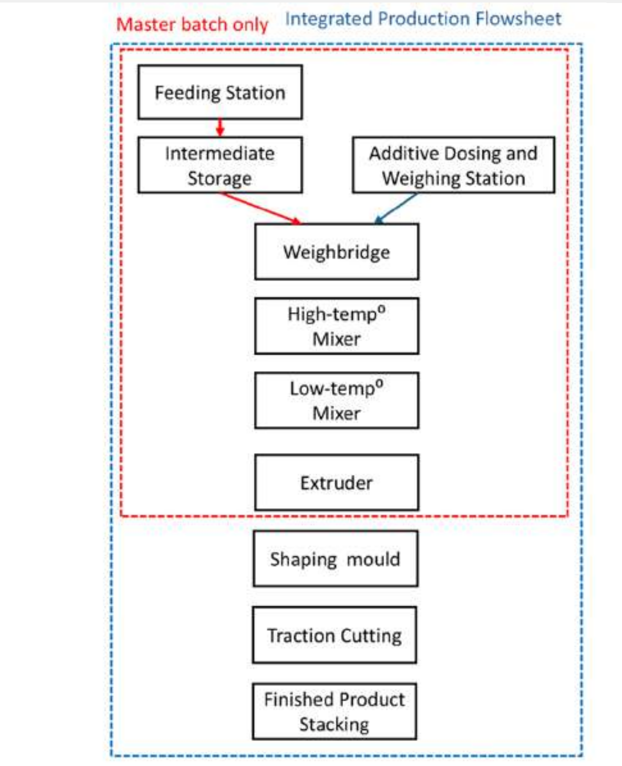


Fig. 21. *Continuous production process flow chart*

4.7 Application of Phosphogypsum in the Field of Polymer Filler

Application representative unit: Guizhou Phosphate Green Environmental Protection Industry Co., Ltd.

4.7.1 Overview

Using phosphogypsum as raw material, it is calcinated at a high temperature to produce anhydrous gypsum, which has excellent performance as a cementing material or polymer filling material.

4.7.1.1 Applications

It can be used as a cementing material for the production of building materials. In the field of polymer fillers, 800-2000 mesh anhydrous gypsum can replace light calcium carbonate, light calcium, talc, barium sulphate and other fillers for resin manhole covers, SPC floors, paints, coatings, biodegradable masks and other fields.

4.7.1.2 Preparation of Product

Anhydrous gypsum packaging box is a new environmentally friendly packaging material made of anhydrous gypsum and polypropylene resin through mixing, high-temperature plasticisation and extrusion (Figures 20 and 21). It is waterproof, moisture-proof, wear-resistant, anti-aging, impact-resistant, oil-proof, and tough. Good, tear-resistant, recyclable and other advantages. It is mainly used for commodity packaging in various industries such as agricultural product transshipment, parts packaging, and product outer packaging.

4.7.1.3 Polymer Production Flow Sheet

Polymer production process flow chart see Figure 20 – Chinese version – and Figure 21 – English version – Master Batch (red) and Integrated Production (blue).

4.7.2 Advantages of Materials/products

4.7.2.1 Resource Technology

Anhydrite has good strength and stability and can enhance the mechanical properties and durability of polymer boards. At the same time, anhydrous gypsum also has a certain hygroscopicity capacity and the resultant ability to adjust to humidity, which helps simultaneously to improve the indoor environment

Fig. 22. *Polymer Packaging Materials - Production Facility, Production Technology, Packaging Samples and Display*

and living comfort. The addition of anhydrous gypsum can also give polymer boards more functional properties, such as fire prevention, sound insulation, heat preservation, further expanding its application fields and market prospects.

4.7.2.2 Environmental and Social Benefits

Anhydrite does not contain harmful substances and is harmless to the human body and the environment. Applying it to polymer sheets for packaging (see Figure 22) can reduce dependence on petrochemical resources, reduce carbon emissions and energy consumption during the production process, and is in line with the development trend of green building materials. At the same time, anhydrous gypsum has good recyclability and degradability, allowing polymer boards to be effectively processed and reused after being discarded, reducing the long-term burden on the environment.

4.7.3 Application Cases

Polymer Packaging Materials - Production Facility, Production Technology, Packaging Samples and Display.

5. Phosphogypsum in Roads

5.1. Application of Phosphogypsum in Roads – Pilot

In September 2016, a 200-meter long, high-concentration water-stabilised phosphogypsum layer was laid on Wenjin Avenue (municipal level) in Wuhan, Hubei Province (Figure 23). The on-site test data passed the performance test.

Fig. 23. *Pilot Phosphogypsum Road 2016 so far there are no failures, cracks or other abnormalities*

In 2017, a 500-meter test section was built on the Wuyi Expressway in Yunnan. In 2018, the project was signed off and won the first prize of the Yunnan Transportation Science Innovation Award of that year. The China Highway Association meanwhile evaluated the project that year, stating that it had reached the international advanced level and concluded that "phosphogypsum roadbed material is suitable for use in expressway construction". Overall, the pilot section has been operating well and has retained its structural integrity in good condition since the road was first laid down.

5.1.1 2019 – 20 Extending the Pilot

In 2019, a 400-meter test section was built on the Jiuchang auxiliary road of the Yiwu Expressway, and there have been no abnormalities so far.

Likewise, in March and April 2019, 202-meter and 145-meter test sections were laid on the internal road of a chemical plant. The thickness is 35cm and no problems have been found to date. In April 2019, Sichuan Lomon New Materials Co., Ltd. continued to use improved phosphogypsum as roadbed filler (Figures 24a and 24b) for the construction of a test section on the approximately 200-meter connection line between the factory area and the extension line of Xinshi Industrial Avenue. The on-site inspection data was validated independently. So far, no failure, cracks or other degradation have manifested in the road.

In September 2020, a 500-meter test section was laid on the Yao-Chu Expressway with a roadbed thickness of 39cm. No problems have been found so far. In general, to date construction on many roads has been started and in a growing number of instances also successfully completed (see road construction image sequence Figures 25 – 34).

Fig. 24(a). *Crushing pretreatment of raw phosphogypsum*

Fig. 24(b). *Mixed material loading*

Fig. 25. *Pavement sub-bed construction*

Fig. 26. *Wearing course construction with geo-membrane*

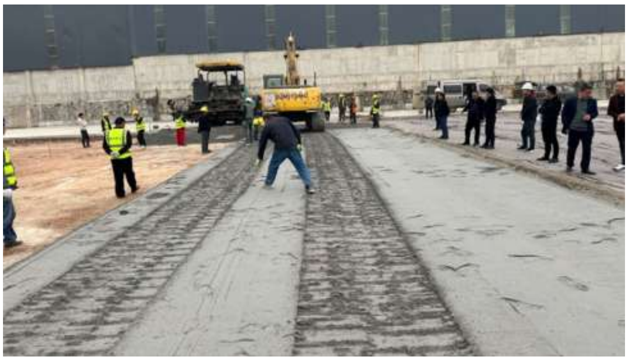


Fig. 27. *Pre-rolling and compaction small roller*

Fig. 28. *Steel wheel machine rolling*

Fig. 29. *Rubber wheel machine rolling*

Fig. 30. *Road shoulder side processing*

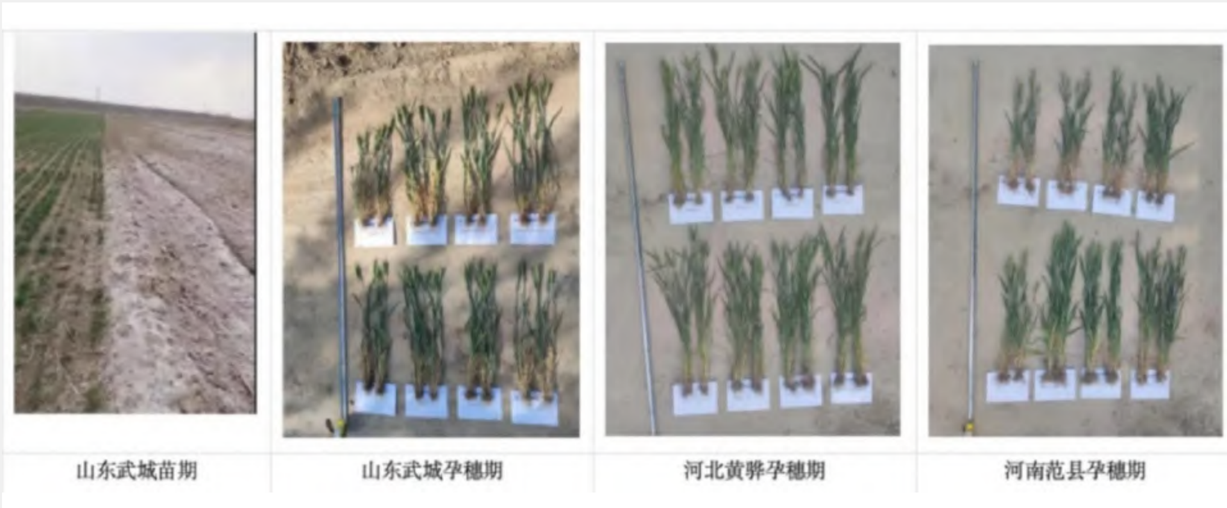
Fig. 31. *Road shoulder side finishing*

Fig. 32. *Rolling compaction effect*

Fig. 33. *Film coating and maintenance*

Fig. 34. *Open air maintenance*

6. Phosphogypsum in Agriculture



Seedling stage (Wu Cheng, Shandong) *Booting stage (Wu Cheng, Shandong)* *Booting stage (Huanghua, Hebei)*

Fig. 35. *Progression from seedling to booting stage - three field trial locations*

6.1 Application of Phosphogypsum in Soil Improvement

At present, the use of phosphogypsum in agricultural land is restricted, but some academies of sciences, the academy of agricultural sciences and related enterprises are conducting relevant experiments to verify the soil improvement and yield-increasing beneficial effects of phosphogypsum. More importantly, the longer-term premise behind the field trials is to assess the impacts of the long-term and large-scale application of phosphogypsum on soil physico-chemical condition and crop-yield while evaluating the mobilisation potential and measurable transfer of heavy metals and radioactivity in soil, along with their follow-on impact on crops and the surrounding environment. A short summary of some recent trials is set out below.

6.1.1 The Chinese Academy of Sciences, the Chinese Academy of Agricultural Sciences and Enterprises Jointly Explore Ways to Improve Saline-alkali Land

The Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, has conducted research on the "Effectiveness and Safety Assessment of Phosphogypsum in Improving Saline-Alkali Soil" in Shandong, Hebei, and Henan (see sequence by province, Figure 35).

6.1.2 The Gansu Academy

The Gansu Academy of Agricultural Sciences and enterprises has conducted a follow-up an environmental safety evaluation test for phosphogypsum use as soil improvement. The focus to study the impact of continuous application of phosphogypsum on soil heavy metal accumulation, transfer, and crops, applying respective doses of 200, 400, 800, and 1,600 kilograms of phosphogypsum per Mu (a unit of area, equivalent to 1/15 of a hectare or about 666.7 square meters).

6.2 Application of Phosphogypsum in Soil Improvement

6.2.1 Ways to Improve Saline-alkali Land with Phosphogypsum

The Institute of Geographic Sciences and Natural Resources of the Chinese Academy of Sciences has carried out a study under the title **Effectiveness and Safety Evaluation of Phosphogypsum in Improving Saline-alkali Lands** in Shandong, Hebei and Henan Provinces (see Figures 36L and 36R).

The Da'an Alkaline Land Ecological Experimental Station of the Chinese Academy of Sciences used phosphogypsum to improve soda saline-alkali land. After repeated tests, it finally determined the most economical and efficient improvement sodic soil amendment material - phosphogypsum. The images show

Fig. 36. *Da'an Alkaline Ecological Experiment Station – Treatment (L) and Post-Treatment (R).*

Fig. 37. *Field trials planting (L) and successful harvest (R)*

the method used to apply the PG and the state of the amended soil following treatment with a disk spreader.

The proposed "three benefit integration" model has been used in Da'an City, Zhenlai. It has been demonstrated and promoted in large areas in typical soda-saline-alkali areas such as Zhenlai County and Qian'an County. For plots with a yield of less than 100 kilograms per mu[29], after 3 to 5 years of "three benefit" treatments, by spreading acidic phosphogypsum and organic fertilisers, the yield per mu can reach more than 500 kilograms. The field trial shown below uses two photos in a "before" and "after" mode to illustrate that if correctly applied phosphogypsum may achieve the farmer's ideal of "repair in the same year, plant in the same year, and harvest high yield in the same year".

The sign in the field (Fig. 37 (R)) summarises the trial conducted, shown just before the harvest. The first picture 37 (L) shows rice being planted on saline-alkali soil improved with PG, and the second picture 37 (R) shows matured rice grown on saline-alkali soil after improvement with PG (Figure 37).

29 1 mu is equivalent to $667m^2$, or 1/15th of a hectare


3

CHAPTER THREE

BREAKTHROUGH IN THE PROCESSING OF PHOSPHOGYPSUM INTO MULTI-PURPOSE TECHNICAL GRADE GYPSUM, RUSSIAN FEDERATION

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1. Problem Statement

The problems of developing effective improvements to the performance quality level of materials used in transport infrastructure to build both road surfaces and the railway subgrades present essentially the most pressing engineering challenge across the road and rail construction industries as a whole. In response, a team of partners from PJSC PhosAgro, the Balakovo Branch of JSC Apatit, LLC Malykovsky Gypsum Plant and FSFEI HE Saratov National Research State University have developed Technical Grade Gypsum (TGG) — an application based on the use of phosphogypsum in the hemihydrate form (phospho-hemihydrate) for a breakthrough construction methodology for road and railway structures.

At the heart of the process, PhosAgro and Malykov have discovered an original primary resource-saving method for activating phosphor-hemihydrate (a form of phosphogypsum manufactured by PhosAgro and Malykov) to produce a ready-made binder for large-scale use in the construction and repair of road and railway foundations, as well as in civil engineering in general. It carries with it the potential for annual high-volume use of PG for the conservation of quantities of primary building materials (e.g. crushed stone, sand, natural gypsum, chalk, etc.) which in Russia alone is estimated at millions of tonnes.

Research by PhosAgro and Malykov has shown phosphogypsum in hemihydrate form can be used in road surface construction if a number of requirements and minor modifications are met. But a major operational constraint concerns the technical viability of using the material at ambient temperatures above 20°C. The problem is that the material in this state remains workable for no more than 24 hours, from the moment of shipment of the phosphogypsum from the production site to the point of use. The material's viability increases from 24 hours to up to seven days during the lower temperatures of the autumn-winter period, but it is not customary to build roads in autumn and winter.

So, the penalty of the short life span of phosphogypsum in hemihydrate form limits the radius of application of the material in the summer period to a distance of no more than 50 km from the manufacturing plant, a severe constraint.

Joint efforts of PhosAgro and the Malykovsky Gypsum Plant have consequently created a technology for processing calcium sulphate phosphor-polyhydrate into a binder that — as long as it has no direct contact with water — can safely be stored for at least one year in a workable form. Once stabilised, it is possible to transport the resulting construction material over an unlimited distance.

1.1 Problem Solving

In developing the new technology, it was necessary to solve several major problems, such as to:

a. ensure that the phosphogypsum does not adhere to the metal surface during heat treatment
b. achieve a zonal heating capability for working phosphogypsum under different, variable, temperature conditions
c. prevent local overheating of phosphogypsum
d. separate the steam mixture from the finished product
e. prevent flue gas mixing with processed phosphogypsum.

A composite mixture was developed for ensuring non-adhesion of the phosphogypsum to the metal surface comprising phosphogypsum and converted calcium carbonate, with the following mass ratio %: phosphogypsum 65.0-93.5%, sorbent substance 1.0-10.0%, converted calcium carbonate — the balance. In addition, the composite binder may contain activated calcium oxide in the amount of mass 0.5-1.0 %.

The process technology for obtaining a composite binder includes mixing the constituents under gradually increasing indirect heating to a temperature of 80±5°C. Next the temperature is raised further to 95-117°C with a continuous mixing of raw materials with further heat treatment, in a constant temperature range of 95 -117°C. At the end of the heating process, the composite binder is activated.

The plant for processing phosphogypsum in hemihydrate form (Figure 38) contains a rotating drum for the heat treatment of materials. The drum has three ZONES of controlled heating on the outer surface of the cylinder. The zone for preheating of the feedstock and introduced components (ZONE-1), the rapid heating zone (ZONE-2), where conditions are created for reaction processes, and the binder product formation zone (ZONE-3). The drying drum (Fig. 38 component 5) is heated from the outside only, while the material with the components mixed in for heat treatment is located in the inner cavity of the drum.

A wide strip loading channel (Fig. 38 component 3) is installed in the head of the drum and a composite binder discharge chamber (Fig. 38 component 10) is installed in the final section of the drum. The discharge chamber is supplied with the activated finished product through the activation chamber (Fig. 38 component 9). The activation block is a cylinder with perforations on all planes and drilled with random holes with diameters ranging from 5 to 20 mm. Metal balls with a diameter of 35-40 mm are loaded into the inner cavity of the activation unit, in which these balls disperse the finished product from the drum surface. Overall, the drum design enables all the component materials introduced into the mix to be distributed evenly across the entire volume of the processed end-product.

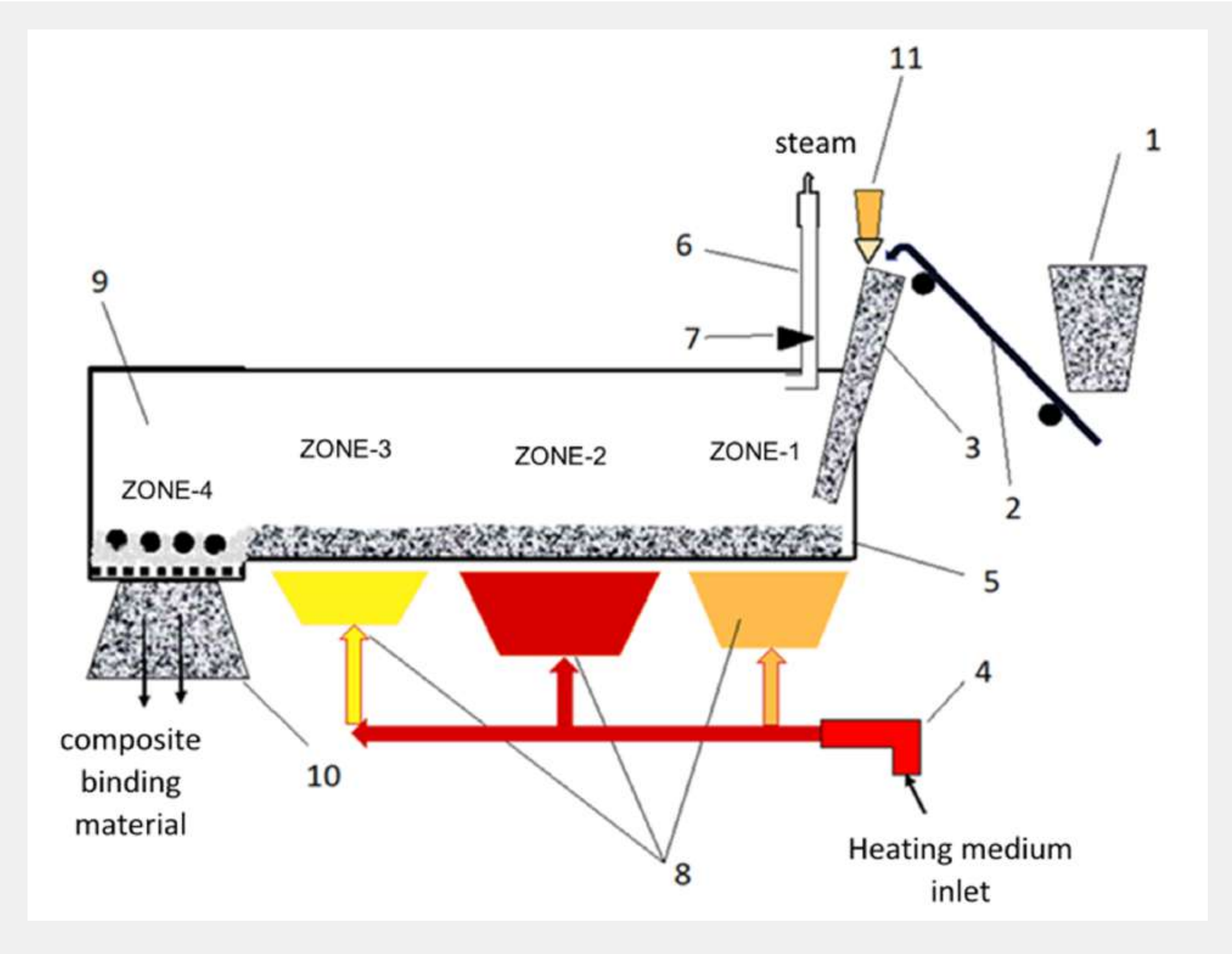


Fig. 38. *Rotating drum heat treatment processing of phosphogypsum hemihydrate into a binder - with unit Components 1-11*

1.2 Process Flow

The process steps are in logical sequence by Zone (see Figure 38). The phosphogypsum material is initially preheated in ZONE 1, by transferring heat from the heating medium through the drum body to the product mix. The outer surface of the metal drum body in ZONE-1 reaches a temperature of 150-250°C, at which specified level the heating of the initial phosphogypsum material mixed in with the added components through the loading wide-band channel (Fig. 38 component 11) first reaches a temperature of 80±5°C.

The highest heating temperature of the drum surface is in ZONE-2, reaching 450-850°C on the outer surface of the drum. This enables high-speed heat transfer to the material layer causing a very rapid transformation of bound and free water into superheated steam. The material itself in ZONE-2 is heated to a temperature of 95-117°C. The maximum volume of superheated steam-air mixture is formed in ZONE 2, which is forcibly extracted through the air duct (Fig. 38 component 6), while both the volume of extracted steam and the related internal pressure is controlled using a fan installed in ZONE-2, equipped with a speed controller and a steam-air mixture controller.

The outer surface of the drum reaches a temperature of 200-250°C in ZONE 3, which ensures the formation of a composite binder with stable physical and mechanical characteristics, the primary attributes of the new material. In this Zone, further extraction of moisture residues occurs in the form of a steam-air mixture resulting in completion of the transition of the binder material to the α-form (α-$CaSO_4$ 0.5 H_2O). The material processing temperature in ZONE-3 thereafter decreases from 117°C to 80°C.

The rate of chemical processes of the formation of a complex compound increases during heating and mixing of the initial phosphogypsum material and the introduced components of calcium oxide and converted calcium carbonate from room temperature to 80±5°C (ZONE-1).

At a raw material temperature of 80±5°C, a complex compound (see Formula 1) is formed in the ZONE-1 drum, which ensures the stable formation of a composite binder product by creating the conditions for the conversion of phosphogypsum into a binder product in the α-form – α $CaSO_4$ 0.5 H_2O – resulting in a binding product with a guaranteed shelf life of at least one year.

$$[CaHPO_4\ Ca_3(PO_4)_2]\ [CaSO_4\ 0.5H_2O\ CaSO_4\ 1.5H_2O\ CaSO_4\ CaSO_4\ 2H_2O\ SrSO_4]\ [Ca(OH)_2\ CaO\ CaCO_3]$$

(Formula 1)

The capture of water molecules by the sorbent creates operational conditions under which the phosphogypsum hemihydrate feedstock does not stick to the inner wall of the drum, and which also retard or block the chemical reaction causing the formation of calcium sulphate dihydrate ($CaSO_4$ $2H_2O$).

Three modes of temperature exposure for calcium sulphate phospho-hemihydrate or calcium sulphate phospho-dihydrate, with a content of super-crystallisation water of no greater than 21%, were proposed for conducting phosphogypsum dewatering processes. The primary challenge set was to achieve the maximum removal of super-crystallisation water within a minimum period of time. At the same time, the content of anhydride and gypsum as a percentage of calcium sulphate phospho-hemihydrate should be minimal, i.e. no more than 10% of anhydrite and no more than 12% of gypsum, while the remainder of calcium sulphate phospho-hemihydrate should be at least 78% of the total mass of the finished binder (Table 5).

Based on the results obtained from the experiments, it was shown that it is sufficient to perform heat treatment for dewatering and obtaining bassanite in the α-form (α-$CaSO_4$ 0.5H_2O) in the required volume of more than 80% for only **38-40 minutes**. The same experiment showed that the anhydrite fraction increases when the material is heat-processed for more than 45 minutes. Studies have shown that the heat treatment interval is in the range 28-55 minutes. Table 5 shows the requirements by parameter for a composite binder:

Table 5. *Requirements (Functional Properties) for a composite binder*

$CaSO_4$ content on dry basis, % minimum	90
P_2O_5 content, % maximum	0.15-0.2
Hydrated (chemically bound) water on dry basis,	7
Bulk density, g/cm^3	0.95
True density, g/cm^3	2.6-2.75
Specific heat capacity, kcal/kg·deg.	0.27
Specific surface area, minimum	3000 cm^2/g

The calcium sulphate phospho-hemihydrate activation technology has been successfully tested on a pilot scale with confirmation of actual product quality parameters. Activated phospho-hemihydrate was produced for confirmation of its functional properties. The results obtained from the use of activated phospho-hemihydrate in civil industries with large-capacity consumption of materials are described in detail below.

1.2.1 New Applications of a Long Shelf-Life Binder (Road Phosphogypsum) Derived from Phosphogypsum Hemihydrate in the Railway Industry

Studies were performed for preparing a technical justification for the use of road phosphogypsum in the railway track subgrade during maintenance and repair (reconstruction) and original construction in the course of which the main problems arising during railway track operation were identified.

Elastic and residual deformations occur in the subgrade and its base under the impact of train load, its own weight and atmospheric factors. Accumulation of residual deformations under certain operating conditions can damage the integrity of the subgrade or its individual parts.

1.2.2 Main Types of Subgrade Deformation

The main types of subgrade deformation that technical grade gypsum was designed to deal with are:

- deformations of the main site
- subsidence and lifting
- creep
- sinkholes
- landslides and shifts
- washouts and underscouring
- frost heaving of the ground of the subgrade.

Technologies using the road construction material "Technical Grade Gypsum" (TGG) were proposed as being able to guarantee the operational performance standards of a sub-ballast layer (SBL) comprised of TGG as the railway track subgrade, across the whole lifecycle of the SBL. As an operational constraint, since all candidate railways for using TGG that required repair or reconstruction are a) located at a significant distance (ie much further away than 50km from the available source of phosphogypsum in hemihydrate (HH) form) and b) the unstabilised HH material had a short life span of only up to 24 hours before it ceased to be workable. This meant that only stabilised binder material obtained from processed phosphogypsum hemihydrate could in any case be considered as a construction materials for repair or construction work on the railway subgrade (SBL).

1.2.3 Main Method of Using the TGG Binder

The main site of the subgrade or sub-ballast layer (SBL), see Figure 39, is constructed using TGG at a compacted thickness of 15 - 30 cm.

Fig. 39. *Use of TGG for the repair (reconstruction) and construction of the railway subgrade*

1.2.4 Basic Requirements When Working with a Hemihydrate Binder

1. The layer of the main site of the subgrade or SBL made of the TGG should be laid to a compacted thickness of to 30 cm on top of the prepared base of the subgrade. The base itself may be prepared from any types of soil allowed for use in accordance with the requirements of Russian Standard SP 238.1326000.2015[30] and other regulatory documents for the railway industry.
2. TGG materials can be used in swamps and marshy areas on the prepared base of the subgrade using a sand drainage layer.
3. A geocomposite reinforcing material (geogrid) with a tensile strength of at least 80/80 kN/m, the size of open pores of the substrate up to 200±20 microns is laid under the TGG layer on a weak base of the subgrade. The main site of the subgrade is made of TGG up to 30 cm thick in a compacted state.

1.2.5 In Situ Pilot – Context

The proposed technological solution for major repairs of the railway subgrade was tested in 2021 on a freight railway track across the site of Balakovo Branch of JSC Apatit (PhosAgro's production asset). The construction of a pilot railway section using TGG material was carried out on a 300-meter-long section. The Section is intended for moving goods in freight open wagons on the territory of Balakovo Branch of JSC Apatit.

1.2.5.1 Process Stage 1 – Preparatory Work

The old railway track and the crushed stone prism were dismantled. The base was prepared on the work site – an excavator excavated the ground along the line of the subgrade with a depth of 35-40 cm and a width of 4 m.

Fig. 40. *Process Stage 1 Preparatory Work (Image courtesy PhosAgro)*

The base was aligned and the points of delivery of TGG material to the work sites along the entire length of the railway track were prepared (see Figure 40 and Figure 41).

30 Russian Standard SP 238.1326000.2015, See https://www.russiangost.com/p-148987-sp-23813260002015.aspx

1.2.5.2 Process Stage 2 – Materials Delivery

Fig. 41. *Delivery of TGG material by tipper truck to the work site (Image courtesy PhosAgro)*

1.2.5.3 Process Stage 3 – Application and Grading of TGG Material in Situ

Fig. 42. *Application (Image courtesy PhosAgro)*

Fig. 43. *Grading (Image courtesy PhosAgro)*

Spreading TGG material to a layer thickness of 30-35 cm on the excavated and levelled subgrade (Figures 42 and 43).

1.2.5.4 Process Stage 4 – Compaction

TGG material is compacted with a single-drum roller in 3-5 passes. After compaction, the thickness of the TGG layer corresponds to approximately 25 cm according to the work execution plan (WEP). The TGG layer is compacted by pneumatic tire rollers or combined vibrating rollers weighing up to 16 tonnes (Figure 44).

Fig. 44. *Roller compaction prior to tracklaying (Image courtesy PhosAgro)*

TGG material is compacted with a single-drum roller in 3-5 passes. After compaction, the thickness of the TGG layer corresponds to approximately 25 cm according to the work execution plan (WEP). The TGG layer is compacted by pneumatic tire rollers or combined vibrating rollers weighing up to 16 tonnes (Figure 44).

1.2.5.4 Process Stage 5 – Laying the Prism and Railway Track

Fig. 45. *Laying the prism and the railway track (Image courtesy of PhosAgro)*

Prisms with a layer thickness of 35 cm are embedded in stone ballast 10 cm below ground level.

2. Summary Findings

The primary laboratory results and positive TGG attributes are:

- Compressive strength 22 MPa
- Splitting tensile strength 3 MPa
- Compressive strength at 15 frost cycles 10-11 MPa
- The material is not destroyed after 50 frost cycles
- Weight loss during 15 frost cycles is not more than 1.0%
- Modulus of elasticity is around 15,000 MPa
- Water resistance of the material Kr is not less than 0.9

The main on-site performance advantages of TGG are

- Binding material is not subject to heaving
- Frost resistance consists of at least 50 cycles
- Resistance to overwetting
- Its monolithic slab structure with concrete properties
- Coefficient of thermal expansion of 0
- It can be used effectively under water pipes in areas with high ground water levels
- It prevents overwetting of the railway subgrade.

2.1 Combined Use of TGG in the Railway Subgrade

Combined applications of road phosphogypsum to create railway subgrade have been developed based on available experimental data from roadbed use. The option described in Figure 39 is proposed if the ground water level reaches up as far as the lower level of the subgrade. A compacted layer of road phosphogypsum with a thickness of 15 to 30 cm inclusive is to be laid in the lower part of the base of the subgrade. Next, the construction of the roadbed to the design height with the deduction of the indicator to minus 25 cm is conducted. The bearing course layer of the roadbed is made up on top of the subgrade consisting of road phosphogypsum with a thickness of 15 to 30 cm – Figure 46.

Fig. 46. *Application of TGG for the construction (arrangement) of the main site and the lower layer of the railway track subgrade at a high surface water level.*

The TGG has a special property in the compacted state, the material retains water from the lower layers and in the process prevents excess moisture accumulating in the subgrade.

This technological solution is used both at high levels of surface (ground) water and for water retention on saline soils. A layer of road phosphogypsum with a thickness of 15 to 30 cm inclusive is arranged in the lower layer of the subgrade. Any type of soil approved for use in accordance with the requirements of the Railway Industry Standards[31] may be applied in the space between two layers of road phosphogypsum.

2.2 TGG Variant with Geocomposite Reinforcement Material

The soil of the subgrade is mixed with phosphogypsum in a ratio of 1:1 from which 30 cm thick layer of reinforced subgrade

31 See Russian Standard SP 238.1326000.2015 https://meganorm.ru/Index2/1/4293756/4293756865.htm

is obtained. The reinforced soil is laid on the surface of the subgrade and compacted by a pneumatic tire roller or combined vibrating rollers weighing up to 16 tonnes (see Figure 44).

A geocomposite reinforcing material (geogrid) with a tensile strength of at least 80/80 kN/m[32], the size of open pores of the substrate up to 200±20 microns is laid on the surface of the compacted reinforced soil (see Figure 47). Up to 40 cm thick layer of road phosphogypsum is spread on the laid geogrid and compacted with a roller. The main site of the road phosphogypsum roadbed should be 15 to 30 cm thick in a compacted state – Figure 47.

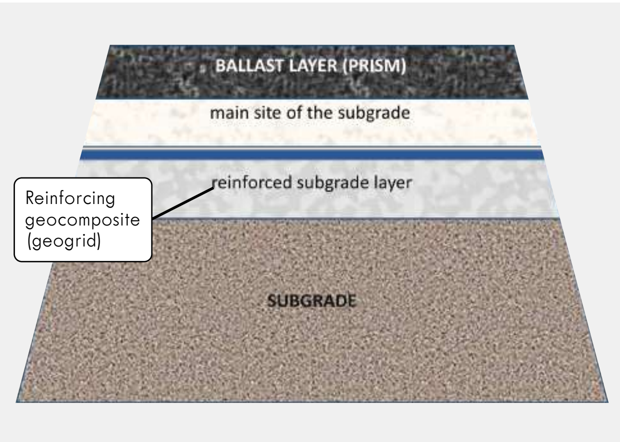


Fig. 47. *Application of TGG for reinforcement of the soil of the subgrade and the main site of the railway track subgrade in combination with a geogrid.*

This technology is applied on weak soils at the base of the subgrade which are either systematically subjected to overwetting or if the lower layers of the subgrade consist of cohesive soils with a high coefficient of plasticity. This technology is also used on the subgrade with heaving soils. The application of this technology allows upgrading railway tracks from category 2-3 to category 1.

2.3 New Applications of a Binder Material in the Road Industry with a Long Shelf-Life of TGG Produced from Phospho-Hemihydrate

One of the typical problems in the operation of motor roads of local and regional significance is high dust content. Therefore, the goal was set in 2020 to apply innovative materials to eliminate the long-standing problem of dust formation using simplified technologies in the construction of regional and inter-village roads.

- A pilot test site was granted a construction permit in Kuvandyksky district, Orenburg region.
- A technological solution was proposed consisting of a combined two-layer structure using a combination of road phosphogypsum, asphalt concrete chips or gravel-sand mixture (GSM) treated with an organic binder.
- 130-150 litres of water and 1 tonne of phosphogypsum were mixed into a slurry of TGG and water using a Wirtgen KMA 200 mixer, (Figure 48).

TGG is delivered to the work site in large bags. The mixture was prepared in the plant and loaded via a conveyor to a dump truck, which delivers the material to the work site at a distance of 100-300 meters from the product mixing unit.

The advantage of this technological solution is that TGG in the dehydrated state is used in exactly the amount needed to execute the task in hand and work can be stopped at any time, if necessary, under prevailing weather conditions.

The resulting mixture has a thickness of 20-40 cm in the uncompacted state which can be applied to an existing road with heavy dusting without a drainage layer (a village road adjacent to a federal highway).

The mixture is spread out by a grader according to technological measurements and is then compacted by a roller. A layer up to 5 cm thick of gravel-sand mixture from local quarries is distributed on the surface of the compacted layer of TGG which was then re-compacted into the surface of road phosphogypsum (Figure 49).

Thus, the task of dust control on regional highways was fully completed. An external examination of the site after a year of operation (Figure 51) showed that the use of a combined method for building regional roads using road phosphogypsum is an effective procedure for eliminating potholes and dust.

But a negative unforeseen consequence of such a good surface is that the local habit of exceeding legal speed limits in unpoliced rural areas was made significantly worse because the surface quality of the new road to the driver new to the surface looks very similar to the asphalt-concrete surface in good condition found previously on much higher specification roads with much safer driving conditions.

32 80/80 kN/m geogrids are used in a variety of civil engineering applications, including: landfill engineering, road construction, and hydraulic engineering.

Fig. 48. *General view of the mixing workstation*[33] *(Image courtesy PhosAgro)*

Fig. 49. *General view of a combined road section treated with an impregnated compound (Image courtesy PhosAgro)*

Fig. 50. *Surface structure of a combined pavement based on the road phosphogypsum treated with an impregnation compound (Image courtesy PhosAgro)*

Fig. 51. *General view of an experimental combined road section using road phosphogypsum after a year of operation (Image courtesy PhosAgro)*

Fig. 52. *Appearance of construction blocks produced from the binder (Image courtesy PhosAgro)*

33 For Wirtgen KMA 200 see https://www.wirtgen-group.com/ocs/en-me/wirtgen/kma-240-18862-p/

2.4 New Applications of Phosphogypsum Hemihydrate Binder in the Construction Industry

While performing tests with a binder produced by processing phosphogypsum-hemihydrate using the technology discussed above, it was discovered that the same material can be used successfully in the production of engineering bricks, ornamental bricks and load-bearing construction blocks (Figure 52).

These innovative materials were first tested on an industrial plant in the Republic of Tatarstan at a specialised factory producing the relevant equipment.

Local regulations require that bricks should have high frost-resistant properties and should not produce or act as growing medium for any fungus and pathogenic bacteria. In reality, the material creates a favourable microclimate in the interior space, while the thermal conductivity corresponds to gypsum. It has sufficient unconfined compressive strength (UCS) for the construction of low-rise buildings (Figure 53).

2.4.1 Brick Production: Plant Performance

The following are key attributes of a high-performance brick production plant using TGG:

- The line is fully automated
- The line is controlled by a single operator
- Bricks are removed and placed on pallets by a stacker robot
- The unit operates in two-way pressing mode with an applied compression force of 270 tonnes
- One compression cycle: **12-15 seconds per batch of 3 bricks**
- The minimum plant capacity: **820 bricks/hour**
- Weight of one brick: **2.7 kg**
- The capacity of one block production plant: **600 blocks/hour**
- The weight of one 200 x 200 x 400 block: **16 kg**

Overall, a plant with these specifications by comparison with the equivalent processing of natural gypsum, enables the manufacture of bricks and blocks at a significantly higher throughput and at a cost 1.5 – 2.0 lower than the conventional alternative.

Bricks and blocks combined enjoy a large niche in the construction market, with a range of applications such as domestic housing units, utility structures, warehouses and street furniture, among others. Taking into account the steady increase in the cost of sourcing and processing natural materials of construction such as gypsum, chalk, and limestone, the use of technogenic phospho-hemihydrate (TGG) greatly lowers the cost barrier compared with equally effective new materials and results in sustainable constructions with identical quality and performance to naturally sourced resources. These are made financially accessible to the mass individual consumer market, small and medium-sized businesses (SMEs), farmers, and as highly affordable for use in certain categories of public building and a range of individual dwellings.

The production of technogenic phospho-hemihydrate on an industrial scale as a Secondary Raw Material (SRM) with a robust supply chain ensures the long-term physical and commercial availability of this secondary resource for the construction material market. It actually replaces the need to deplete declining stocks of natural raw materials whether mined by open-pit or underground resulting in the negative externalities of the destruction of the natural landscape, the generation and disposal of high volumes of "waste rock", entailing a further significant cost resultant from the End of Life closure and remediation of mine workings.

Fig. 53. *The potential of using TGG feedstock in high-capacity manufacture of high-performance materials of construction*

The development of activated TGG reveals the potential of its application as a product of phosphogypsum processing, available in high volumes at affordable levels (Figure 53), including high materials performance even in difficult hydrological conditions (high water content).

Technical and economic parameters for the production of materials for road construction, construction of railway sleepers, building bricks and blocks enable natural gypsum resources to be replaced by phospho-hemihydrate as a raw material.

In the near future, optimal production process parameters will be chosen for the pilot plant for producing TGG from phospho-hemihydrate of the Balakovo Branch of JSC Apatit. This will include an assessment of the operational reliability of the main process equipment, together with the evaluation of the quality parameters and stability of TGG. Sample batches of TGG will be also independently tested by future customers in the various markets of road and railway construction, and the manufactures of building materials and products. The operational (FEED) data obtained will provide the basis for the development of technical specifications and normalised predicted data for designing an industrial plant with a high-volume throughput of TGG for phospho-hemihydrate feedstock (i.e. capacity of > 100 thousand tonnes per year).

Taking into account the availability of industrial equipment for the hardware design of a large-capacity phospho-hemihydrate in a TGG processing plant, it is advisable to create standard (modular) plants and build them in a short time at phosphate-processing enterprises. **No additional stages of phospho-hemihydrate preparation, such as removal of heavy metals, arsenic, and radioactive elements, are required in the case of processing high-grade apatite concentrate in Kirov Branch of JSC Apatit**. This removes an additional barrier in terms of capital and operating costs.

2.5 The Business Case

During the pilot project, the functional properties of the obtained materials, as well as the physical and cost advantages of the material and products in comparison with natural materials, were confirmed to-scale and are ready to be widely rolled out. TGG is fully suitable for industrial implementation deploying modular, multipurpose scaling of a single, standardised plant capacity. This lowers the unitary cost and life-cycle cost of ownership of road or rail infrastructure, shortens supply chains while enhancing value-add and value-chain resilience – both key circular economic objectives.

TGG offers overall a potential breakthrough technology for year-round phospho-hemihydrate valorisation and use. It was originally developed and tested for the development of the direct use of phospho-hemihydrate in road or rail construction on a continuous basis, irrespective of season of use or haul distance to the place of use. This overcame the two main obstacles to market entry and scalability: eliminating the haul distance limit of 50km and resolving the issue of workability in temperatures above 20C (the binding properties of fresh phospho-hemihydrate). These issues used to prevail during the summer season when most roadbuilding occurs which, untreated, has severe territorial limitations related to the preservation of the material's workability. Now it can work irrespective of the season.

This transformative TGG material property enables the preservation of the functional properties of the activated material for a long time, storing it over time in an unchanged state, and transporting it to the place of use with full preservation of its original properties. It brings with it an unforeseen but high-value potential that TGG materials can be deployed in other markets for different stakeholders – **individual consumers, small and medium-sized businesses (SMEs), farmers, retailers and shopkeepers.**

A TGG facility can simultaneously diversify the scale and expanding the range of applications to cover the construction of roads and railways, as well as civil infrastructure.

C H A P T E R   F O U R

PHOSPHOGYPSUM: A DRIVER OF SUSTAINABLE GROWTH FOR OCP

Authors: This Strategy Overview connects the three PG application specific Case Studies. It was compiled by General Editor and Kamal El Omari on behalf of OCP.


4

1. Strategy Overview

In the 2023 OCP Sustainability Report [22], PG value creation is one of the priorities within OCP Group's strategy for diversification, the whole of which is defined by adherence to the circular economy (CE) defining the business principle of value creation, and based on a four environmental-pillar framework.

Value creation from PG is achieved first by applying three of the environmental pillars in temporal sequence to a core business process: 1. Sustainable production, 2. Using resources conscientiously, 3. Recycling and transforming waste to resource, with one unifying desired outcome and 4. Feeding the planet sustainably (see Figure 54).

Fig. 54. *Pillars of OCP's Sustainability Program*

1.1 Resource Management and PG

From a resource management perspective, OCP positions PG valorisation as part of Pillar 2 ("Using resources conscientiously") – considering PG a coproduct, with the directive to "**Maximise phosphogypsum valorisation** while using safe storage". The valorisation process itself begins with developing a formal sustainability policy and business strategy: "As part of its Sustainability Strategy, OCP has undertaken to gradually store phosphogypsum from 2024" – a necessary first step for the valorisation process to be carried out. This is recognised as "a significant challenge for the phosphate industry" to meet, and one which "OCP is actively seeking innovative and sustainable solutions to ensure the responsible stewardship of natural resources and ecosystems".

1.2 PG Production at OCP

An ambitious, well-planned strategy for the high-volume valorisation and use of PG is certainly required. OCP produces PG in significant quantities at its Jorf Lasfar and Safi industrial complexes, at an approximate rate of 40 million tonnes per year. Of this, ~32.5 Mt/y are produced at Jorf Lasfar, while the remainder comes from Safi. Globally, this positions Morocco after China, as the second-largest PG producing country in the world.

2. The Great Transition to Storage and Use

To set the value creation process in motion, the goal is to "Transition from phosphogypsum (PG) dispersion into the marine environment to storage/valorisation, in order to develop PG as a coproduct" [22]. The transformative nature of this decision – to store and use PG rather than disperse it – can hardly be overstated, whether in terms of scale, complexity, or human and financial resources. Unlike other major producers planning large-scale PG use, OCP has begun with, rather than arrived at, a coherent yet pluralistic strategy for achieving its goal. In practice this strategy means the "deployment of phosphogypsum recovery in different routes (quantities per route, regions to be targeted, etc.)" [22]. For this purpose, OCP has carried out a comprehensive study aimed in particular at:

a. developing a model to assess the potential for **extracting sulphur from PG**
b. updating models to evaluate the potential for **using PG in road construction/soil improvement/reforestation & the fight against desertification**
c. assessing the potential for recovery of PG in other identified applications (ammonium sulphate, fertilisers, cements, concrete or prefabricated elements, building materials, etc.).
d. Continue the development of different valorisation pathways with various partners.

2025 marks the year when the strategy will start to be implemented/deployed on a large scale.

3. Case Studies

Among the options identified in OCP's strategic plan, three are represented by use cases in this Report: 1. **Road construction** and maintenance, 2. **Agricultural development**, and 3. **As a strategic anthrosol resource for combating desertification**, whether at a national level in Morocco or regionally in the Sahel and wider Sahara. The latest use case is presented as a highly significant contribution by OCP to the UN Convention on Combating Desertification[35] (UNCCD), channelled through the

35 For UN Convention to Combat Desertification (UNCC) https://www.unccd.int/convention/overview

Great Green Wall initiative (GGWI).[36] The other two case studies, roads and agriculture development (see below), update direction-setting studies featured in IFA's PG Report 2 (2020) [17].

The updates in this report take a distinctly innovative approach from a materials science perspective and show great promise from a business case perspective. In PG2, the approach was based on benchmarks, leveraging well-documented methods for use of PG in road building and agriculture, which were implemented with precision. By contrast, PG3 highlights innovative and appropriately targeted mixes (anthrosol and mixtures for road construction), to meet national and regional needs and priorities for both the short and longer term.

The case studies presented in this report demonstrate the practical application of the Pillar 3 principle, Recycling and transforming waste to resource (see Figure 54), from a circular economy perspective. By using PG as a core roadbed material to replace primary quarried aggregates traditionally used in Moroccan road construction, millions of tonnes of valuable primary resources are preserved annually for future generations.

This represents a textbook example of a well-researched, field-tested, and science-based beneficial use of secondary raw materials that aligns with ESG performance goals. Although the direct use of PG in road construction does not directly contribute to feeding the world, the roads built with PG play a crucial role in addressing the logistical and distribution challenges associated with growing, harvesting, and transporting high volumes of food produced with phosphate fertilisers and PG coproducts, ensuring long-term sustainability.

4. ESG Investment and Double Materiality

The enabling capital investment in particular for each of the three PG applications covered in this report is detailed in financial terms in the 2023 OCP Sustainability Report [22]. Simultaneously, the case studies illustrate how this financial capital allocated to the PG transition is turned to advantage into new knowledge and capabilities (social capital). This transformation is driven by the expanded engagement of the University Mohammed VI Polytechnic (UM6P) in the PG-use nexus, in collaboration with its subsidiary companies and national and international partners. The two processes merge in the 2023 report into an elegant double materiality summary of the “new” OCP, whose emerging capabilities are strategically focused on development of new innovative applications. The fight against desertification is one example, particularly through the development of a highly innovative PG-based anthrosol.

36 For the Great Green Wall Initiative see https://www.unccd.int/our-work/ggwi

While OCP's engagement with UNCCD science, policy, and best practice is robust and well planned, it also brings in a radically new anthrosol mix to meet these ambitious targets. This mix combines PG with other abundant secondary raw materials from the Moroccan P/PG value chains, such as phosphate mine tailings, rock beneficiation slimes, as well as processed sewage sludge or farmyard manure, which provide both nutrient content and organic matter.

5. Sustainable Project Management System

The Sustainable Project Management (SPM) is an innovative system developed by OCP and DOOC (Dupont OCP Operations Consulting) specifically for CE transition projects [22]. From a principles perspective, it integrates Environmental, Social, and Governance (ESG) criteria into industrial development and business initiatives, such as PG storage and valorisation, anchoring the connection between business and socio-environmental impacts in OCP's strategic definition of double materiality analysis.

At its core, the SPM methodology aims to adapt procedures for such strategic projects and initiate a comprehensive OCP project management process to proactively identify, assess and manage environmental, socio-economic, and social impacts, as well as the related risks and benefits of any such transformative project.

5.1 SPM Key Components

The SPM system being deployed consists of four key phases:

1. A Checklist for OCP unmissable sustainable commitments, which provides actionable guidelines for each quantified target.
2. An ESG impact assessment tool, which encompasses over 80 ESG topics and more than 100 key performance indicators to measure potential positive and negative externalities (KPIs).
3. ESG scorecards (inherent impact analysis + managed impact analysis) for project monitoring based on the information obtained in the two previous stages.
4. SPM Governance Procedures: Outlining roles and responsibilities for project managers, sustainability support, OCP/JESA, and SPM governance bodies, including meeting frequency and reporting.

The three OCP / UM6P Case Studies included in this report show that, at the project templating scale, the SPM system works well on an application by application basis. What remains an open challenge, however, is the ease with which the lessons learned template scale can be deployed at a strategic, whole enterprise level. This scaling process begins in 2025 with a quantum jump into progressively comprehensive storage as the feedstock for large-scale valorisation of PG products and services for national and international use.


5

C H A P T E R   F I V E

PHOSPHOGYPSUM AND ROAD MATERIALS, MOROCCO - THE OCP APPROACH

Authors: This case study is based on original research and development conducted by OCP and its partners. It was compiled and edited by Aleff Group, reviewed and finalised under the guidance of and contributions from Chaimaa Diouri Ayad (UM6P), Amina Alaoui Soulimani (UM6P) and Kamal El Omari (OCP)

1. Building Experience and Expertise through Partnership

1.1 The Partnership

Driven by value creation, in 2013 OCP mobilised partners to enable the large-scale deployment of PG valorisation in road construction [23]. This brought together a range of highly respected institutions:

- Ecole Hassania des Travaux Publics[37] (EHTP) (The Hassania School of Civil Engineering),
- Ecole des Ponts ParisTech[38] (ENPC) (The National School of Bridges and Roads, Paris),
- Centre National d'Etudes et de Recherches Routières[39] (CNER) (National Roads Research and Development Centre - Part of the Ministry of Equipment and Water),
- Les Grands Travaux Routiers[40] (GTR) (Major Roads Projects) / COLAS[41], a road building specialist.

The outcomes of this collaboration are documented in detail in the second IFA Phosphogypsum Report (2020) [17] facilitating the partners' engagement in a new objective, the results of which are presented in this publication.

Subsequently, this partnership was expanded to capitalise on the combined expertise and resources available in Morocco, including:

- JACOBS Engineering SA[42] (JESA)
- Mohammed VI Polytechnic University[43] (UM6P)
- INNOVX[44]
- Laboratoire Public d'Essais et d'Études[45] (LPEE) (Public Laboratory for Experiments and Studies).

1.2 The Process

The UM6P/OCP collaboration process followed a sequence of six major steps:

1. Detailed continuous internal literature review.
2. Targeted laboratory tests: Analysis of various mixtures containing phosphogypsum (PG).
3. Consistent cement content in laboratory-tested mixtures: The cement content in laboratory-tested mixtures is maintained at a constant dosage 7%, as literature suggests this level complies with environmental standards. This conclusion was further validated by pollutant potential tests conducted on the selected mixtures by OCP and its partners.
4. Construction of test sections: Test sections were built using subbase layers composed of mixtures determined by laboratory results. The pilot road includes five sections: four incorporating PG mixtures and one serving as a control section.
5. Mechanical, environmental, and sanitary assessments: comprehensive evaluations of mechanical properties, environmental impact, and sanitary conditions have been conducted.
6. Validation of PG use in road construction: Results from the Safi pilot road [16] have confirmed the viability of using PG in road construction:
   - Development of appropriate product mixture (New product development),
   - Environmental impact assessment,
   - Project execution in 2017 at Safi plant site with focus on:
     - onsite mechanical performance,
     - onsite environmental / sanitary assessments,
     - Life-cycle analysis and techno-economic balance.

A second pilot project was conducted in Jorf Lasfar to validate the commonly used road construction techniques for treated soils. Further details of progress in developing a new Moroccan standard for road building with PG may be found below.

1.3 The Knowledge and Experience Platform

Since 2017, OCP has been actively building a robust platform of technical, scientific, and engineering expertise in road materials and structures, in close collaboration with its partners. Together, they are working to valorise PG as part of the development and maintenance of Morocco's growing road network. This initiative aligns with UN Sustainable Development Goal, SDG 17, Partnerships for the Goals, while also contributing to SDG 12, Responsible Consumption and Production with its references to a key principle of the circular economy, achieving "zero waste" outcomes.

The experimental foundation of this platform of expertise and partnerships has been established through the construction

37 For Ecole Hassania des Travaux Publics, see http://www.ehtp.ac.ma/

38 For Ecole des Ponts ParisTech, see https://ecoledesponts.fr/

39 For Centre National d'Etudes et de Recherches Routières, see https://www.equipement.gov.ma/Infrastructures-Routieres/CNER/Pages/Missions.aspx

40 For Grands Travaux Routiers, see https://www.colas.com/en/group/locations/

41 For Bouygues Group Transport Infrastructure, COLAS, see https://www.colas.com/en/group/who-we-are/

42 For JACOBS Engineering S.A., see https://www.jesagroup.com/

43 For Mohammed VI Polytechnic University, see https://um6p.ma/en

44 For INNOVX, see https://innovx.com/

45 For Laboratoire Public d'Essais et d'Études, see http://www.lpee.ma/en

of pilot PG roads at OCP's initial production sites in Safi and Jorf Lasfar.

This new case study updates the exploratory piloting process and outlines the new strategic direction enabled by the success of the pilot program, aimed at supporting the expansion phase of the national road network. From a materials perspective, the subsequent studies focused on:

- Incorporating alternative materials as a substitute for sand: steel slags / phosphate tailings.
- Varying cement type and content: Exploring the use of CEM II and RHB binders to identify mixtures that satisfy mechanical and environmental criteria for subbase and subgrade layers.

The results confirmed that these criteria can be met with a binder content of less than 7%.

A parametric study was conducted to determine the most suitable pavement structures, taking into account platform load-bearing capacity, traffic conditions, and the mechanical quality of the PG-based mixture. The dual objective was to maximise the use of treated PG layers while adapting the structure to local constraints.

Based on these technical studies, OCP and JESA developed a model to evaluate the potential for PG utilisation in Morocco. This model plays a key role in defining the scope and operational parameters of the expansion driven by OCP's long-term strategic partnership with JESA. This initiative integrates the use of PG in road construction seamlessly into OCP's new circular economy (CE)-based business model, as outlined in its 2023 Sustainability Report [22].

2. The Strategic Business Case

OCP and JESA have established a business case framework for PG valorisation, focusing on strategic market development rather than product branding or prospective sales figures. This approach has resulted in an integrated and coherent strategy for sustainable utilisation of PG, rather than its application in one-off infrastructure mega-projects. The framework considers demand, supply, and cost factors: road demand in km, PG supply in terms of tonnage and volume, and costs related to materials or construction, measured in Moroccan Dirhams (MAD).

After a meticulous analysis of these factors, the conclusion is clear: "There is a relevant potential in road construction, with the Moroccan road market expected to be largely dominated by maintenance over the next decade (2018-2028)." This insight is particularly astute given historical evidence from PG road construction [6] which highlights its unique property of strengthening over time. This characteristic makes PG one of the least expensive materials for roadbed applications across diverse climates, including sub-tropical and monsoon regions, deserts, and freeze-thaw conditions, as seen in countries such as Finland and the Russian Federation.

OCP and JESA's emphasis on maintenance shifts the valorisation of PG in roads from a focus solely on developing new infrastructure to a dual-purpose strategy encompassing both construction and maintenance. This lifecycle management approach aligns seamlessly with the circular economic principles at the core of OCP's business model.

From a quantitative perspective, the study concludes: "This option could allow OCP to valorise several million mt of PG per year". If implemented, this would significantly reduce the demand for PG storage space while yielding substantial capital expenditure (CAPEX) and operating expenditure (OPEX) savings. The strategy also paves the way for monetising PG as a fully validated business proposition, moving beyond the current assumption of PG as a "zero-cost" material for roadbed use. The ability of OCP and JESA to reach such a level of precision and confidence in their business model after only seven years of intensive preparatory R&D is a remarkable achievement.

2.1 OCP Pilot Project on Co-Valorising Phosphate Tailings and Phosphogypsum in Road Construction

As part of its Corporate Social and Environmental Responsibility (CSR) and commitment to sustainable development, OCP made an early and deliberate decision to transition from a one-dimensional business objective to a circular economic (CE) approach. This shift aimed to restore value to a variety of secondary raw materials previously categorised as waste. The focus was no longer merely on transitioning away from disposing of phosphogypsum into the sea to valorising and utilising PG residues on land. Instead, OCP sought to implement a holistic, CE-based solution to address the linear economic issue of discarding millions of tonnes of potentially valuable secondary resources from the phosphate value chain, including overburden, mine tailings, and processing residues such as PG.

2.1.1 Understanding the Nature of the Challenge – from Residue to Secondary Raw Material

The real challenge was as much one of policy and definition as scientific, though with profound regulatory consequences. Materials such as PG were classified as waste based on the legal-technical definition that waste is a resource for which the owner cannot foresee any further use, rather than an indication of the inherent uselessness of the material. The waste classification, made with a mere stroke of the pen, imposed a massive "negative externality" on future generations, burdening them with billions of tonnes of such "wastes" across various mineral industries - not just phosphate.

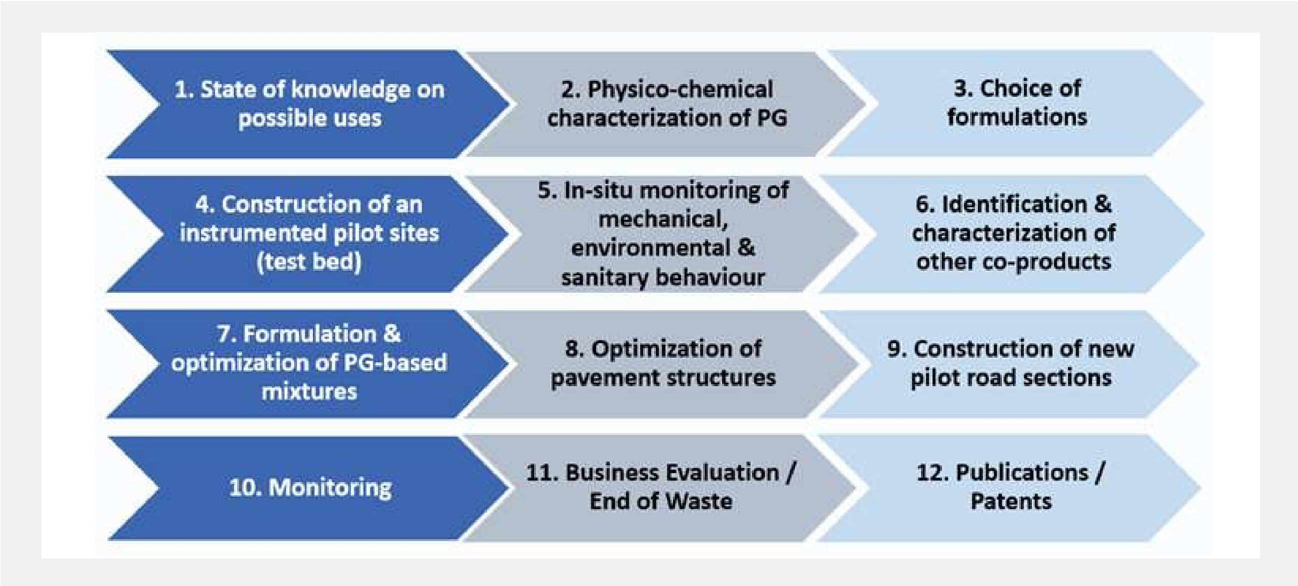


Fig. 55a. *12 Step Research and Development - PG Valorisation and Use in Road building*

2.2 The Anchor Policy Change

The EU Green Deal policy decision was to recontextualise residues and tailings such as PG, along with many others, as "secondary raw materials" (SRMs). SRMs are defined by the European Parliament as "recycled materials that can be used in manufacturing processes instead of or alongside virgin raw materials." This reclassification by economic policy determination transforms waste into a resource, opening the door to its valorisation and practical use. In parallel, international organisations such as OECD and IAEA are adopting similar approaches to the EU. For IAEA this means working on an evidence based case to valorise residues from NORM (Naturally Occurring Radioactive Materials) related industries also as secondary raw materials. This shift represents a significant step toward sustainable resource management and aligns with global efforts to promote circular economic principles.

In making its decision, OCP has aligned with these new internationally increasingly recognised science- and evidence-based procedures, best practices, and emerging standards. This included initiating the pilot project detailed in this case study on roadbuilding with PG to achieve what the European Union now defines as "End of Waste" status for these resources. As of July 22, 2022, within the EU, the use of phosphogypsum in agriculture has a legally binding pathway to attain End of Waste status[46], enabling its transition into commercial use as a legitimate product. This development underscores the potential for broader applications of PG and validates OCP's strategic approach to resource valorisation.

2.3 The 12 Step Research and Development Pathway (2013-2025)

The twelve-step R&D pathway used by OCP, designed to strategically enter the Moroccan domestic road construction and annual maintenance market is illustrated in Figure 55a.

2.4 Safi 2017

In 2017, OCP Group launched the first pilot road project utilising phosphogypsum for road construction within the perimeter of the Safi site, located on the Moroccan Atlantic coast (Figure 55b).

Fig. 55b. *Panoramic view - PG pilot road, Safi*

46 Regulation (EU) 2019/1009, https://single-market-economy.ec.europa.eu/single-market/european-standards/harmonised-standards/fertilising-products_en

The PG used in this project was sourced directly from the Safi plant itself. This project was the subject of a detailed case study in IFA PG2 [16] [17].

2.4.1 Jorf Lasfar 2019

The first pilot road project at Safi yielded encouraging results, so the research study was extended in 2019 to Jorf Lasfar, the largest OCP production site [16] [17]. The main aim of the second pilot project was to validate the existing road construction techniques used for treated soils.

2.5 Phosphogypsum Mixtures Optimisation

In the context of the strategic objective of utilising PG in road construction in Morocco to maximise usage and offset the increasingly high costs of surplus PG disposal, it is noteworthy that the quantity of PG consumed per km of road built, using Morocco's specially developed mixture, is in some scenarios lower than that of the pilot PG-only roads constructed in Central Florida under the supervision of the Florida Institute of Phosphate Research (FIPR).

In Morocco, the usage rate ranges between 2.5t and 9.7 t/lane-km for a PG-treated pavement structure, aligning with the circular economy objective. At the upper end of Morocco's range, the usage is effectively the same as the IAEA/World Bank reference, while at the lower end, it is only 25% of the reference. This comparison is based on actual figures for PG roadbed use and materials of construction containing different phosphogypsum mixes in Texas during the 1970s and in Florida during the 1970s and mid-1980s, such as the Parrish Road[47] and White Springs pilot roads [16].

3. A New Approach

The Moroccan approach deliberately applies different criteria from those used by FIPR. It proposes "a new treatment protocol for PG as a roadbed resource using both Cement and HRB as a low-cost, eco-friendly binder and as contaminant-fixing agent and explores the possibility of incorporating either phosphate mine tailings and /or steel slag as a granular corrector instead of the primary material crushed sand". Of the two secondary raw material options P mine tailings is new, while steel slag is a roadbed material of choice in the US. Either combination enables the valorisation of more than one by-product from the phosphate or steel industries. The approach deepens the application of circular economy principles, emphasising primary resource conservation, carbon footprint reduction, and environmental stewardship, particularly in protected or socially disadvantaged areas.

3.1 Maximising PG Use

To maximise the use of PG in roadbuilding and maintenance in the growing Moroccan highway system the OCP approach applies the dual criteria of engineering and economic performance in equal measure, to maximise the level of PG use, compatible with road materials' properties requirements. The process focused on optimising the mixture ratio for PG treated with a hydraulic binder (Cement 'C' / Road Hydraulic Binder (RHB), with content minimised to reduce costs) and a granular corrector (Sand 'S' / Phosphate Tailings 'T' / Steel Slag 'SS'), ensuring compliance with reference mechanical criteria for materials used in sub-grade and sub-base pavement layers. As a prelude to describing the work done, its scientific and technical base is referenced first to illustrate the methodology followed and the results obtained [22] [24] [25].

3.2 Mixture Design

3.2.1 Fields of Study

The selection of study ranges for the various parameters was informed by a literature review which focused on the effects of pH [26]. The addition of sand was justified by its ability to enhance bearing capacity, ease of use, and neutralisation of acidity. Conversely, cement was incorporated to raise the pH above the neutrality threshold, trap impurities, and improve mechanical strength. Encouraging results from onsite tests conducted at Safi [17] [6] prompted the research team to explore extended ranges of the components.

The objective in determining the optimal composition of materials was to maximise the use of PG while minimising the reliance on hydraulic binders. This was typically studied within the following ranges:

- PG (phosphogypsum): 45%-70%
- S or SS (Crushed sand/Steel Slag): 23%-48%
- C (CEMII cement): 4%-7%.

47 See https://fipr.floridapoly.edu/wp-content/uploads/2014/12/01-033-077Final.pdf

3.2.2 Simplex of Experimental Points

The design expert software was utilised to model each of thedesired mechanical responses (Figure 56):

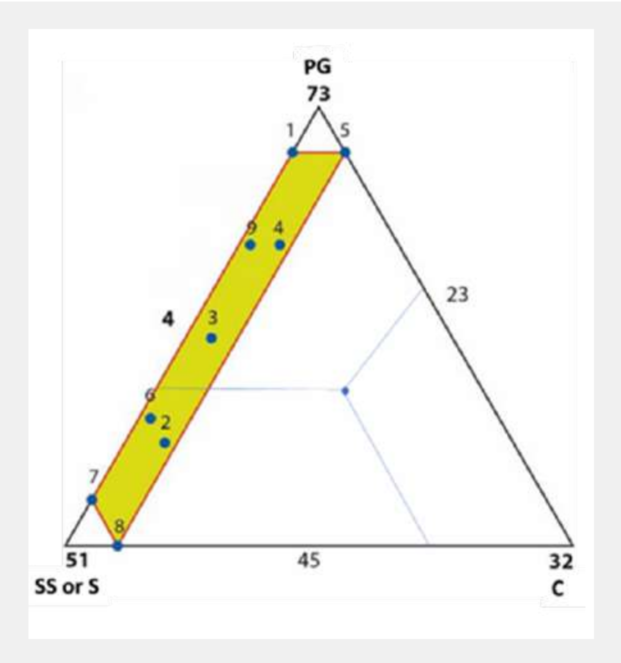


Fig. 56. *Graphical representation of the experimental points*

The variants modelled were based on the dosage range of the mix constituents.

3.3 Technical Criteria of Treatment Suitability Test

The treatment suitability test, as outlined in the French standard SETRA [27], evaluates the vertical swelling and/or tensile strength of soil treated with hydraulic binders. These values are measured on samples immersed in water after four or seven days.

Table 6 presents the threshold values for treatment suitability technical criteria, which determine whether an alternative material can be treated for road construction purposes. In cases of uncertainty, additional onsite characteristics should support the proposed treatment technique. No treatment solution should be applied in cases deemed unsuitable.

Given the Moroccan climate context, tensile strength criteria were disregarded.

3.3.1 Criteria (Subgrade and Subbase)

The objective was to evaluate the effect of varying the mixture component dosages on the physical and mechanical characteristics, as outlined in road design guides, for use in mechanical assessments.

Materials criteria for subgrade layer use were [28]:

- CBR-4d > 20 and CBR-4d/IBI > 1
- UCs28d > 1MPa (for trafficability purpose)
- (Ts360d, E360d) at least in zone 5 of the classification chart [29]

Mixture criteria for subbase layer use are similar to those above, except [29]:

- UCs28d > 1.2 MPa to consider average site traffic (trafficability)
- (Ts360d, E360d) at least in zone T1 of the classification chart [30]

3.3.2 Targeted Responses

Based on the criteria in 3.3.1, the responses measured (see Figures 57 a-d) were:

- IBI[48], CBR-4d and Gv according to NF EN 13286-47 (57(a), (b))
- UCs7d, 28d: according to NF EN 13286-41 (57(c))
- Ts28d: according to NF EN 13286-42 (57(d))
- E28d: according to NF EN 13286-43 (57(d)).

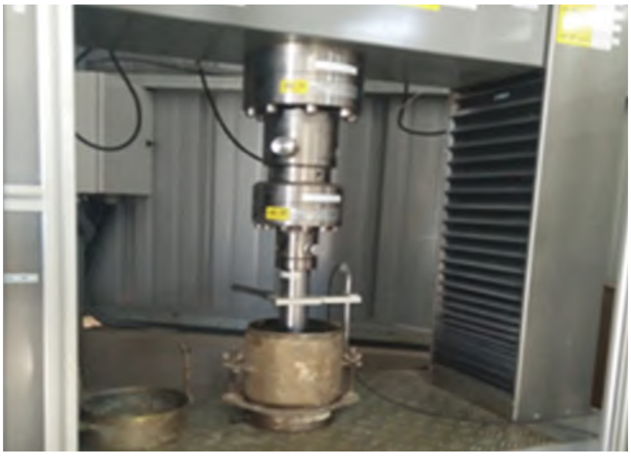
3.3.3 Compaction Procedure

Unconfined compressive strength (UCS) tests are conducted at a material density set to 98.5% of the Proctor dry density (NF P 94-093 | NF EN 13286-2), while tensile strength (Ts) tests are performed at 96% of the Proctor dry density. Consequently, it is essential to determine the optimal Proctor density of the experimental mixtures before analysing the targeted responses.

Table 6. *Eligibility criteria - Materials treated with hydraulic binder*

Soil suitability	Vertical swelling Gv (%)	Tensile strength Ts (MPa) after seven days of immersion at 40°C
Suitable	Gv < 5 %	Ts > 0,2
Doubtful	Gv from 5% to 10%	Ts from 0,1 to 0,2
Not suitable	Gv > 10%	Ts < 0,13

48 IBI = Immediate Bearing Index



57(a) *Immediate bearing index (NF EN 13286-47)*

57(c) *Unconfined compressive strength (NF EN 13286-41)*

57(b) *Californian bearing ratio after four days of water immersion and vertical swelling after four days of water immersion with overload (NF EN 13286-47)*

57(d) *Diametral tensile strength and elastic modulus (NF EN 13286-42 and 43)*

Fig. 57. (a): *Immediate bearing index (NF P 94-078)*. **(b)**: *Californian bearing ratio after four days of water immersion and vertical swelling after four days of water immersion with overload (NF P 94-078)*. **(c)**: *Unconfined compressive strength (NF EN 13286-41)*. **(d)**: *Diametral tensile strength and elastic modulus (NF P 98-232-3)*

3.3.4 Samples Preparation

PG is highly sensitive to compression, necessitating the use of thin layers with an increased number of passes and heavier rollers, hence requiring higher compaction energy compared with conventional materials. For this reason, all compression tests were conducted using modified Proctor energy and in CBR Moulds.

According to French national road-building standards GTS [29], two cylindrical samples are used to perform these tests. The first is for unconfined compression strength UCS with 5" x 10" cylindrical moulds (Ø = 50 mm; h = 100 mm), which were prepared with a water content Proctor W_{OPM} and 98.5% Proctor dry volume mass P_{dOPM}, made by static compacting according to the standard (NF P98-230-2). The second is for the tensile test (Brazilian test), cylindrical 10" x 10" specimens (Ø = 100mm; h= 100 mm) were prepared with optimum water content W_{OPM} and 96% of Proctor dry density P_{dOPM} and carried out by static compaction in accordance with the standard (NF P 94-230-1).

To determine mechanical strengths, four samples were taken per test (three are required for averaging and one as a reserve in the event of damage to one of the samples). The samples were prepared using a mechanical press with Proctor Modified water content W_{OPM}.

3.4 Mechanical Performance

3.4.1 Bearing Capacity and Swelling

The bearing capacity and swelling indices of PG mixtures are displayed in Figure 58. The CBR is always higher than the Immediate Bearing Index (IBI) after 4 days of water immersion, in part because water enables the cement to react and generate Calcium Silicate Hydrates (CSH) which improves the load-bearing capacity. First, all swelling values are less than 5% [26]. Secondly, significantly greater load-bearing indices were obtained with larger steel slag dosages (42.1% and 48%); for instance, at the same cement content (4.75%), 42.1% steel slag produced an IBI value of 138, whereas 31.1% steel slag produced a value of 98.

This is due to the steel slag's ability to compensate for grain distribution, which produces a more uniform distribution of grain sizes overall and, as a result, increased load-bearing capacity.

Nevertheless, cement is needed to increase the load-bearing capacity of sand alone. The following example clearly illustrates the impact of cement: The CBR-4d value rises from 142 with 4.75% cement to 165 with 6.25% cement when 42.1% steel slag is added (Figure 58).

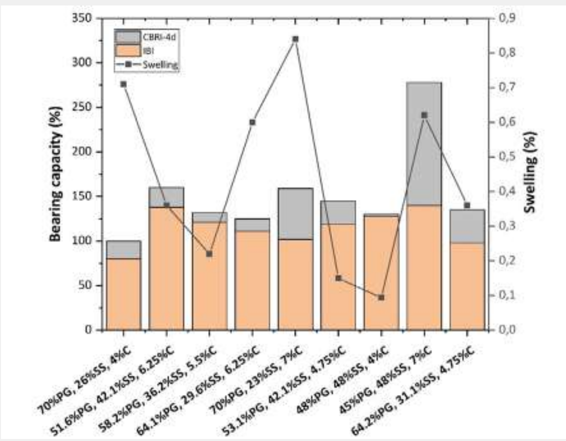


Fig. 58. *IBI, CBR-4d and Gv (%) of the 9 experimental mixtures*

3.4.2 Unconfined Compressive Strength

As cement content and curing time rise, so does the unconfined compressive strength (UCS) (Figure 59). The UCS increases from 0.16 MPa (4% C) to 0.26 MPa (6.25% C) after 28 days and from 0.9 MPa (4% C) to 1.38 MPa (6.25% C) at 7 days.

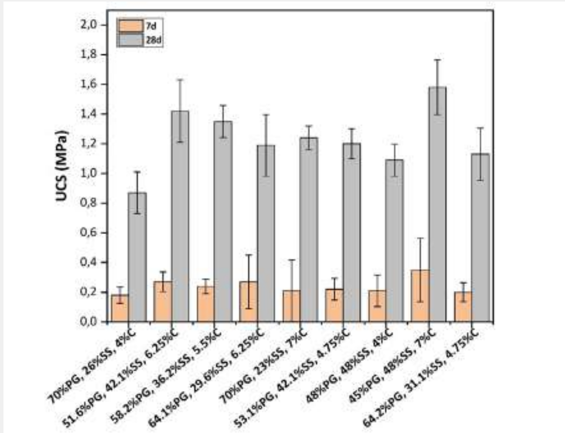


Fig. 59. *UCS -7d and UCS -28d of the 9 experimental points*

3.4.3 Tensile Strength and Elastic Modulus

The higher the cement dose, the greater the tensile strength and elastic modulus (Figure 60). The Elastic Modulus increases from 1100 MPa at 4% C to 1300 MPa at 6% C, whereas the Tensile Strength increases from 0.05 MPa at 4% C to 0.1 MPa at 7% C. These results are consistent with a 2007 study [30] showing that cement dose affects tensile strength. Tensile strengths of 0.26 MPa at 28 days with 7% cement and 0.34 MPa with 10% cement were reported in that investigation.

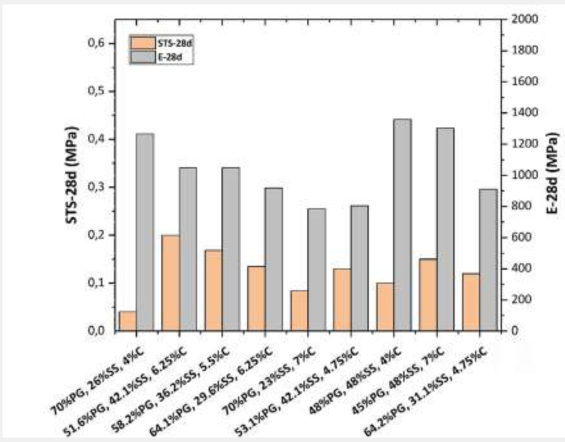


Fig. 60. *Ts-28d and E-28d of the 9 experimental points*

3.5 Mechanical Response Modelling

The DOE approach [31] was used to quantitatively model each of the targeted reactions throughout the whole study region based on all available experimental results. Table 7 displays the mathematical models that were produced for the PG-S-C mixture responses.

3.5.1 Model Validation

After modelling all the necessary responses, it was possible to graphically identify the domains where the material properties satisfy the criteria defined in Section 3.3.1 Figure 61 illustrates the mixture designs for PG-SS-C formulations that meet the requirements for subgrade or subbase layers. The figure highlights a substantial area that fulfils all the criteria outlined in Section 3.3.1, allowing these formulations to be further optimised by incorporating additional economic, environmental, or sanitary considerations, where appropriate.

An experimental verification of the model is conducted for a special point, chosen inside the experimental domain, by making and testing new samples at 28 d, 90 d and 360 d to determine the experimental values and compare them with model values, which were extrapolated from 28 d, following Eq. 4 and Eq. 5 [28]. It is clear that relative deviation (less than 8% [28]) remains acceptable (Table 8).

E_28days/E_360days = 0.65 Eq. 1

E_90days/E_360days = 0.7 Eq. 2

It is possible to combine mechanical criteria with additional economic or environmental criteria to identify mixtures of interest within the defined domains and it is clear that the cement content can be less than 7%.

3.6 Leaching Tests

It is essential to evaluate the possible environmental effects of each PG-based mixture on groundwater since PG contains traces of heavy metals that were passed down from its parent sedimentary rock. Three samples weighing 100 g each were used to measure two different mixtures leachates through the pollutant potential test in accordance with the standard (NF EN 12457-2).

According to the highest recorded concentrations of every heavy metal in [32], several trace elements moved into the water in amounts between 0.005 and 0.13 mg/l, below the national and international limit values.

For heavy metals, immobilisation rates due to binder treatment were calculated and vary from 89% to 99%.

3.6.1 Pavement Structure Optimisation

To identify the optimal pavement structure for enhanced road use of phosphogypsum, a parametric study was conducted on three types of pavement structures (Figure 63), considering three variables: soil bearing capacity (BC), traffic level (Tr), and the mechanical performance of phosphogypsum mixes (PG).

- For the supporting soil designated by BC, the two values of the Elastic modulus E and the Poisson's ratio μ refer to the library adopted by the ALIZE-LCPC software [33] (BC-: E = 50 MPa; μ = 0.35 and BC+: E = 120 MPa and μ = 0.35).
- As for the traffic level, designated by Tr, the values of the

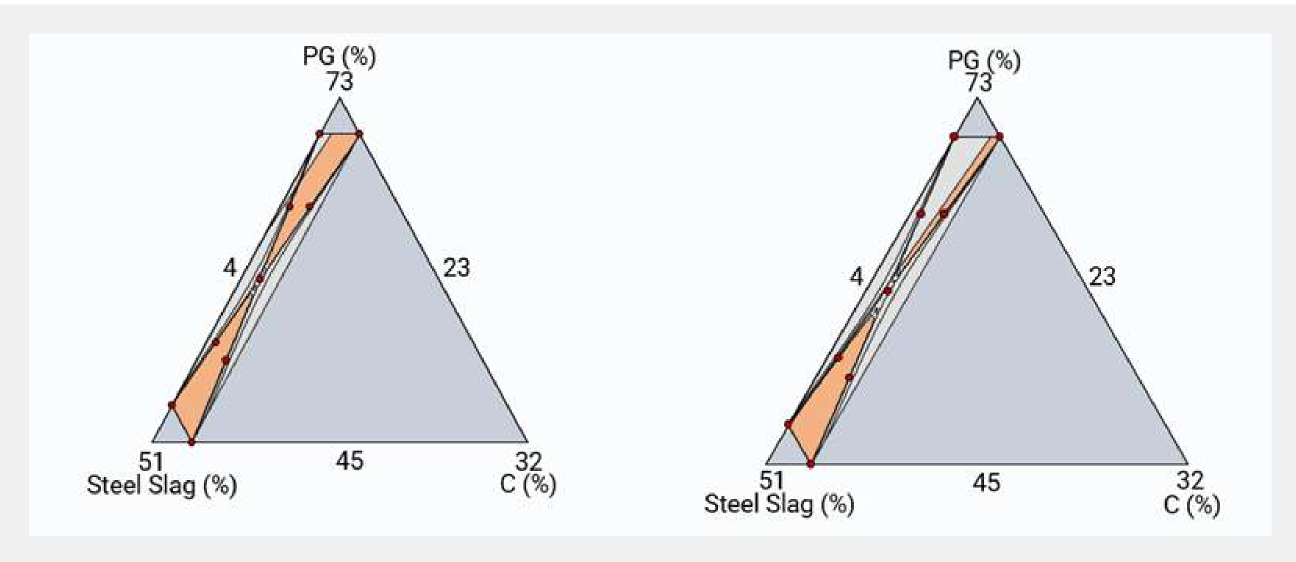


Fig. 61. *Graphical representation of PG-SS-C respecting (a) Subgrade and (b) Subbase layer criteria*

Table 7. *Examples of responses mathematical models for PG-SS-C mixture*

Mathematical model responses of the PG-SS-C mixture (dosages in %)	Adjusted R^2	p-value
IBI = 1.14*PG – 14*SS + 4,324*C + 0.08*PG*SS – 47,971*PG*C – 48,169*SS*C	97%	0.002
Gv = 0.056*PG + 0.0039*SS + 11.9*C – 0.13*PG*C – 0.12*SS*C	97%	0.017
Cs7d = 0.015*PG – 0.051*SS + 20.8*C + 0.0032*PG*SS – 0.23*PG*C – 0.23*SS*C + 0.00013*PG*SS*C	96%	< 0.001
E28d = 150*PG – 598*SS + 193,016*C + 33*PG*SS – 2,152*PG×C – 2,146*SS*C	92%	< 0.001

Table 8. *Values verification of the mathematical model E28d for a specific mixture PG-SS-C.*

	Model value (MPa)	Experimental value (MPa)	Relative deviation
E28d	1,184	1,125	5%
E90d	1,275*	1,383	7.8%
E360d	1,821**	1,975	7.8%

*** Extrapolated from E28d following Eq. 4.*
** Extrapolated from E360d following Eq. 5.*

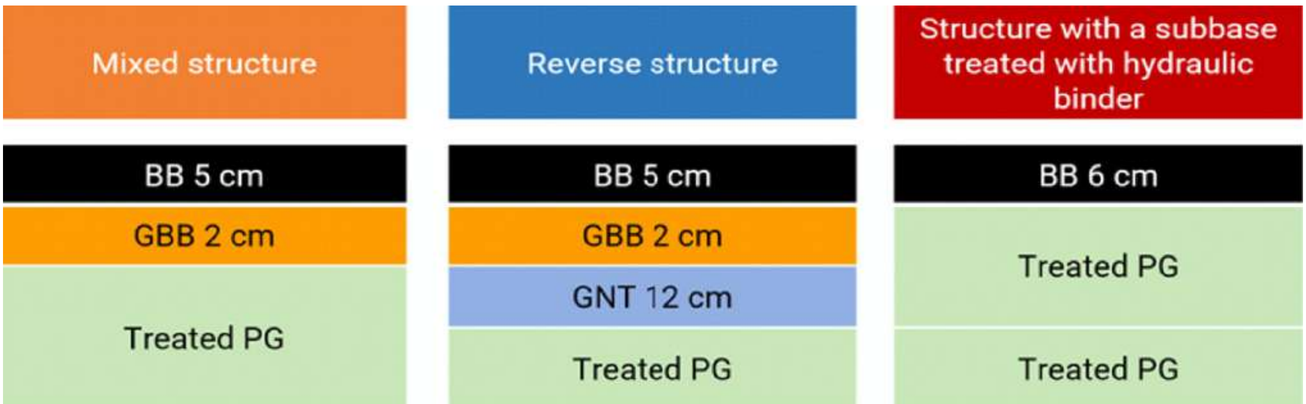


Fig. 62 *Types of pavement structures considered in parametric study*

annual average daily traffic TMJA, the class T, and the number of axles NPL of 13 tonnes of heavy goods vehicles travelling the roadway refer to the values from the average of the traffic class T2 and T3 of PNM 2019 [34] (Tr-: TMJA = 65; T3; NPL = 280.000 and Tr+: TMJA = 180; T2; NPL = 790.000).

- For treated phosphogypsum performances, the two values of Elastic modulus E and tensile strength Ts at 360 days the high and low level of PG treatment by varying cement dosage (PG-: E = 2,000 MPa; Ts = 0.2 MPa and PG+: E = 8,000 MPa; Ts = 0.35 MPa).

3.6.2 Factors Effect

For the three types of pavement structure soil bearing capacity has an important effect on pavement total thickness (Figure 63). This has a particular significance for the treated phosphogypsum layer, which decreases when going from a low soil bearing capacity (BC-) to a high level one (BC+). Mixed-structure pavements are generally thinner than other types of pavements, in all configurations. As hydraulic binder treated sub-base pavements have two layers of treated phosphogypsum, they consume more PG. In fact, this type of

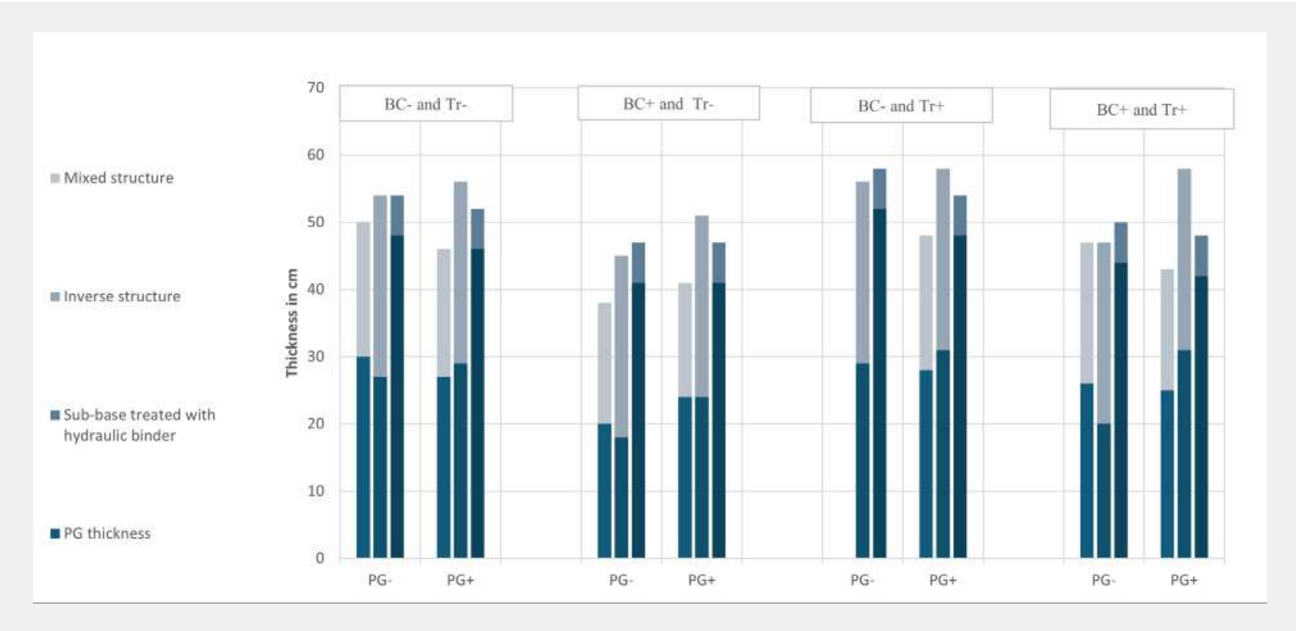


Fig. 63. *Effect of each factor on PG layer thickness and total pavement thickness.*

pavement can consume up to twice as much phosphogypsum as pavements with a mixed structure, and up to 2.3 times more phosphogypsum than pavements with an inverse structure.

For the three types of pavement, the total thickness of the pavement, as well as the thickness of the treated PG layer, increases with heavy traffic. In this particular case, an inverse pavement structure can be more effective (Figure 63). In general, the total thickness of the pavement and that of the treated phosphogypsum for mixed structures tend to reduce by raising the rigidity of the phosphogypsum mixture. The total thickness of an inverse pavement structure increases by increasing the rigidity of the PG based material. This is not the case for pavements with sub-base treated with hydraulic binder. For a softer phosphogypsum mix, an inverse pavement structure tends to be thinner than the one with hydraulic binder treated sub-base. For a more rigid phosphogypsum mix, the first layer is thicker than the second (Figure 63).

A gain of up to 15 cm in total thickness may be achieved by adopting a mixed structure compared with an inverse one. This difference is particularly noticeable when the phosphogypsum mixture is more rigid.

There is also a gain possible of up to 9 cm in total thickness by adopting a mixed-structure pavement compared to a pavement with a sub-base treated with hydraulic binder (Figure 63). Substitution of PG in roadbed construction in a mixed structure can conserve a total 53%-60% of conventional primary resources, notably gravel and sand; in an inverse structure the range is 40%-54%, and in a treated PG sub-base this figure may increase to 87%-89% of total roadbed thickness.

Ultimately, the parametric study supported a key finding that pavements with hydraulic binder-treated subbase are competitive when compared to pavements with reverse and mixed structures, regardless of traffic, soil carrying capacity and the relative performance of the treated PG layer(s).

4. From Lab to Market

4.1 Interaction Between Laboratory Tests and Models

The design of experiment (DOE) tool was used to mathematically model each targeted mechanical response, enabling a graphical determination of suitable mixtures.

Based on this analysis, two different mixes were prepared in the laboratory and tested to verify the accuracy of the models. Then these benchmark mixtures were subsequently used as references for the environmental compliance study. The results confirmed agreement between lab results and models, demonstrating that key leaching values for heavy metals in the mixes tested at the conventional temporal aging intervals stayed below international critical limits, ensuring compliance with environmental performance requirements.

4.2 Looking Ahead - Science and Commercial Balance

Building on these results, this case study, rather than merely documenting past achievements at both laboratory, bench and pilot scale, places the evaluation of the use of significant quantities of PG in road construction in the context of a circular economy (CE) driven business strategy for the road building and maintenance markets. This approach forecasts total PG production volumes across all present and potential future OCP manufacturing sites. In the case of the road market, the work undertaken and summarised in this case study provides a robust techno-economic foundation for:

- A robust evidence-based scientific approach for pilot project design and execution
- Development of standardised product mixtures including detailed characterisation of all component materials
- Resulting in
  - Optimisation of mixture formulation
  - Optimisation of pavement structure
- Techno-economic and environmental assessment
- Regulatory compliance.

Key elements of OCP's strategic business case for using PG and phosphate tailings as alternative road materials can now be integrated into its new circular economic (CE) business model. The appeal is clear: both high-volume residues, PG and tailings, are integral to OCP's supply chain, spanning from the "in-ground P resource" to the "to-ground fertiliser resource" value chain. Historically, both residues have represented significant negative externalities in the phosphate fertiliser supply chain, with high costs associated with handling and transporting them in large volumes.

The ability to blend materials from different supply sites offers multiple benefits, including reduced logistics and transportation costs, mitigation of capacity shortages, and carbon footprint reduction. Additionally, this approach maximises the value added per tonne-kilometre of construction materials transported, enhancing overall efficiency and sustainability.

5. Systematic Use of Mixed Secondary Raw Materials from the Phosphate Industry in Moroccan Road Construction and Maintenance – the Business Case

The business case for country-wide use of secondary raw materials from Morocco's rapidly expanding phosphate industry is grounded in a number of key assumptions:

1. The secondary raw materials proposed are of two main readily available sources — phosphate mine tailings and phosphogypsum residues.
2. Available supplies of these materials will continue to be restocked annually.
3. Mixes of these proposed materials have been exhaustively tested according to national and international standards.
4. From an engineering design and performance perspective they perform as well as or better than conventional materials.
5. Use of these secondary materials conserves primary raw materials for future generations on a tonne for tonne substitution basis from 40% to as much as 89% - typically 53%-60%.
6. As a rule, the carbon footprint of reusing or recycling secondary raw materials is lower — often significantly so — than mining, processing and using primary raw materials.
7. Potential combinations with other secondary raw materials such as steel slag and flyash, both widely used globally in roadbuilding are well documented and have also been tested.

5.1 Methodology

Based on these key assumptions, the policy anchor case for in this strategic PG utilisation project at scale is very robust.

To assess the valorisation potential for PG valorisation in Morocco's road construction, the economic analysis is based on three classical axes: Supply, Demand, and Cost. These factors are evaluated separately for each province [23] [28] and then correlated to provide an overall assessment for Morocco.

5.1.1 Demand Analysis: in t per year per province

- Sizing of road construction and maintenance: demand by province – in km.
- Technical evaluation of the parameters by work-type and road-type.
- Sizing of the demand for conventional & substitute materials.

5.1.2 Supply Analysis: in t per year per province

- Identification of production from quarries per:
  - Province
  - Production capacity per year

5.1.3 Cost Analysis: in t per year per province

- For conventional materials (natural gravel) and substitute materials (mixtures based on PG, Tailings, cement and sand):
  - Supply costs including raw material purchasing, intra-city transportation and implementation costs.

– Transportation costs (inter-city) according to product availability and proximity to the province.

5.1.4 Key Assumptions (OCP/JESA model)

- When demand exceeds supply for a given province, materials are transported from the nearest province with available products.
- The potential of PG is limited to road base and sub-base (other layers are excluded).
- In certain provinces, where the soil is of good quality, the sub-base is not necessary, only soil treatment is required.

5.1.5 Key Modelling Parameters

- Anticipated Road (Highway/Expressway/Rural/Provincial) construction and maintenance needs in coming years.
- Layer thickness and composition for conventional material.
- Layer thickness and composition for PG formulations.
- Supply of conventional materials - 38 million tonnes of GNA (untreated gravel, type A), GNF (untreated gravel, type F), and GBB, (bituminous concrete gravel) in approximately equal proportions.
- Costs in MAD/t

5.2 Estimation of Potential

There is significant potential in road construction, as highlighted by the national policy on infrastructure development, with the Moroccan road market expected to be largely dominated by maintenance activities over the next decade (2018-2028). The national road program led by the Ministère du Transport et de la Logistique (METLE)[49] (Ministry of Transport and Logistics) focuses on three types of roads: Highways, Express and rural roads. The urban roads are mainly in the hands of local authorities who provide less visibility as to their future spending programmes.

5.2.1 Construction Programmes

Highways:

- Construction of 545 km of highway network 2018-2028 (vs. 943 km 2007-2017) – resulting in 2,315 km total route in 2028.

Express Ways:

- Construction of 793 km of express ways from 2018-2028 (plus 588 km of national road expansion) vs. 536 km 2007 – 2017.
- The METLE program forecasts the construction of 793 km by 2028 and an additional 115 km by 2035.

Rural Roads:

- Construction of 1,427 km/year of resurfaced rural roads from 2018-2028 (vs. 882 km/year between 2007-2017).
- Completion of 14,267 km by 2026 (vs. 14,267 km planned by 2024) and extension of the rural roads program by 2035.

5.2.2 Maintenance Programmes

Highways:

- Maintenance of 2,000 km between 2018-2028 (vs. 611 km between 2007-2017), impacted by highway construction over the period 2005-2015.
- Assumption that network maintenance is done every 10 years, spread over two years.

Classified Network[50]:

- Linear progression maintained at a rate of 3,722 km in 2028 per year (vs. 1,723 in 2018, and
- 2,276 km in 2013 in a period of low expressway construction).

Municipal Network:

- Constant maintenance rate of 2.8% of the municipal road network.

The METLE has accelerated the deployment of its plan due to the staging of the 2030 FIFA world cup in Morocco, which was already covering almost all the prerequisites of the FIFA bid book. Some minor projects have since been added such as the connection to the new Benslimane stadium.

5.3 Sources and Demand Factors – Primary and Secondary Raw Materials

The maps below provide summaries a) of supply volumes for available primary raw materials from quarries (Figure 64) and b) demand volumes / absorption capacities for secondary raw materials (PG) by province (Figure 65).

5.3.1 Supply Centres

- Most of the production sites for substitute materials are located in the northern and central axes (Jorf Lasfar, Safi, Khouribga, Youssoufia and Benguerir).

49 Ministère du Transport et de la Logistique https://www.transport.gov.ma/Pages/accueil.aspx

50 Morocco has a classified road network (managed and operated by the State through the Ministry of Equipment, Transport and Logistics) of 59,000 km, including around 44,000 km of resurfaced roads.

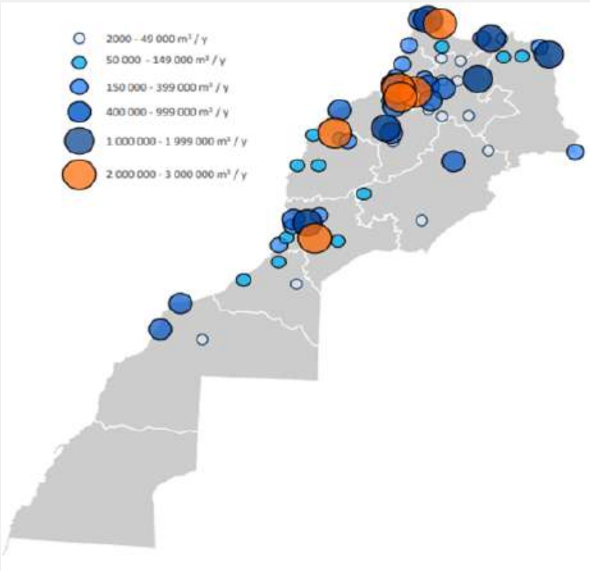


Fig. 64. *Quarries for building materials*

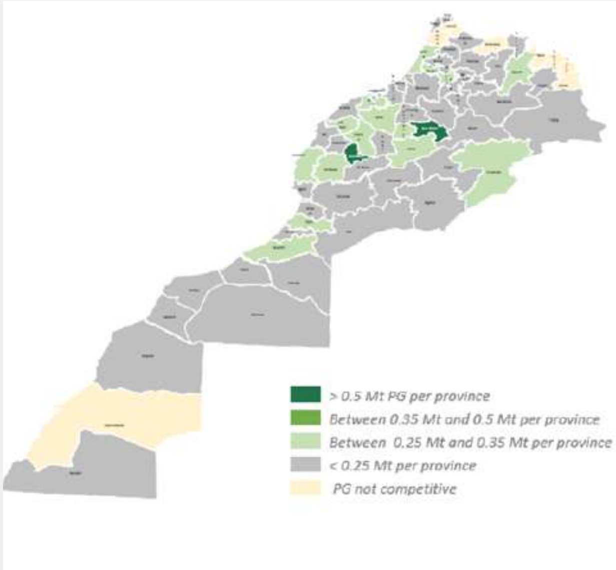


Fig. 65. *Absorption capacity for secondary raw materials by province*

- The southern axis, including Laâyoune and Boucraâ, is expected to produce substitute materials able to meet the needs of these regions.

5.3.2 Demand

- Most of the roads to be constructed and maintained are located on the northern and central axes
  - Provinces that are self-sufficient in conventional materials (internal production exceeds demand) are not interested in using PG.
  - The supply of conventional materials (quarry location) thus has a strong impact on the regions of interest for PG.
  - Optimal composition of road layers is essential to gain competitiveness and use the maximum amount of PG.

CHAPTER SIX

UTILISING PHOSPHOGYPSUM FOR OPEN PIT RESTORATION, CHINA

Author: Nadav Turner, ICL China

6

1. Context

While ICL manages its phosphogypsum (PG) resources in China under the wider national Comprehensive Utilisation policy (now applied to all PG resources as part of the strategic objective of fully balancing PG production and use on an annual basis), from an ICL perspective, the primary driver for the particular use made of these materials is the application type more than the use policy. In this case, it concerns open pit mine restoration. And at a time when there is growing pressure worldwide to move away from open-pit mining in pursuit of the sustainability environmental goal of an "invisible mine", finding ways to implement this objective is of global sectoral importance to the mining industry, not just in China.

If conducted skilfully, the PG resources used in this procedure can effectively be future-proofed for future generations to access, a goal associated with the circular economic principle of "at a minimum, conserve the value of all resources and where possible enhance them". In that context, restoring old mine pits offers significant environmental and social benefits.

2. Implementation Concept

The concept of these projects revolves around the sustainable and innovative use of phosphogypsum for ecological restoration. The projects adhere to the General Industrial Solid Waste Storage and Landfill Pollution Control Standards (GB18599-2020), ensuring that the restoration process meets stringent environmental regulations.[51]

All projects follow the same basic process to modify the gypsum to the required conditions. This involves:

2.1 Adjusting pH Value

Reagents are added to maintain the pH value between 6-9, ensuring the material is safe for the environment.

2.2 Passivation

Soluble phosphorus and fluorine are converted into insoluble fluorine phosphorus double salts. This reduces their mobility and environmental impact, with main indicators being Phosphorus (P) at 0.5 mg/L and Fluorine (F) at 10 mg/L.

2.3 Condensation and Solidification

The modified phosphogypsum forms stable particles with wrapping performance, enhancing its suitability for ecological restoration. The phosphogypsum is placed in layers to ensure stability and prevent leaching of harmful elements. This multi-layered approach ensures that the phosphogypsum is fully encapsulated, preventing any potential contamination of the surrounding environment.

2.4 Layering Process

The layering process includes (bottom to top) (see Figure 66) - Clay 30 cm: This base layer provides a stable foundation and acts as a barrier to prevent the upward movement of contaminants.

Geotextile (300g/m²): A permeable fabric that separates different layers, prevents mixing of materials, and providing filtration.

Geomembrane 1.5 mm: An impermeable membrane that acts as a barrier to prevent the leaching of contaminants into the surrounding environment.

Geotextile (300g/m²): Another layer of geotextile to protect the geomembrane from punctures and provide additional filtration.

Filter: This layer ensures that any water passing through is filtered, preventing the movement of fine particles.

Modified phosphogypsum: The main restoration material, treated to stabilise and encapsulate harmful elements.

Top layers: Additional geotextile, geomembrane, clay, and soil to support vegetation growth.

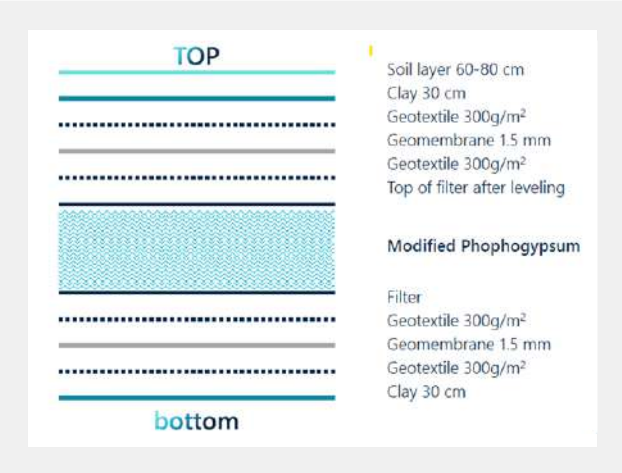


Fig. 66. *The layering process*

3. Environmental and Social Benefits

Rehabilitation and restoration of abandoned mine sites helps to reestablish natural habitats, promote biodiversity and stabilise ecosystems that were previously disrupted by mining

51 China Standard GB18599-2020 is available for sale in English translation on a range of websites.

activities. This same process can also improve water quality by reducing acid mine drainage and controlling soil erosion.

Socially, rehabilitated mines can be transformed through skillful master planning and land use into recreational areas such as parks or sports facilities, or agricultural land to offset agricultural land lost to urban development, providing new commercial, industrial or community spaces each with the wider benefit of bringing new economic opportunities and revenue generation to unproductive land resources.

Additionally, the restoration of old mines can enhance the aesthetic value of the landscape, fostering a sense of pride and well-being among local residents. Overall, the rehabilitation of old mines of all types contributes to sustainable development and the long-term health of both the environment and the communities that depend on it.

4. Application Cases

The following projects in Yunnan Province, China, are pioneering examples of using phosphogypsum for open pit restoration. These innovative and groundbreaking projects demonstrate the potential of phosphogypsum in ecological restoration and set a benchmark for future initiatives.

4.1 Yunlong Project

Summary (Figure 67 an 68)

- Restoration Area: 1,026,627 square meters
- PG Utilisation: 9.8 million tonnes
- Investment: 370 million RMB
- Status: Completed
- Gypsum Condition and Treatment: Dry form, transported via conveyors, modified through pH adjustment, passivation, and solidification

Fig. 67. *Yunlong Restoration Project*

Fig. 68. *Yunlong Restoration Project*

4.2 Shuangshao Project

Summary (Figure 69)

- Location: Yunnan Province, China
- Restoration Area: 480,503 square meters
- PG Utilisation: 13.5 million tonnes
- Investment: 665 million RMB
- Completion: End of 2025
- Gypsum Condition and Treatment: Dry form, transported by trucks, modified through pH adjustment, passivation and solidification.

Fig. 69. *Shuangshao Restoration Project*

Fig. 70. *Taoshu Project (Before)*

Fig. 71. *Taoshu Project (After)*

4.3 Taoshu Project

Summary (Figures 70 and 71)

- Location: Yunnan Province, China
- Restoration Area: 784,179 square meters
- PG Utilisation: 19.25 million tonnes
- Investment: 1.1 billion RMB
- Completion: End of 2025
- Gypsum Condition and Treatment: Slurry form, pumped via pipes, filtered, washed, and modified through pH adjustment, passivation, and solidification.

5. Conclusion

The use of phosphogypsum in open pit restoration projects, offers significant environmental and social benefits. By enhancing soil fertility, reducing erosion, and mitigating pollution, these projects contribute to the sustainability of the local ecosystem. Additionally, they provide social benefits through community engagement, improved quality of life, and educational opportunities. The successful implementation of the Yunlong, Shuangshao, and Taoshu projects demonstrates the pioneering potential of phosphogypsum as a valuable resource for ecological restoration.


7

CHAPTER SEVEN

GYPSUM COMMERCIALISATION IN PETROKIMIA GRESIK, INDONESIA

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1.Background

Petrokimia Gresik[52] is subsidiary of the holdings company Pupuk Indonesia[53] which is wholly owned by the Government of Indonesia and managed through the Ministry of State-Owned Enterprises. The company takes its name from the administrative Regency of Gresik (see Figure 72). Petrokimia Gresik and Pupuk Indonesia share a common commitment to national food security, and through its mission as a fertiliser manufacturing company has delivered on that mission by supporting the national food security program all over Indonesia for the past 50 years.

Petrokimia Gresik is the most diversified fertiliser producer in Indonesia offering a range of fertilisers, non-fertilisers and specialty chemicals for agro-industrial solutions in the country. The company is committed to continuing its long history of growth, working together with community stakeholders across the national agriculture sector to further agricultural and crop production capabilities and the priority objective of maintaining a secure agricultural and food value chain.

Fig. 72. *Location of Gresik Regency, Indonesia*

52 See https://petrokimia--gresik-com.translate.goog/?hl=en&_x_tr_sl=id&_x_tr_tl=en&_x_tr_hl=en&_x_tr_pto=sc

53 See https://www.pupuk-indonesia.com/

2. Facilities and Phosphoric Acid Plant

Petrokimia Gresik facilities occupy 550 hectares housing 31 fertiliser and non-fertiliser factories, with a total production capacity of 8.9 million tonnes per year. To support its business processes, Petrokimia Gresik also has its own supporting infrastructure including a water purification unit, jetty, loading & unloading facilities, electricity generation unit and a wastewater processing unit.

The company's original "wet process" phosphoric acid (PA) plant (Figure 73), in which phosphate rock concentrate is acidulated with sulphuric acid to produce the co-products PA and phosphogypsum (PG), was commissioned in 1985. It uses the Hemi-dihydrate (HDH) process (Figure 73) and has operated continuously since then.

Fig. 73. *Hemi-hydrate Phosphoric Acid Production Plant (Image Courtesy PK Gresik)*

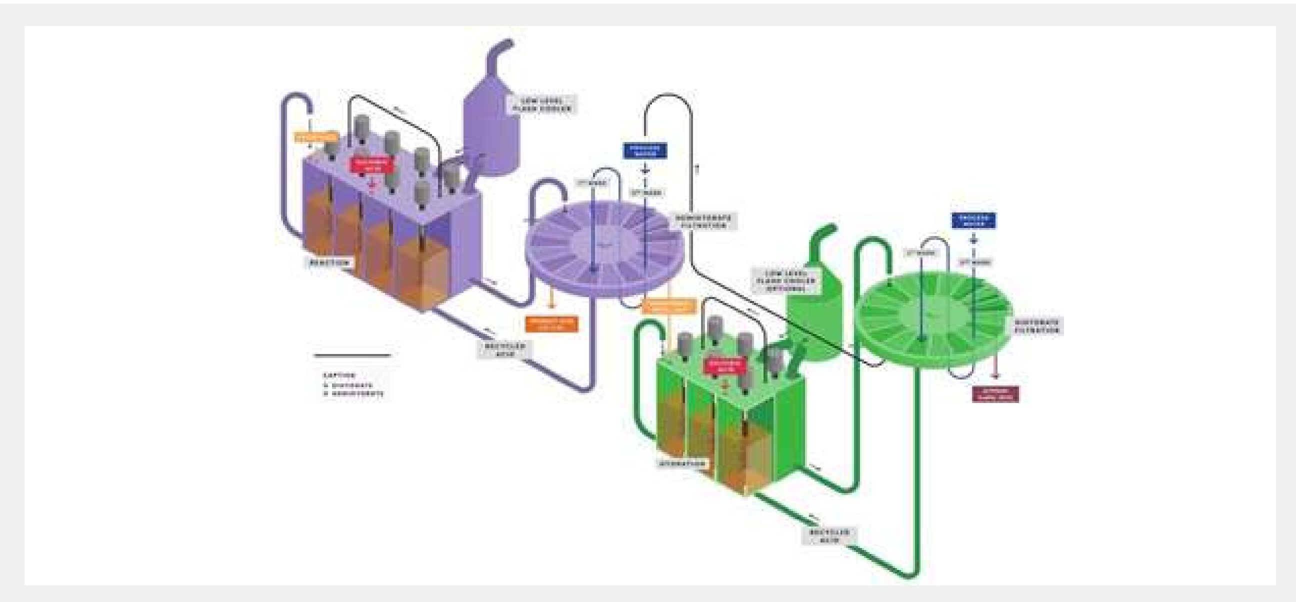


Fig. 74. *The Hemi Di-Hydrate flow sheet, (Image Courtesy Prayon)*[54]

54 For the Hemi Di-Hydrate production process see https://www.prayon.com/en/processes/hemi-dihydrate

A second phosphoric acid facility, the refinery, see Figure 75, has been operational since 2015. The PA production unit's nameplate production capacity is up to 400,000 tonnes per year (100% P_2O_5).

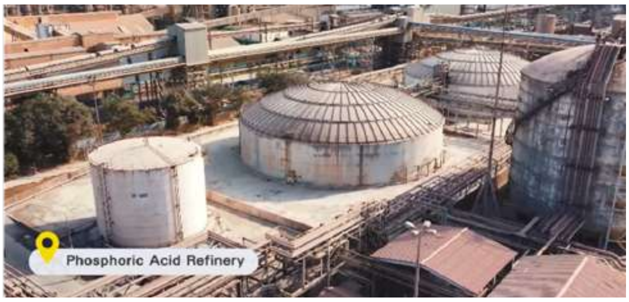


Fig. 75. *Phosphoric Acid Refinery, PK Gresik (Image Courtesy PK Gresik)*

As shown in Figure 76, the co-product PG can be treated in three different ways: 1. to make purified ammonium sulphate (AS) Fertiliser, a profitable premium product, which also generates lime (calcium carbonate) as a co-product for use in the cement industry; 2. to make neutralised crude gypsum; and 3. to make purified PG in effect a synthetic equivalent to natural gypsum.

The Petrokimia Gresik purified gypsum facility is shown in Figures 77, 78 and 79.

The PG Purification process technology is shown in Figures 79 and 80.

Crude gypsum produced from the Phosphoric Acid Plant (Figure 73) is sent to the Purified Gypsum Plant (Figure 77) via a conveyor and then fed to the slurry mixing tank (Figure 78). In the mixing tank, crude gypsum is washed using treated water. Treated water is water from wastewater processing in Effluent Treatment. In the slurry mixing tank, crude gypsum is mixed and stirred with Treated Water into a slurry to a concentration of 35%. Then, the slurry is pumped to the belt vacuum filter (Figure 79), to separate and reduce the free moisture it still contains to below 18%.

The quality of the gypsum cake and its filtrate is determined by the treatment of the PG cake. In the Filter, the PG cake is sprayed with steam to purify it. The PG is maintained at a total P_2O_5 content including soluble P_2O_5 below 0.5% according to SNI 715-2016[55] for Type 2 Gypsum products. The filtrate from the filtering process is then pumped to the Effluent Treatment Unit, then the processed water is reused as a medium for washing crude gypsum.

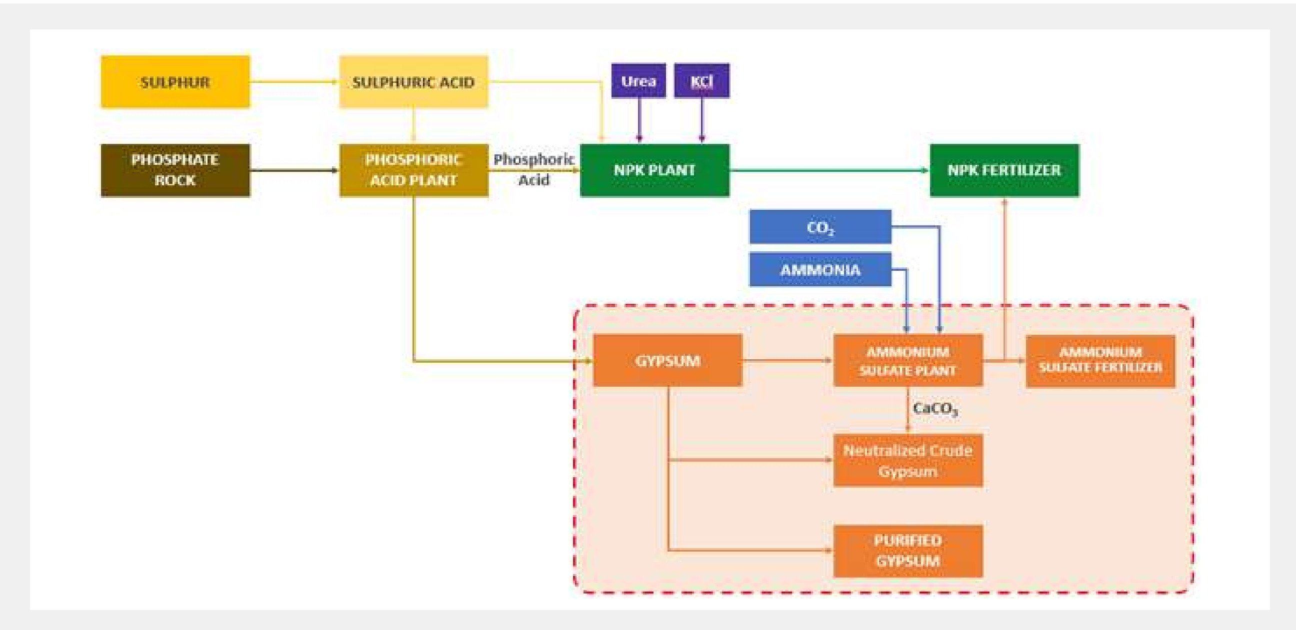


Fig. 76. *Product Linkage of Gypsum*

55 See Indonesian National Standard NSI 715-2016 http://sispk.bsn.go.id/SNI/DetailSNI/10922 and https://bsn.go.id/uploads/download/pbsn_4-2023_lampiran_xxx_skema_pupuk_gipsum.pdf

Fig. 77. *Petrokimia Gresik Purified Gypsum I Plant (Image Courtesy PK Gresik)*

Fig. 78. *Slurry mixing tank (Image Courtesy PK Gresik)*

Fig. 79. *Gypsum Purification Process – belt vacuum filter (Image Courtesy PK Gresik)*

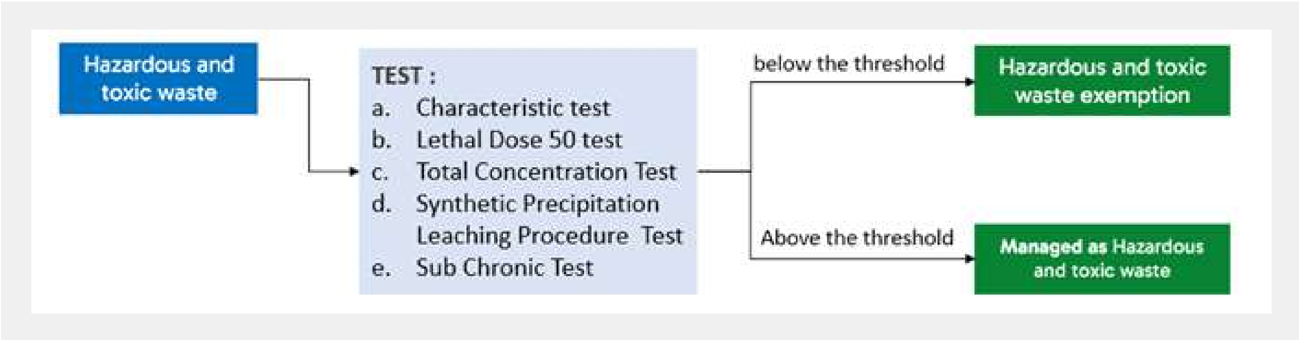


Fig. 80. *Hazardous and toxic waste exemption procedure*

2.1 Business Solutions Offering – Resource as a Service

In recent years the company has progressively extended its business offering with a range of innovative solutions that fit well within a circular economy "Resource as a Service" (RaaS) framework, such as soil cultivator, probiotic and decomposer product/service combinations to strengthen its positioning as an agroindustry solutions provider.

2.2 Transitioning to the Circular Economy

An implementation principle of the circular economy that Petrokimia Gresik closely follows is the prioritisation of innovation in every business process, in order to maintain environmental sustainability. Against that background, and fully consistent with its long-standing commitment to product and service diversification, Petrokimia Gresik now strives to utilise gypsum as an innovative secondary raw material to further extend the company's specialty chemical offering in a series of beneficial PG-based products. These include ammonium sulphate fertiliser, purified gypsum, and neutralised crude gypsum (NCG). The success of gypsum commercialisation carried out by Petrokimia Gresik is the result of collaboration and partnership between the company and academia, with significant encouragement and support from the Government as part of its own circular economic transition efforts. The gypsum product linkage in detail is depicted in Figure 76.

3. The Regulatory Context – from Waste to Inventory

On October 17, 2014, the Ministry of Environment and Forestry issued Government Regulation Number 101 of 2014, concerning management of hazardous and toxic waste which states that gypsum waste is categorised as hazardous and toxic. Such waste may come from various sources, including:

1. Gypsum from the desulphurisation process at steam power plant
2. Gypsum from the process of making phosphate fertiliser with a wet process using sulphuric acid in the fertiliser industry.
3. The process of decalcification of molasses with sulphuric acid in the Mono Sodium Glutamate (MSG) industry.

An exemption from the onerous conditions for handling and use of these materials can be granted if the materials initially classified as hazardous and toxic waste are tested in a suitably independent and experienced laboratory, and if the characterisation results are evaluated by a team of experts and recategorised as non-hazardous and non-toxic waste. This procedure is called the Hazardous and Toxic Waste Exemption. But even when the exemption has been granted the company still has responsibility for the resultant materials produced. The Hazardous and Toxic Waste Exemption procedure is depicted in the flow sheet, Figure 80.

Petrokimia Gresik's application for the Hazardous and Toxic Waste Exemption of PG began in 2016 with the drafting and approval of Terms of Reference (TOR) for the exemption application and the completed application dossier was submitted in January 2017 to the Ministry of Environment and Forestry which has responsibility for evaluating the case for exemption under the Hazardous and Toxic Waste Exemption of Gypsum reference framework. The application was approved some two years later in December 2019. After the approval of the Hazardous and Toxic Waste Exemption of Gypsum reference framework, a characterisation test was carried out based on the Terms of Reference. The test results are as follows:

3.1 Characterisation Testing

1. **Explosive:** The explosive test results showed negative results, meaning that the gypsum sample tested did not respond after the sample was tested at a temperature of 25 ± 3°C and a pressure of 760 mmHg. The test results re-

mained[56] negative after a validity test was carried out by comparing the test results with the reference materials in this method. Test validation is carried out to adjust the test stimulus relative to a series of substances, all of which have the capacity to release energy.

2. **Ignitable**: The results of the ignitable test showed negative results, meaning that the gypsum sample tested did not ignite at temperatures <140°F. Based on the method used, samples that have flammable properties will produce smoke, heat, and/or flames when heated at temperatures <140°F.
3. **Reactive**: Reactive Test was conducted on sulphide and cyanide parameters. The test results showed that sulphide and cyanide parameters were not detected in gypsum samples. PT Petrokimia Gresik's gypsum waste under normal operational conditions is stable and does not cause material changes. The unreactivity of gypsum samples is directly proportional to the pH value which is still within the specified range.
4. **Corrosive**: Corrosive test of gypsum waste by measuring the pH value showed a result of 3.26. Referring to our Indonesia national regulation, waste is categorised as corrosive if it has a pH of equal to or less than 2 for acidic waste and equal to or greater than 12.5 for alkaline waste. So Petrokimia Gresik gypsum is not categorised as corrosive waste.

3.2 Toxicity Characteristic Leaching Procedure

The Toxicity Characteristic Leaching Procedure (TCLP) concentration was obtained after the extracted sample was measured using ICP OES for inorganic parameters, GC MS for organic parameters, and spectrophotometer and titrimeter for anion parameters. The test results obtained from the PT Petrokimia Gresik gypsum sample had a concentration lower than TCLP A and TCLP B . These results indicate that the potential for leaching metal, inorganic, and organic content in PT Petrokimia Gresik gypsum does not exceed the required quality standards or critical limit values for elements of interest or concern.

3.2.1 Lethal Dose (LD) 50 Test Capitalisation

The LD50 value of Gypsum is >5000 mg/kg BW so it can be concluded that the toxicological characteristics of Gypsum are 99.9% Non-Toxic.

3.2.2 Total Concentration Test

Based on the test results for the total metal concentration of Sb, and Cd in PT Petrokimia Gresik's gypsum, the value is less than the TK A and TK B values found in Appendix II of the Ministry of Environment and Forestry Regulation No.10 of 2020.

3.2.3 Synthetic Precipitation Leaching Procedure (SPLP) Test

Based on the results of the SPLP test on PT Petrokimia Gresik gypsum waste, the results were obtained: Sb <0.001 and Cd = 0.0471. The SPLP test was conducted to determine the potential for Sb and Cd metal contamination.

3.2.4 Sub Chronic Test

Based on qualitative and quantitative data obtained in the oral sub-chronic toxicity test referring to OECD Guideline 408[57] [35], after 90 days of treatment using gypsum preparations from PT Petrokimia Gresik, it is known that:

1. Repeated administration for 90 days of oral gypsum preparations did not show any effect on the central nervous system and somatomotor, autonomic nervous, respiratory, cardiovascular, gastrointestinal tract, genitourinary, mucous membranes and eyes in male and female mice.
2. Repeated administration for 90 days of oral gypsum preparations did not show any effect on the average daily weight gain of male and female mice.
3. Hematology examination of repeated administration for 90 days of oral gypsum preparations also did not show any significant changes in the hematological parameters of the test animals in both male and female mice.
4. Gross pathology examination, oral gypsum preparation treatment for 90 days in male and female mice did not find any macroscopic changes in vital organs such as the brain, lungs, liver, stomach, spleen, right kidney, left kidney, and intestines.

After the tests were carried out, a presentation was made of the results of all the tests that had been carried out by the independent academic expert team to convince the team of experts from the Ministry of Environment and Forestry that an exemption could be granted. From the results of all the tests, it was stated that gypsum waste was not dangerous and could be removed from the list of hazardous and toxic wastes. In consequence, the team of experts recommended the issuance of a hazardous and toxic waste exemption permit.

Finally, on May 2021, the Ministry of Environment and Forestry of the Republic of Indonesia approved and issued the PG waste exemption as non-hazardous and toxic waste, based on the results of the evaluation of the fertiliser and chemical industry activities at PT Petrokimia Gresik.

56 The changes from C to F in Indonesian regulatory practice regarding temperature metrics is in the regulations, not the random choice of the operating company or service laboratory

57 See OECD Test No. 408: Repeated Dose 90-Day Oral Toxicity Study in Rodents https://www.oecd.org/en/publications/2018/06/test-no-408-repeated-dose-90-day-oral-toxicity-study-in-rodents_g1gh2931.html

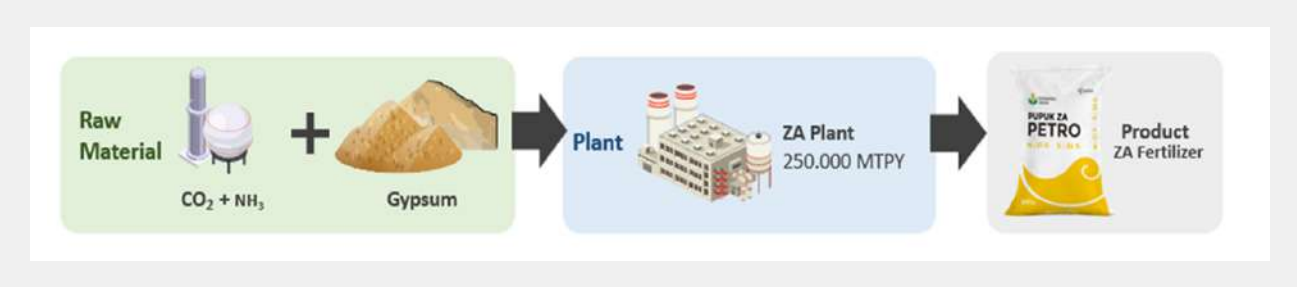


Fig. 81. *Ammonium Sulphate (AS) Fertilizer Production - Block Diagram*

Fig. 82. *Petrokimia Gresik ZA II Plant (Image Courtesy PK Gresik)*

Fig. 83. *P AS II Production Equipment – Reactor*

Fig. 84. *AS II Production Equipment – Dryer-Cooler*

4. Valorisation and Use of Phosphogypsum

4.1 Ammonium Sulphate Fertiliser

Ammonium sulphate (AS) (Dutch "zwavelzure ammonia" or ZA fertiliser $(NH_4)_2SO_4$) is a type of fertiliser increasingly being produced using PG. As in the form of white crystal granules is produced from the reaction between crude gypsum and ammonium carbonate following the ICI (CHEMICO) reaction process using an SSIC evaporator. The AS production process is depicted in the block diagram Figure 81.

NH_3 gas and CO_2 gas are first reacted with water to become ammonium carbonate $(NH_4)_2CO_3$. Then the co-products AS and calcium carbonate are derived from the slurry.

Crude Gypsum originating from the by-product of the phosphoric acid plant is sent to the AS Plant (Figure 82) by conveyor, fed into an agitating reactor and mixed with ammonium carbonate solution. In the reactor, ammonium carbonate reacts with gypsum, becoming a slurry/magma solution of ammonium sulphate and lime (calcium carbonate). The slurry solution is then filtered in a rotary drum vacuum filter.

The filtered cake in the form of lime is sent to the lime warehouse, and the filtrate in the form of ammonium sulphate solution, which still contains a little lime solids, is separated in the clarifier to precipitate the remaining lime solids that are not filtered.

The clean ammonium sulphate solution is then reacted with sulphuric acid in the centrifuge (Figure 83). The resultant crystals that are already slightly dry are then fully dried and cooled acid to react the unreacted ammonia. The ammonium sulphate solution is then fed to the concentrate until ammonium sulphate crystals are formed. The wet AS crystals are then separated in the rotary dryer-cooler (Figure 84).

4.2 Ammonium Sulphate Production Details and Summary Specification

Fig. 85. *Petrokimia Gresik ZA Fertilizer Specification*

High-level details of the annual production volume of the ammonium sulphate and its primary constituents and ratios are shown in Figure 85 next to the packaging.

The advantages of using AS fertiliser produced from processing PG include:

a. Increases sugar crop production
b. Helps plants grow greener
c. Increases protein content in the harvest
d. Accelerates and improves plant growth

The quantum of gypsum that can be utilised for AS fertiliser is an average of 200,000 tonnes per year contributing to the company's profit by USD 23 million net per year. More details about the AS fertiliser product are shown in Figure 86.

4.3 Purified Chemical Gypsum as Product

Chemical process gypsum is a side product of various industries and the main source of gypsum to control the hardening time of Portland cement and blast furnace slag cement (cement for fire bricks). Phosphogypsum is a by-product of the phosphoric acid factory. Its global production volume is the highest among the chemical industry gypsums. It is known that the impurities generally present in phosphogypsum greatly affect the setting times of Portland cement.

The impurities that affect the hydration of Portland cement are:

a. P_2O_5 in the gypsum crystal lattice
b. P_2O_5 soluble in water
c. Water-soluble that sticks to the surface of gypsum crystals.

These issues are resolved from a product marketability perspective by the purification process notably for use as a retardant in the cement industry (Figure 87).

The advantage of gypsum purification products is to regulate the hardening process in cement so that this product is very suitable for the cement industry. The quantum of gypsum utilisation that is used as gypsum purification products averages 1,100,000 tonnes per year, with profits obtained from the sale of the product amounting to USD 80 million per year. The product form and its specifications can be seen in Figure 86.

Fig. 86. *Petrokimia Gresik Purified Gypsum – Image and Specification*

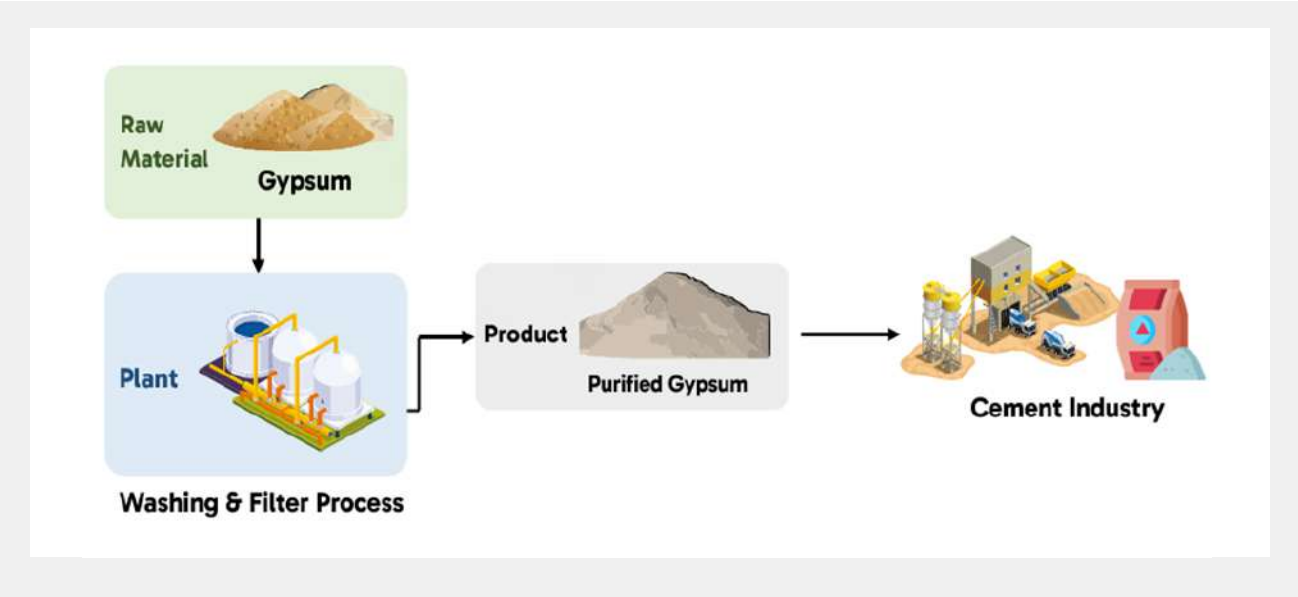


Fig. 87. *PG purification for use in cement*

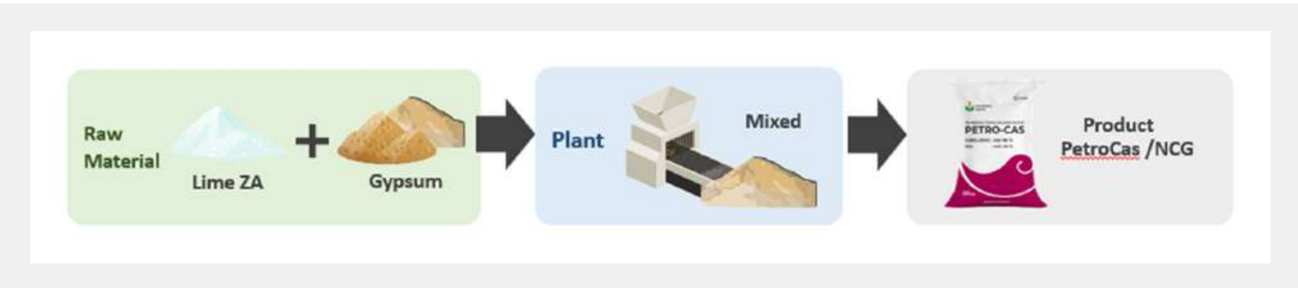


Fig. 88. *Petro-CAS/NCG fertiliser*

Fig. 89. *Neutralised Crude Gypsum – primary ingredient of Petro-CAS (Image Courtesy PK Gresik)*

4.4 Neutralised Crude Gypsum (NCG) / Petro-Cas

The process of transforming gypsum into petro-calcium sulphate fertiliser (Petro-CAS), a byproduct of AS-II fertiliser, is carried out by mixing 98% neutralised crude gypsum (NCG) (Figure 88) with 2% lime as shown in the block diagram (Figure 88).

The product is shipped in either in 20 kg or 50 kg bags (Figure 89).

Petro-CAS 90% $CaSO_4.2H_2O$ (21% Calcium, 18% Sulfur and pH 6-7). The main advantage of Petro-CAS is that it can provide Ca and S nutrients for plants and improve plant roots. The Petro-CAS products as marketed meet the national standard SNI 715-2016 for the Gypsum Type 3 product category.

The benefits of NCG/PetroCas products can be utilised as soil conditioner on peat soil and as raw material in the plaster board industry. It also enhances the physico-chemical properties of the soil.

The quantum of gypsum market uptake for NCG/PetroCas product averages 300,000 tonnes per year with the profit obtained from the sale of these products being USD 21 million per year. More details about Petro-CAS product analysis can be found in Figure 90.

Fig. 90. *Petro-CAS Product Packaging and Specification*

4.5 Roadbed

In addition to applications as a fertiliser or in cement, PG can also be used as a subbase or basic road material (Figure 91). Research has been conducted by Petrokimia Gresik in collaboration with the Sepuluh November Institute of Technology Surabaya, which shows that the CBR (California Bearing Ratio) value of PT Petrokimia Gresik gypsum is higher than the limestone in Gresik. It can be concluded that technically Petrokimia Gresik gypsum has better specifications than limestone for use in road bed.

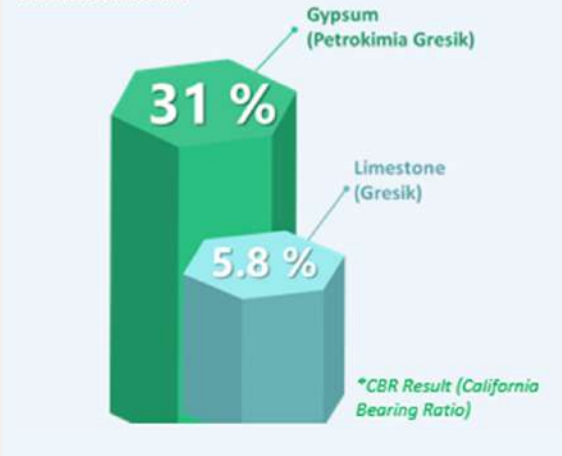


Fig. 91. *Gypsum Utilisation for other use as base material and/or road base. Findings of study by Sepuluh November Institute of Technology, Surabaya on relative California Bearing Ratio values of PK Gresik industry gypsum CBR 31% vs natural limestone 5.8%.*

C H A P T E R   E I G H T

BRAZILIAN PHOSPHOGYPSUM MARKET [MERCADO BRASILEIRO DE FOSFOGESSO]

Authors: Henrique Oliveira, Walter Martins, Mosaic Fertilizantes, Brazil


8

1. Introduction

In the 2020 IFA publication, "Phosphogypsum Leadership In novation Partnership", Mosaic detailed its approach to and experience with PG applications in agriculture, including a case study on its use in soybean production, one of the main crops of the Cerrado for both domestic and export use.

This case study provides a brief contextual overview of current PG use in agriculture – by volume significantly still the dominant use – but highlights more the developing business case for PG reuse in the building industry, specifically for cement. But by way of introduction to the way Mosaic has experienced the growth of its profitable PG based business, it traces some of the key steps the company has taken on the way to the sustainably profitable PG business it has created on the PG journey "From Waste to Inventory" (Figure 92).

Fig. 92. *From Waste to Inventory – Corinne Ricard and Alzbeta Klein Define the PG3 Report's Title - PG Storage Facility, Uberaba (Image courtesy Mosaic Fertilizantes)*

During the visit of Alzbeta Klein, Chief Executive Officer of IFA, to the PG storage facility in Uberaba in late 2023, Corrine Ricard, Senior Vice President of Mosaic, emphasised a significant achievement. She remarked: "Mosaic has successfully converted PG, a byproduct of phosphate fertiliser production, into a valuable soil amendment for Brazilian agriculture and premium feedstock for the cement industry. By addressing logistical, economic, and regulatory aspects in a holistic manner, the company has created a sustainable and economically viable market for phosphogypsum, which benefits both the environment and Mosaic's financial performance."

2. Acidic Soils

Phosphoric acid production in Brazil has generated large quantities of PG as a byproduct. The main regional phosphate production centre is in Uberaba, Minas Gerais where, until the 1970s, PG was mainly stored in stacks. Over time, the agricultural use of PG began to grow, especially due to the need to amend acidic and sulphur-deficient soils, common in the Brazilian Cerrado[58], the largest agri-business growing surface in the world.

Brazilian soils are predominantly acidic, presenting high levels of free aluminium as Al^{3+} in solution across their profile. The Cerrado is a vast tropical savannah eco-system covering 21% of Brazil's surface area. As such, it is second only to the Amazon in terms of its size and significance among Brazil's many ecosystems. The use of PG for complexing Al in deeper layers and for transporting Ca through the soil profile to where liming is not effective (below 20 cm), has shown to be the best management alternative for ploughing into the soil amending lime in most Brazilian soils, especially in the Cerrado region.

In general, most Brazilian soils are likewise S-deficient because of having little or no organic matter content. Consequently, these soils have no capacity to retain sulphates (SO_4^{-2}) in the mineral phase, considering the critical threshold level of 10 mg kg^{-1} (extractor $CaHPO_4$ 500mg L^{-1}). This means that many crops require annual S addition for heathy development and good yields, whether by means of S rich fertilisers or by application of PG.

2.1 PG as Calcium Sulphate Soil Amendment

PG acts by carrying calcium to soil subsurface layers, so effectively neutralising the aluminum content which is toxic to most agricultural crops. In addition, PG is a rich source of calcium and sulphur for plants[59] [36] [37]. Mosaic acquired Vale's phosphate production facilities in Uberaba and Cajati in 2018, consolidating its position in the PG market. The company implemented a business model that involved collecting, drying, and sieving PG to ensure suitable properties for agricultural application.

2.2 Logistics and Distribution

One of the main challenges was the transportation cost of PG to distant agricultural regions. The high cost often made the use of PG economically unviable for farmers. Mosaic and other companies developed solutions to improve logistics and reduce costs. Initially, there was resistance from farmers due to the additional cost of PG compared to other nutrient sources.

58 For an overview of the Cerrado region see https://en.wikipedia.org/wiki/Cerrado

59 Regenerative agriculture in Brazil: challenges and opportunities (2023) pp.47-49, https://cebds.org/wp-content/uploads/2023/11/CEBDS_CTALIMENTOS-ING.pdf

Mosaic invested in research and development to demonstrate the agronomic benefits of PG, such as improving soil structure and providing essential calcium and sulphur for crops, like a soil conditioner.

3. Waste to Inventory

Mosaic successfully transformed phosphogypsum from a waste /byproduct into a valuable soil amendment for Brazilian agriculture and for secondary raw material for Portland cement [38]. By overcoming logistical, economic, and regulatory challenges, the company established a sustainable and economically viable market for PG, simultaneously benefiting the environment and turning PG resources into a sustainable and profitable business (see Figures 93 and 94).

Fig. 93. *Trucks waiting in line at Uberaba to collect PG for use on the soils of the Cerrado (Image courtesy Mosaic Fertilizantes)*

Fig. 94. *PG loading for shipment (Image courtesy Mosaic Fertilizantes)*

4. Phosphoric Acid and Phosphogypsum Production and Use in Brazil – the National Strategic Perspective

According to the "Secretaria Especial de Assuntos Estratégicos" [39] (Special Secretariat for Strategic Affairs, 2021) in the National Fertilizer Plan, the production of phosphoric acid in the last 5 years has been around 1.1 million tonnes/year of P_2O_5 (phosphoric acid) yielding some 1.7 -2.0 million tonnes/year of phosphate fertiliser (ie containing P_2O_5) contained.

The issue of phosphogypsum cogeneration as a co-product of the manufacture of phosphoric acid is however, a sensitive topic. Producing 1 tonne of phosphoric acid generates approximately 5 tonnes of phosphogypsum. The use of this product (see Figure 95) has become extremely significant for both environmental and governmental reasons as well as reducing significantly operational, storage and disposal costs.

Fig. 95. *PG Storage Management – preparation for use (Image courtesy Mosaic Fertilizantes)*

Regulating the use of PG was a significant challenge. The National Nuclear Energy Commission (CNEN) published Resolution 179/14[60] (Brazil, 2021), which regulates the use of phosphogypsum in agriculture and the cement industry[61].

60 See Comissão Nacional de Energia Nuclear https://www.gov.br/cnen/pt-br/acesso-rapido/normas/grupo-4, Published on 05/31/2021 at 10:00 AM Updated on 08/16/2021 at 1:52 PMw

61 See also IAEA Safety Reports Series No. 117, Regulatory Control of Exposure Due to Radionuclides in Building Materials and Construction Materials, which provides an example of the establishment of exemption levels for the use of phosphogypsum in agriculture or in the cement industry in Brazil. A maximum activity concentration of 1 Bq/g is set for each radionuclide 226Ra and 228Ra, based on the recommendations provided in IAEA Safety Standards Series No. RS G 1.7, Application of the Concepts of Exclusion, Exemption and Clearance.

Table 9. *PG inventory 2020-2023*

Year	Uberaba		Cajati	
	Gyp produced (t dry basis)	Gyp produced (t wet basis)	Gyp produced (t dry basis)	Gyp produced (t wet basis)
2020	4.416.248	5.316.586	899.951	1.080.975
2021	4.200.476	4.938.461	668.668	780.514
2022	4.266.996	5.103.662	676.623	780.091
2023	4.164.338	4.933.092	696.815	805.646
Total	17.048.058	20.291.801	1.345.291	3.447.226

Table 10. *Phosphogypsum Markets*

PG	2020 (Ton)	2021 (Ton)	2022 (Ton)	2023 (Ton)
Cement	1.021.992	1.103.963	979.921	1.067.320
Agricultural	3.850.502	4.610.963	4.177.036	4.120.567

4.1 Zero Waste

Mosaic also stood out for its sustainability practices, publishing detailed reports on PG use and promoting the reuse of areas previously used for PG storage. In its manufacturing and technological role, by a combination of experience and investing in product innovation, Mosaic has now reached a level of 80% reuse of phosphogypsum production. Within the next 3-5 years, the business objective is to reach 100% PG use as an indicator of reaching a "zero waste" circular economic milestone, and also making good on Mosaic's commitment to sustainable development.

4.2 PG Production Centres and Markets

The manufacture by Mosaic of phosphoric acid and phosphogypsum in Brazil is located in two main centres, in the city of Cajati (São Paulo state) and in Uberaba (Minas Gerais state).

Phosphogypsum has two significant markets: in agriculture, where Mosaic reaches the agricultural user through specialist marketing and distribution companies that sell and process phosphogypsum, and the civil construction market where Mosaic processes and sells PG directly as feedstock to cement plants. Table 9 demonstrates the inventory of phosphogypsum by Mosaic and its respective quantities by application type.

The relationship between Produto Interno Bruto (PIB) Gross Domestic Product (GDP) and the growth of the construction industry is quite significant, as construction is one of the fundamental sectors for a country's economy. The construction industry directly contributes to GDP through the production of goods and services. When the sector is growing, there is an increase in the production of construction materials, hiring of labour, and execution of infrastructure projects, which according to the trade body CBIC, increases GDP[62]. The growth of the construction industry is often seen as an indicator of economic development. A robust construction sector generally reflects a healthy and growing economy, with investments in infrastructure and housing [40].

4.3 Brazil PG Sales

The use of phosphogypsum in Brazilian agriculture by Mosaic Fertilizers is now a well-established reality. Agricultural gypsum is an irreplaceable soil conditioner in the Brazilian agricultural economy, in particular in the Cerrado region. The solubility of phosphogypsum facilitates the availability of Calcium (Ca) and Sulphur [41] [35] [42] (SO_4^{2-} ion), helping to reduce the activity of impurities or potentially toxic elements,

62 Association of the Construction Industries of Brazil (CBIC) Report Economic Performance of the Construction Industry available at: https://cbic.org.br/wp-content/uploads/2024/04/29-04-24-desempenho-economico-cc-abril-2024.pdf

such as aluminum (Al). The assured availability of the nutrients calcium and sulphur supports the root development of plants, enabling growth in depth and volume [41] [43] [44]. Complementing this, in times of water shortage, stress or drought the use of phosphogypsum as physico-chemical soil amendment can enable greater absorption, retention and slow release of water while providing other essential nutrients for the growth and development of different crops at higher levels of nutrient use efficiency [41] [42]. This results in a significant overall increase in agricultural and livestock productivity and yield, so also optimising land use [41] [42] and enhancing farmer incomes and margins.

Mosaic's current major phosphogypsum feedstock markets are exemplified in Table 10.

4.4 Mosaic PG for Brazil Construction Industry

Over time, Mosaic has become fully familiar with the attributes of both the Brazilian construction raw materials markets and the use of phosphogypsum - calcium sulphate - as soil amendment in agriculture. Resultant high user acceptance ensured that PG added a new page in the Mosaic gypsum business catalogue.

The Brazilian construction materials market requires 5 different types of cement, due to a combination of market footprint extension and the developing availability of secondary raw materials [37]. In particular, the Portland cement variants in demand are due to their relative composition, commonly clinker, calcium sulphate and additives [45] [46]. Calcium sulphate is used to control the cement setting time, delaying the hydration of the tricalcium silicate (C3S), without which the cement would harden quickly in contact with water [47] [37] [44]. In general terms, a 3% fraction of gypsum is added by mass to 97% clinker [37] to create a cement with a controlled setting time suitable for use in conditions in Brazil.

In terms of business case, the key is transportation and distribution costs, which also of course now include carbon emissions and loading factors. The high shipping cost of moving primary raw materials (natural gypsum) from their sources in the northeast of the country the long distances to the point of use in market, in line with the competitive price advantage and sustainability policies, make phosphogypsum an attractive alternative to natural gypsum (native calcium sulphate) [48] [49]. Due to the similarity in the chemical formula of gypsum ($CaSO_4 2H_2O$) and the similarity in its physical properties, good results from substituting PG for natural gypsum has become a technically and commercially appealing alternative material as a retardant of cement setting time [50] [45]. Against that background, historically phosphogypsum has been widely used in the South and Southeast of Brazil; but the impurities in its composition still require further environmental impact studies of its use to be conducted, in particular in respect of use in roads and drywall [46] [50].

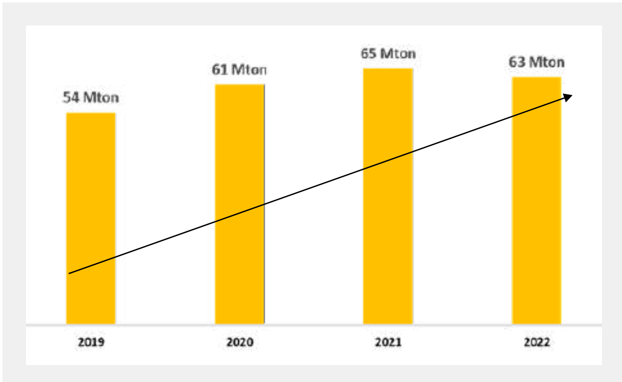
In that context, and in the quest to serve the cement market with the feedstock specifications they require and in the spirit of the industry core value of transformation and constant enhancement, Mosaic has developed a PG treatment procedure to better meet the market demands. Accordingly, different ways of neutralising phosphogypsum have been studied [51] while simultaneously having a positive impact on immobilising or eliminating impurities. It was found that the action of lime was effective in neutralising phosphogypsum and reducing impurities, such as soluble phosphates and soluble fluorites. Anchored in a trusting relationship between Mosaic and its customers, a specification and operating procedure for managing phosphogypsum and impurities was created so that treated PG could be added confidently to the cement market.

Currently the cement market works to a PG product specification based on four main factors:

- Moisture
- SO_3 content
- Total P_2O_5
- Acidity Index.

Figure 96 shows cement production in Brazil, a growth of 16.7% from 2019 to 2022.

Fig. 96. *Brazilian Cement Production 2019-2022 – Brazil*



(Mton/year)[63]

Mosaic has two gypsum stacks (Uberaba and Cajati) to serve the cement markets. Taking into account the approximate technical index of 3% PG as retardant, it is possible to estimate

63 See data from National Cement Industry Union (SNIC) Brazil, http://snic.org.br/index.php?lang=en

the likely national market size for using PG for that purpose as a setting time additive.

Mosaic meets the market demand for an effective phosphogypsum pretreatment process, with the commercial and environmental dual purpose of transforming a material previously classified as a waste generated by the manufacture of phosphoric acid into an attractive substitute for the cement market to natural gypsum. In the process, millions of tonnes per year of natural gypsum are conserved for use by future generations.

Neutralisation aims to adapt the attributes of PG, reducing acidity, impurities and humidity, while making the product an alternative to gypsum in controlling cement setting time. The result is a win/win outcome, whereby this secondary raw material becomes an intermediate product, with considerable sales volume and profitability for the company. At the core of this value transformation is the circular economy focus on value add, and the chosen way to give market confidence to this is the voluntary development of and adherence to product and service standards, which is where the global PG market is now heading.

5. Mosaic's Social Program, a Success Story in Sustainable Agriculture and Community Development

5.1 Villages Programme, Brazil

As an agro-mining company, Mosaic is deeply committed to socio-environmental transformation in the regions where it operates. Its goal is to develop products and solutions that not only increase agricultural productivity, but also preserve natural resources, guaranteeing sustainability. With a mission to ensure global food security and promote the inclusion of vulnerable communities, Mosaic continues to implement programs that generate income and improve nutrition, strengthening the future of family farming and contributing to a more sustainable world.

The Mosaic Institute's Village Program began in 2019. The first city to benefit was Barreiras, in western Bahia. As time went by and good results were achieved in the field, the initiative grew and the actions reached two more municipalities in northeastern Brazil: Balsas, in Maranhão, and São Desidério, also in Bahia. The initiative stands out for its commitment to sustainability and improving the quality of life of rural families. The program also includes integrated actions in the education sector, such as improving the infrastructure of rural schools and training teachers.

In the Village Programme, inclusion and diversity are also fundamental objectives. 50% of the families served by the program are headed by women. 25% of them are over 60 years old and 92% are black- and brown-skinned people. With the support of a multidisciplinary team, the program offers technical assistance to farmers who previously lacked essential information. This support is crucial to raising both income and quality of life, promoting more efficient and sustainable agricultural practices. Actions include the construction of cisterns and the installation of irrigation systems, which are essential for the conscious use of water and the sustainable expansion of crops.

Over five years, Mosaic has invested more than R$10 million in the program, benefiting 120 families. So far, 81 cisterns have been built and 100 irrigation systems delivered, improving the management of water resources in the municipalities served. These investments bring a very positive outcome for those who live off the land. On average, the farmers assisted by the Village have seen a 230% increase in their income and a 40% increase in productivity.

5.2 Villages Programme Gallery Some photos from the Mosaic Village Programme are shown below, Figures 97-104.

Fig. 97-104. *Mosaic Villages Project gallery (Images courtesy Mosaic Fertilizantes)*


9

CHAPTER NINE

PHOSPHOGYPSUM OVERVIEW, INDIA

Source: Fertiliser Association of India,
Technical Director Manish Goswami
Analysis: General Editor

1. PG Production in India, the Current State

The provisional data for production of phosphoric acid, generation and utilisation of phosphogypsum in the Indian fertiliser industry during the most recently completed fertiliser year, 2023-24 is given in the Table 11.a below. Presently, nine plants are producing phosphoric acid for production of fertilisers and a tenth is soon to come on stream, adding a further 1 million tonnes/y to annual production.

Table 11.a *PG Generation and Utilisation Fertiliser Year 2023-24*

Sl No	Year	Phosphoric acid production	Phospho-gypsum generation	Utilisation of Phosphogypsum*				Invento-ry as on 31.03.2024
				Cement	Agriculture	Building Materials	Others	
		MMT	MMT	MMT	MMT	MMT	MMT	MMT
1	2023-24	1.962	10.576	4.605	0.98	0.819	0.687	66.3

*(MMT= million metric tonnes) *some data has been estimated*

M/s Coromandel International Limited has announced a new phosphoric acid production facility at one of its sites (Kakinada, Andhra Pradesh, Southern India) with a capacity of 650 tpd. The process used will be the DA-HF (dihydrate attack-hemihydrate filtration) process. This will result in further generation of about 1 million tonnes PG/year going forward.

1.1 Current State Analysis

There has been steady increase in the past fertiliser year of consumption of PG in agriculture to 0.98 million tonnes. This was 0.38 and 0.46 million MT during fertiliser seasons 2021-22 and 2022-23 respectively, so 2023-24 has effectively seen agricultural consumption double. This is all the more striking because in his valedictory contribution to the IFA PG Reports in 2020, Dr. S. Nand, in his then capacity as Technical Director, commented on the relative under-use of PG in agriculture:

> *"There is considerable headroom in the market for growth. Even if 50% of sulphur required is supplied through PG to Indian soils, it will create annual demand of more than 2 million tonnes of PG in agriculture."*

This is a major achievement nonetheless, and from a market segmentation perspective, PG use in agriculture is now half-way to the challenge issued by Dr. Nand to reach the optimum use point of 2 million tonnes/y on India's sulphur deficient soils.

1.2 Trends Fertiliser Year 2017 to 2024

From a trend analysis perspective, India's phosphoric acid production in fertiliser year 2017-18 was 1.47 million tonnes (see Table 11.b). This was the first fertiliser year since publication of the first IFA PG report in 2016.

It declined during in 2017-18 due to the closure of some smaller plants but recovered slightly in 2018-19, with PG output rising in 2018-19 to 8.27 million tonnes from 7.79 million tonnes, equating to a slight rise in phosphoric acid production. There was also an inventory of some 56.0 million tonnes nationally, very small considering the annual production output and indicative of a PG economy already close to supply/ demand equilibrium. Inventory grew by 2024 to 66.3 million tonnes, the outcome of an overall increase in PG use volume, from 6.37 million tonnes to 7.089 million tonnes – a slight % fall from 75% to 71.5%. The agriculture headroom identified by Dr. Nand would be an appealing candidate for increased consumption, rewarded most likely by increased yield.

Table 11.b *PG Generation and Utilisation Fertiliser Year 2023-24*

YEAR	Phosphogypsum Generation (mt)	Utilization of phosphogypsum (mt)*			
		Cement	Agriculture	Other	Total
2017-18	7.79	2.67	0.42	2.21	5.30
2018-19	8.27	3.96	0.59	1.82	6.37

(*estimated, mt=million metric tonnes)

When the data in Tables 11.a and 11.b are compared, it can be seen that PG inventory had risen by some 10 million tonnes, or 2 million per year an annual use rate of some 75%. Cement is clearly the leading use.

1.3 India as Pioneer and Regulatory and Policy Benchmark

As referenced in Section B, Chapter 12, India has long been a pioneer in systemic PG use, led from the start by uptake in cement production but within a broadly scientific, evidence-based policy and regulatory framework. Having two regulatory agencies overseeing it, the radionuclide (NORM) aspects were dealt with first by the Atomic Energy Regulatory Board (AERB), which as early as 2008 took a graded approach in its risk assessment of PG, formally allowing it to be used in a range of applications, most conspicuously in agriculture where subject to regular monitoring of crops and soils, PG could be used with restriction.

Later in 2014-15, the other potential hazards from PG, notably heavy metals content and similar, were reviewed under a similar graded approach. The outcome was a meticulously calibrated hierarchy of risks and benefits as presented with each application and use setting, resulting in detailed and contextualised permitting requirements derived from real-world empirical data aligned to appropriate risk thresholds rather than decontextualised deterministic models. Having a settled use rate over many years of ~75% and a legacy of 66.3 million tonnes is remarkable. And with the adoption of PG into one of the priorities of India's circular economy transition plans in 2022, it not only gave confidence to major PG-producing companies in India to increase PG use by volume, it also gave confidence to major PG-producing countries such as Morocco to likewise see in the CE a new and positive pathway to sustainable PG use. The impact of that lesson on Morocco can be seen in case study Section B.12 of this report. This makes an important comparison between attitudes in India and Morocco towards PG agricultural and forestation uses. This is all the more of interest as both Indian and Moroccan PG are largely generated from identical rock, from Morocco. Everything is connected to everything.

CHAPTER TEN

PHOSPHOGYPSUM USE FOR SOIL HEALTH IMPROVEMENT, OCP

Compiled and edited: General Editor assisted by Paulo Pavinato, University Sao Paulo, based on original source materials provided by OCP, reviewed and finalised by the OCP specialist team of Khalil El Mejahed (AITTC-UM6P), Amina Alaoui Soulimani (UM6P) and Kamal El Omari (OCP)


10

1. Introduction

During the decade from 2014[64] [48] there has been a significant effort to generate reliable data on three problems that climate change has been significantly aggravating during the same period. These problems conversely offer PG a major opportunity for use in the numerous climate-stressed, salt-impacted soils of large regions of the world which also house phosphoric acid and PG production:

1. What is now the worldwide land area of soil salinity built-up in irrigated soils?
2. What is the compound annual growth rate (CAGR) of that build up?
3. What may be the economic, social and environmental costs of that degradation in terms of annual loss of yield and the longer term value destruction caused to the land asset itself.

1.1 Yield Loss – the Business Case Baseline

In 2014 a baseline study was conducted [52] which, assuming PG was not applied at all to degraded, saline soils, estimated the annual economic loss at "US$ 27.3 billion because of lost crop production":

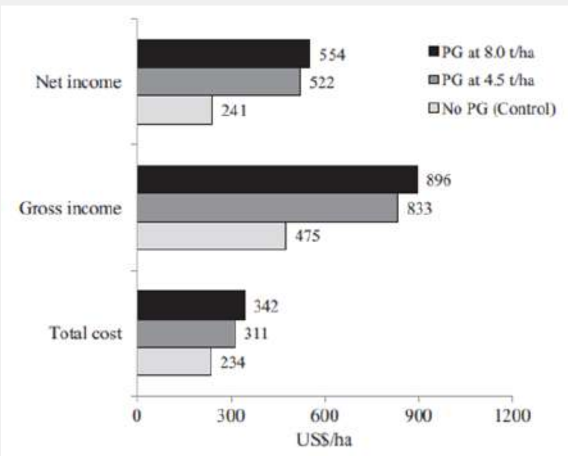


Fig. 105. *Net income from PG application as soil amendment* [53]

Figure 105 shows total cost, gross income and net income reflecting the comparative economics of "action" and "no action" under PG and control treatments [52]. The four key elements of the very high annual loss are:

1. cultivation and production cost (seed and seedbed preparation, use of farm equipment and fuel, insecticides, pesticides, and herbicides, where needed)
2. fertiliser cost (purchase, transport, and application of fertiliser)
3. labour cost (ploughing and sowing, field operation and cleaning, harvesting, and post-harvest management)
4. irrigation cost (delivery and cost of irrigation water, pumping cost where applicable).

The same study includes a PG-specific example from Kazakhstan quantifying the economic benefit to cotton farmers of the applications of PG as soil amendment over a three-year period. Results are shown in Fig. 105 above. In fact, farmer net income more than doubles whether at a rate of 4.5 t/ha or 8.0 t/ha[65].

1.2 Salt-Affected Land Area

In terms of accurate data in respect of how much degraded land area, the most detailed study, using extensive satellite data estimated that:

> *More than 954 million hectares (ha) of land worldwide are salt-affected, and between 25% and 30% of irrigated lands are rendered unproductive due to salinity [54]. The increase in the world population is expected to expand salinisation further through an array of processes, including an increase in treated wastewater reuse for irrigation [55], [56], [57], [58], [59], groundwater contamination due to percolated salts from irrigated lands [60], [61], [62], and an increase in the use of brackish or saline water for irrigation [63], [64], [65]. The consolidative nature of these processes suggests that salinity issues are inherent to crop production and agricultural water management strategies in many water-constrained regions.*

Estimated CAGR of salt-affected soils is conservatively estimated at 3%, or an additional 30 million ha/y. What this figure also masks is that the existing baseline number of affected hectares will, without intervention, have deteriorated further in terms of yield loss.

64 2014 is taken by IFA as a baseline date for what has been achieved by the industry in partnership with governments, academia and inter national organisations in the field of PG valorisation and use since the landmark speech by Esin Mete in February 2014 (see Section 1).Mrs. Mete set future approaches to PG within the then emerging Sustainable Development Goals and Paris Agreement on Climate Change.

65 The agricultural details of this intervention may be found in a case study IFA PG2 written by the same author, Manzoor Qadir. But this economic analysis was not included at the time and is of particular significance to the baselines business case for PG use as a soil amendment is salt-affected soils worldwide.

1.3 Convergence Between Salinity Build-up and Economic Decline – Annual Yield and Overall Land Value

Crop market price determines the revenue generated from crop production and is critical to the amount of profit that can be generated. In the Central Valley California, which until 1989 was a heavy consumer of PG as soil amendment to remediate salinity and maintain yield, from 2013–2017 the historical market price and net profit for alfalfa, almonds, grapes, and processing tomatoes declined at a rate equal to 1.5 of the 2017 market price at various ECiw[66], ie pricing margins reduced in close correlation with declining relative ECiw margins.

> *Alfalfa's market value showed a declining trend with losses recorded from 2015 irrespective of the water ECiw. As water prices increased, losses were recorded even with high quality irrigation water. But for almonds, production was profitable irrespective of water price, except in 2016 and 2017 when the market value of almonds was low. Regardless of water quality and cost, all other years resulted in net loss, except for the projected market value of 1.5 times the 2017 price. [66]*

Overall market prices reported in 2013 and 2017 triggered profitability losses resulting from high saline water and water prices.

2. Context

Phosphogypsum (PG) contains several constituents of potential value to agriculture, mainly calcium sulphates ($CaSO_4$), but also magnesium, aluminum, iron and manganese, as well as rare-earth elements, silicon, titanium, as well as heavy metals such as cadmium and trace quantities of radium salts which are now the focus of attention for the development of innovative cancer treatments.

Considering the importance of $CaSO_4$ as a source of nutrients, there is a great potential for PG use in agriculture and for the amelioration of some plant-harmful elements such as Al^{+3} in acidic soils like the ones in Brazil and Sub-Saharan Africa countries [67] [68] [69] or to overcome excessive levels of salinity in arid soils [70].

Despite use restrictions in some countries, in the light of a range of evidence-based reviews of the relative risks and benefits of PG use as a soil amendment, the use for saline-sodic soil amelioration for agricultural purposes to combat the effects of climate change, water salinity and water shortage, is very common (e.g., Australia, Brazil, India, Egypt, Spain, etc.).

66 Replace with ECiw is the acronym for the relative Electrical Conductivity of irrigation water, to measures its relative salinity. There is a correlation between declining financial margins in the farming sector and declining quality of water: the saltier the water, the poorer the soil and the crop and the lower the yield and financial return.

Several benefits of PG application in agriculture have been reported worldwide, and PG has been used either as a fertiliser or amendment for different types of soils including degraded ones (sodic, saline, and acidic soils). Moreover, some reports about PG increases in irrigation/water use efficiency, reduces soil surface crusting, and improves soil water infiltration rate [71] [72] [73] [74] [75]. The advantage of using PG in agriculture compared to other potential uses is that it does not need to be purified from P content; this impurity plays a positive role in suppressing the impact of fluorine, which is a component of PG, and additives can be used to form insoluble compounds in the soil [76].

The PG utilisation rate worldwide is impacted by several uncertainties and constraints such as:

- radioactivity, heavy metals, and acidity: The concentrations of radionuclides and heavy metals in PG wastes vary considerably depending on the source and nature of the rock phosphates as well as the extraction processes.
- transport and application costs: It depends on the distance between the production site and the application site.
- standards and regulations: The restrictions on PG recycling vary depending on the country and the approach adopted

As planned in 2020, hence significantly intensify the use of PG for agricultural purposes and amelioration of some soil problems, many test pilot studies were conducted at University Mohammed VI Polytechnic (UM6P) for the purpose of improving soil profile nutrient distribution and inhibit salinity effect. This has signalled a consolidation of innovation and R&D in regard to PG, around the UM6P. This body of work, which is broadly discussed here, forms the basis for recommendation of PG use in Morocco and other countries in Africa with which Morocco is already collaborating, or plans to – see also the Great Green Wall project under the UNCCD.

2.1 Rationale

Soil is among the most important natural resources that can be degraded in varied forms. Soil degradation is a change in the soil's health that reduces its ability to provide goods and services [77]. Population and income growth are expected to necessitate a 70% increase in global food production by 2050 and up to 100% in developing countries [78]. In contrast, the land resources are deteriorating. Indeed, 33% of the land surface is subjected to some form of degradation, whether physical, chemical, biological, or ecological [79].

The use of PG in agriculture is an altogether preferable and more profitable alternative to treating or reversing soil degradation, and at a minimum the "no action scenario" for PG use as summarised above transportation and storage of PG in disposal stacks itself entails investment and operating costs. For example, up to 10% of the prime cost of phosphoric acid is attributable to the costs for PG transportation and storage [80]. Such disposal stacks as destination points for processed industrial minerals are continuously accumulating new residues at scales that threaten the sustainable function of biocenoses. The current production rate of PG is estimated at 225 million tonnes per year, with a reported mass utilisation rate recently reaching 35% of total volumes produced thanks to a surge of use in China under its new Comprehensive Utilisation policy.

2.2 Use of PG in Agriculture in Tropical Acidic Soils

Acidic soils (pH≤ 5.5) account for nearly half of arable land area worldwide, steadily increasing due to ongoing soil acidification [81]. Acidification mostly occurs in developing countries such as in Central Africa, South America, and Southeast Asia [76]. Soil acidity is one of the most critical factors limiting crop yields in the tropics and subtropics, where acidic soils account for 60% of the total land [80]. Soil acidification processes can be induced by natural factors (such as long-term rainfall and soil weathering processes) or more commonly anthropogenically by human intervention such as one or more of highly use-inefficient application of ammonium-based fertilisers, acid-inducing fertilisers and related phytosanitary treatments.

2.2.1 Soil Acidification and PG Mitigation

Soil acidification deteriorates soil quality by inducing nutrient loss such as calcium, magnesium, and potassium and by increasing aluminum and manganese concentrations in the soil solution. It also increases the bioavailability of toxic metals such as cadmium and lead [82]. Acidic soil conditions represent chemical and physical barriers to root growth and cause nutrient deficiencies (such as potassium and molybdenum) and consequently reduce crop yields [83]. Soil acidification is often associated with aluminum (Al) toxicity. High concentrations of Al significantly constrain the plant's physiological and metabolic functions [84].

The ability of PG to alleviate the adverse effects of high Al saturation in the subsoil on plant growth was first observed in the late 1970s in Brazilian soils [85]. Since then, PG has been recommended as a conditioner for soils with medium-to-high subsoil acidity [86] [87]. As a result, PG considerably increases the mobility of basic cations such as exchangeable Ca^{2+}, Mg^{2+}, and K^+ associated with SO_4^{2-} ions in the subsoil mainly, thereby reducing the activity and toxicity of exchangeable Al^{3+} and improving water and nutrient uptake by plants [71] [86] [88].

Taking into account the direct effect of PG in Al toxicity in soil [71]. evaluated the impact of four rates of PG (0, 1, 3, and 9 t/ha) on Al speciation in the soil solution of three different acid soils. The finding was that the PG, when applied at feasible on-farm rates (1-3 t/ha), can significantly reduce the activity of Al^{3+} in acid soil solution. By contrast, higher rates of PG (9 t/ha) should be avoided on acid soil (pH < 5) as this would further acidify the soil causing a release of Al and its accumulation unless combined with a pH neutralising material such as lime. Such a caution is however as much economic as agronomic in nature and the relatively low additional cost of lime, which is unlikely to affect the overall transportation or field application cost, may still be cost-efficient and benefit the wider physico-chemical condition of the soil.

In summary, PG is widely used in acidic soils because it reduces Al toxicity, one of the main constraints to crop production, increases nutrient availability, and improves soil physical properties. However, its application must be based on a clear characterisation and analysis of the soil properties as found at field level.

2.3 Use of PG in Agriculture in Saline/Alkaline Soils

The direct use of PG in agriculture for fertilisation and reclamation of soils, especially saline soils, is becoming an even more promising direction than hitherto, owing to the changes in climatic parameters and aridification, with increasing areas of anthropogenic (secondary) saline soils [75]. The acidic nature of PG (2 ≤ pH ≤ 5) improves its solubility [89], which is ~ 2.7 g/L [90]. Because of its high solubility, PG is a good choice for lowering the soil pH, reducing salinity and improving solubility of nutrients in alkaline agricultural soils from arid regions.

Salinity is one of the main forms of soil degradation that impedes food security, particularly in arid and semi-arid regions. Globally, salinity adversely affects approximately one billion hectares of agricultural land with an upward trend in the wake of climate change [91]. At present, soil salinity affects 20% of cultivated land and 33% of irrigated agricultural land worldwide [92].

2.3.1 Salt Accumulation in Soil – the Strategic Cost in Morocco

Salts accumulate in the soil as a result of mineral alteration and marine sedimentation (primary salinity). Secondary salinisation occurs when evaporation exceeds precipitation and crop water requirements, and when poor water quality is used for irrigation. This is especially the case if water is loaded with electrolytes or total soluble solids that, after evaporation, accumulate in the soil [93] [94]. The soil salinisation is classified on a 5 point scale of severity as shown in Figure 106 [95].

Salinity and sodicity are the main challenges facing agricultural production systems in arid and semi-arid regions such as Morocco. In Morocco, the total soil affected by salinity is

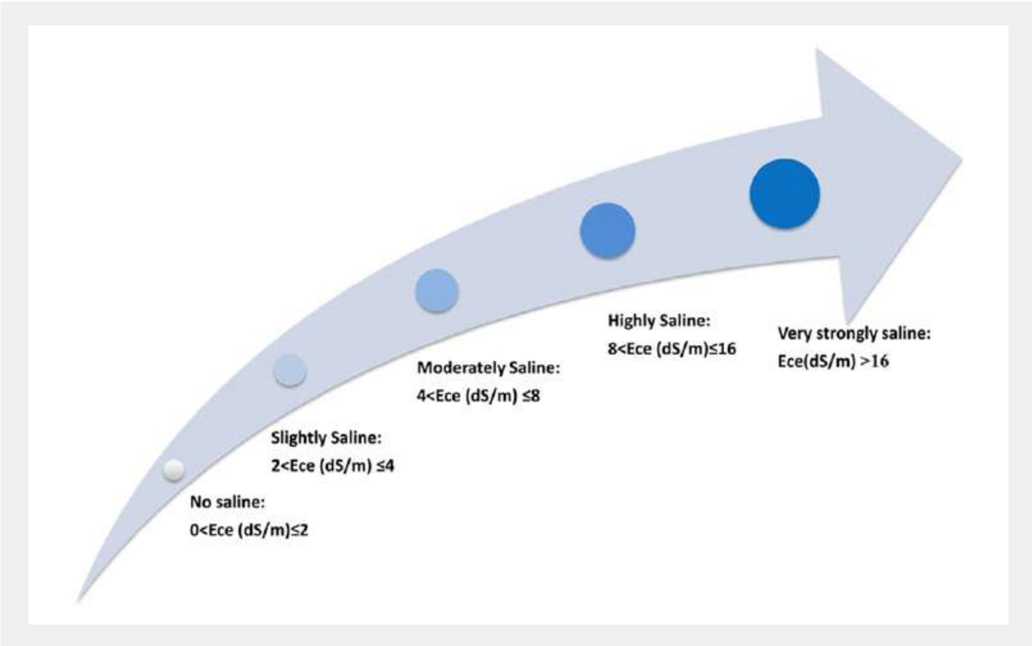


Fig. 106. *Soil salinisation classification scale* [97]

Table 12. *Chemical composition of phosphogypsum from different countries.*

Element	Morocco[a]	Tunisia[b]	Egypt[c]	Brazil[d]	China[e]
CaO (%)	31.71	31.85	28.31	40.06	38.39
SO_3 (%)	43.40	31.40	40.45	44.5	56.68
H_2O (%)	20.80	7.00	19.71		
P_2O_5 (%)	1.20	0.81	1.98	0.64	2.26
F (%)	1.10	0.92	0.26		
Na_2O (%)	0.27	0.48	0.29	0.03	0.07
K_2O (%)	0.05	0.02	0.02	<0.01	0.12
SiO_2 (%)	0.74	1.86	8.29		1.37
Al_2O_3 (%)	0.26	0.69	0.17	0.30	0.35
MgO (%)	0.08	0.01	0.21	0.05	0.12
Fe_2O_3 (%)	0.07	0.03	0.31		0.45
Ba (ppm)	30.08	30.22	78	1537	
Cd (ppm)	1.34	24.73		<0.1	
Hg (ppm)	0.65	1.99			
Pb (ppm)	0.73	8.06		9	0.3
Cr (ppm)	7.50	6.12	34	11.1	
Zn (ppm)	43.00	93.2	25	<0.1	1.7
Cu (ppm)	55.00	70.82	12	6.3	3.3

Legend: [a]Ennaciri et al. (2020) [91]; [b]Zmemla et al. (2020) [102]; [c]Kandil et al. (2017) [103]; [d]Lütke et al. (2020) [104]; [e]Li et al. (2017) [105].

about 1.148 Mha (FAO, 1988) [96]. The salinisation effect may be overcome by PG addition in agricultural areas, especially by dropping soil pH. According to JESA forecasts, based on current conditions and trends in Moroccan soil salination - weighted to soils in irrigated areas - could be responsible for a significant cumulative cost by 2030 (estimated to be several tens of billions of dirhams between 2024 and 2030).

2.4 Contaminant Levels – at What Level of Risk?

The content of radioactive elements in PG is strongly related to the origin of the phosphate rock. A 2023 study show the chemical composition of PG of various origins in PG [97]. It is also well-known that radioactivity is indeed one of the significant challenges for PG valorisation and use [98] particularly if taken out of context as NORM risk in particular is not well understood. Depending on the nature of the deposit from which the rock phosphate is mined, radioactivity may be a factor to be kept under active monitoring before, during, including consternation given to pretreatment options specific to PG from P rock from deposits.

In respect of other potential sources of harm, the geo-accumulation index revealed that the PG-treated soils were not contaminated with vanadium (V), Zn, Cr, Pb, Ni, or Cu, while a slight level of contamination by Cd was recorded when huge quantity of PG is used in rehabilitation (65% PG). Other elements such as Zn, Cd, Pb, and Cr were comfortably below the permissible limits for food production and consumption. The daily metal intake and health risk index values were <1. This suggests that the consumption of vegetables and fruits cultivated in PG-amended soils is inherently safe [103]. Others [104] found that the application of PG at 10 and 40 t/ha did not cause any accumulation of trace elements (Pb, Cu, Zn, and Cd) in the soil and in the plants (Kochia scoparia). Fluorine concentrations in plants did increase after PG application but remain below permitted levels. Other authors have demonstrated that PG application rather reduces than increases heavy metal uptake by plants: it was reported 2015 [105] that PG reduced the content of Pb, Cd, and Zn in canola plants. It has also been confirmed that the addition of PG during composting process reduced the content of heavy metals in the final compost product [106].

In the same vein, a recent field trial (2022) [107] confirmed a significant finding that using PG as saline/sodic soil amendment did not affect faba bean grain quality in respect of heavy metal content, field evidence showing that applying PG did not significantly impact soil heavy metal level content. [108] It was also established [109] that the concentrations of heavy metals in the drainage water of PG-amended soils did not exceed the recommended limits.

Nevertheless, monitoring studies are required to evaluate the accumulation of heavy metals in the soil over time after a repeated application of PG using different crop species. Also, measuring the total amount of heavy metal in the soil or plant tissues may not be the best way to assess the environmental safety of PG use in agriculture, because the risk is rather related to the bioavailable fraction of heavy metal than the total amount. Hence, the need for continuing soil and crop-specific speciation studies.

3. OCP Project Scalability – Testing PG use to Scale in Morocco and Neighbouring Countries

Development of scalable technologies for applying PG from OCP SA processing units for improving agriculture development and C sequestration in soils, for Morocco, neighbouring countries, and potentially spreading to Sub-Saharan Africa is now seen as the next logical step in the strategic process of market entry for PG as soil amendment or anthrosol constituent component. The objectives are threefold, to:

1. develop the use of PG in agriculture for distinct soils and regions
2. strengthen the technical capacity of all stakeholders
3. develop a techno-economic scalable model in many regions of Africa.

Such significant objectives naturally bring with them certain questions.

3.1 What is the Measurable Benefit on Soil Performance of PG in the Soil Profile Nutrient Distribution?

The ability of PG to mitigate the adverse effects of high Al saturation in the subsoil on plant growth and the capacity to redistribute the nutrients (Ca, Mg, K, S) in the soil profile are the main proven benefits observed under the addition of PG. Since that finding has been confirmed, PG has been recommended as a conditioner for soils with medium-to-high subsoil acidity [85][86]. As also mentioned above, for saline/alkaline soils, the acidic nature of PG ($2 \leq pH \leq 5$) improves its solubility [88], with a high likelihoolowerinf soil pH is not directly responsible for reducing salinity but results in solubilising soil Calcium, besides Calcium brought by PG. This is a considerable market benefit.

3.2 Implications for Moroccan National Market and Potential Export Opportunities

As presented in two case studies in PG2, OCP and partners had already progressed significantly by 2020 at the UM6P experimental farm in 1. highlighting the significance of S as the fourth macronutrient (with N, P and K) and 2. establishing baseline values for potential beneficial impacts on domestic agricultural production and maintaining both yields and capital values of land, for example in barley and maize [110] [111]. These connect the line of reasoning followed by OCP for subsequently setting the baseline values for salt affected soils and the adverse social, economic and environmental consequences but likewise confirm that the parameters for assessing the strategic business opportunity for Morocco and OCP are consistent with those driving changes of attitude and approach for PG uses in agriculture.

The 2020 studies [17] yielded a wide range of largely positive findings of which selected highlights were as follows:

3.2.1 Barley Trials

- Yield on plots treated with 30 t/ha is 40-50% higher than the control (no PG)
- Application of PG increased irrigated water use-efficiency because all the plots received the same amount of water but yields in PG treated plot were higher. The burning of the tips of leaves of barley were reduced in plots treated with PG at 30 t/ha in comparison with the control
- The effect of PG application on soil exchangeable Na, Ca and Mg, especially the benefit to Ca uptake is most pronounced in the upper soil horizon (0-20 cm) with more general benefits to both plant and soil condition.

3.2.2 Maize Trials

- Yield in terms of green biomass from plots treated with PG are significantly higher than that of control. This increase is mainly due to the increase in average weight per stalk/stem
- Application of PG increased dry matter by 45% and 69% respectively for PG rates of 20 t/ha and 40 t/ha
- Although the corn was grown for forage production and not grain, grain yield, even in the milk stage, was positively affected by the application of the PG
- Test pilot studies were conducted at University Mohammed VI Polytechnic (UM6P) for the purpose of improving soil profile nutrient distribution and inhibit salinity effect for agricultural crops.

3.2.3 PG Field Trials 2020-2024, UM6P Experimental Farm

These in turn set the basis for work done between 2020 and 2024 at the UM6P Experimental Farm, Ben Guerir:

1. Conduct of new field trials with PG as soil amendment. Only in the field (different soil types, crops, and with varying PG rates and sources, in partnership with INRA (Ministry of Agriculture, Fisheries, Rural Development, Water and Forests) and Mohammed VI Polytechnic University (UM6P).
2. Continue the production of salinity/ sodicity soil maps for different regions of Morocco, in partnership with the National Institute of Agronomic Research (Institut National de la Recherche Agronomique - INRA), Ministry of Agriculture, Fisheries, Rural Development, Water and Forests, (Ministère de l'Agriculture, de la Pêche Maritime, du Développement Rural et des Eaux et Forêts).

3.3 What are the Optimum Levels of PG for Use in Agriculture?

In developing metrics for use in calculating PG applications rates and frequencies for regular inclusion in plant and crop nutrition regimes, the following metrics can reasonably be applied for the business case.

1. The feasible on-farm PG dose rates for acidic soils should be ~1-3 t/ha, reapplied every 3-5 years. Higher rates of PG should be avoided on acid soil (pH < 5) as this would further acidify the soil causing a release of Al and its accumulation, unless combined with a pH neutralising material such as lime.
2. The PG dosage considered for saline/alkaline soils may range from 5 to 45 t/ha, depending on soil salinity and type of soils. Salinities below 2 dS /m may be considered to have a low impact on agricultural yields and do not require PG. Above 14 dS /m of salinity cultivation should be avoided altogether.
3. Frequency adjusted according to crop irrigation level, the more often a crop is irrigated, the greater the salinisation of the soil, hence requiring more frequent application of PG.
   - Cereals and industrial crops, % of irrigation below 50, PG application frequency 4 years
   - Almond and date trees, % of irrigation below 50, PG application 3 years' frequency
   - Pulses, oilseeds, sugar crops, fodder crops, market gardens, citrus fruits, olive trees, vines, rosaceous plants % irrigation greater than 50, PG application frequency 2 years.

3.3.1 How much Can Annual Yield be Improved with Regular PG Use?

A compilation of 43 reference results observed in Brazilian acidic soils [68] reports that crop response on PG application (up to 12 t/ha) is related to soil type and nutrient availability, as well as crop species (soybean or cereals), climate zone and water stress conditions. Based on the results, the cereal crops were more likely to respond to PG with gains up to 25% in yield, soybean was not so responsive, with gains up to 5%. The increase in grain yield was roughly twice as high when the crop was not under conditions of water deficiency than under water stress. This was the outcome of regular PG use as soils amendment that in years of water stress the residual benefit of greater root development in the deeper soil layers resulting from regular annual PG application. Despite water stress, the roots were in a condition to reach further into a higher root/soil volume and hence to absorb more water and nutrients [112].

It is widely confirmed that soil physical properties significantly influence yield parameters. In this context, phosphogypsum plays an essential role by introducing divalent calcium ions (Ca^{2+}) into the soil solution, which replace monovalent sodium (Na^{+}) and potassium (K^{+}) ions. This ion exchange contributes to the formation of soil aggregates and macro-pores, thereby enhancing soil structure and water retention capacity. These improvements in soil physical properties ultimately support better plant growth and increased yield [107]. The use of PG also impacts the chemical properties of soil, offering a dual effect: it directly enhances soil fertility by increasing nutrient content (specifically sulphur, calcium, and phosphorus) and indirectly improves nutrient availability. This indirect effect is achieved by lowering soil pH, which can enhance nutrient solubility and availability, further supporting plant growth [113].

IFA (2018) [114] suggests that using PG as a fertiliser is one of the most promising approaches for saving sulphur and calcium resources. It is also reported [115] that PG positively affected the vegetative development of several major global crops including rice, cotton, and soybean, with a gain of up to 50% in yield. Likewise, it is reported [87] that PG application increased the sulphur content of rice leaves and grain yield and a different study [116] demonstrated that Ca and S content in corn, wheat, barley, and bean leaves was improved, while Mg content decreased after PG application. In addition, the yields of corn, wheat, and barley were increased by 11%, 10%, and 10% respectively. The combination of PG and compound fertilisers on peanut crops was tested [117], noting a yield increase of 45% as compared with the application of the compound fertiliser alone. Additionally, in a study investigating the use of PG as a fertiliser [112], it is reported that applying 1.5, 3, and 4.5 t/ha of PG led to notable increases in barley grain yield by 21%, 34%, and 39%, respectively, compared to the control. Furthermore, shoot and grain nutrient uptakes (N, P, K, Ca, Mg, and S) were significantly enhanced with PG application. Collated findings of fertilising effects of PG on major crops are shown in Table 13.

3.3.2 How Much PG Can be Used in Agriculture in Africa?

In irrigated areas in Morocco, the demand for PG as soil amendment is expected to increase. A first estimate (Figure 107) was made to define the potentially relevant areas of interest. This estimate is currently being re-evaluated based on new data to consolidate the obtained results.

PG (Calcium sulphate) is rich in calcium, an essential nutrient for plant growth. Most soils in sub-Saharan Africa have low calcium content, which leads to low agricultural yields. Therefore, addressing calcium deficiency in African soils through the application of phosphogypsum, as a low-cost product, can contribute to sustainable agriculture and improve food security in the region. At the same time as having calcium to offer PG also contains sulphur. The main source of S in soil in the African region is organic matter, which is very low in African soils in general and in Moroccan soils in particular.

Therefore, applying PG as a source of S is highly recommended in soils with low organic matter contents. This suggests that the use of PG could be a promising way to overcome to great benefit endemic S deficiency-related problems (yield and quality) and the cost associated with the use of expensive remedial S-based fertilisers.

An estimate of annual PG demand on various Moroccan soils is shown in Figure 107.

Annexe: Constructing the Knowledge Hub – 'Resource as a Service' Circular Economic Transition

UM6P Experimental Farm PG Use Thumbnail Case Studies, 2020-2024

A series of agronomic pot experiments were conducted under controlled conditions at the experimental farm of Mohammed VI Polytechnic University in Morocco (2020/2023), using saline soil collected from the Chichaoua region and saline-sodic soils collected from Ras Al Ain, Sidi Zouine, and Sed El Masjoune regions. Different PG rates were used (0, 15, 30, and 45 t/ha) in order to:

1. evaluate the effect of PG application on salts, nutrients, and trace elements removal in the leachate of saline/sodic soils,
2. investigate the impact of different PG rates on soil physical properties of different saline/sodic soils,
3. assess the effects of PG on barley and faba bean yield, nutrient uptakes, and heavy metal contents under saline/sodic conditions
4. compare the effects of PG and natural gypsum on salt leaching, soil physical properties, nutrient uptakes and crop production.

In parallel, a two-year field experiment was carried out to

Table 13. *Fertilising effect of PG on several crops [117]*

Crops	PG rates (kg/ha)	Effects
Rice	1.125	Developed the stems and reduced the lodging
Cotton	2.250	Boosted the vegetative development
Soybean	2.300	Yield increased by 16%
Malten Barley	1.500-4.500	Yield increased by 8.3-46.3%
Feed Barley	1.500-4.500	Yield increased by 43.3-50.0%

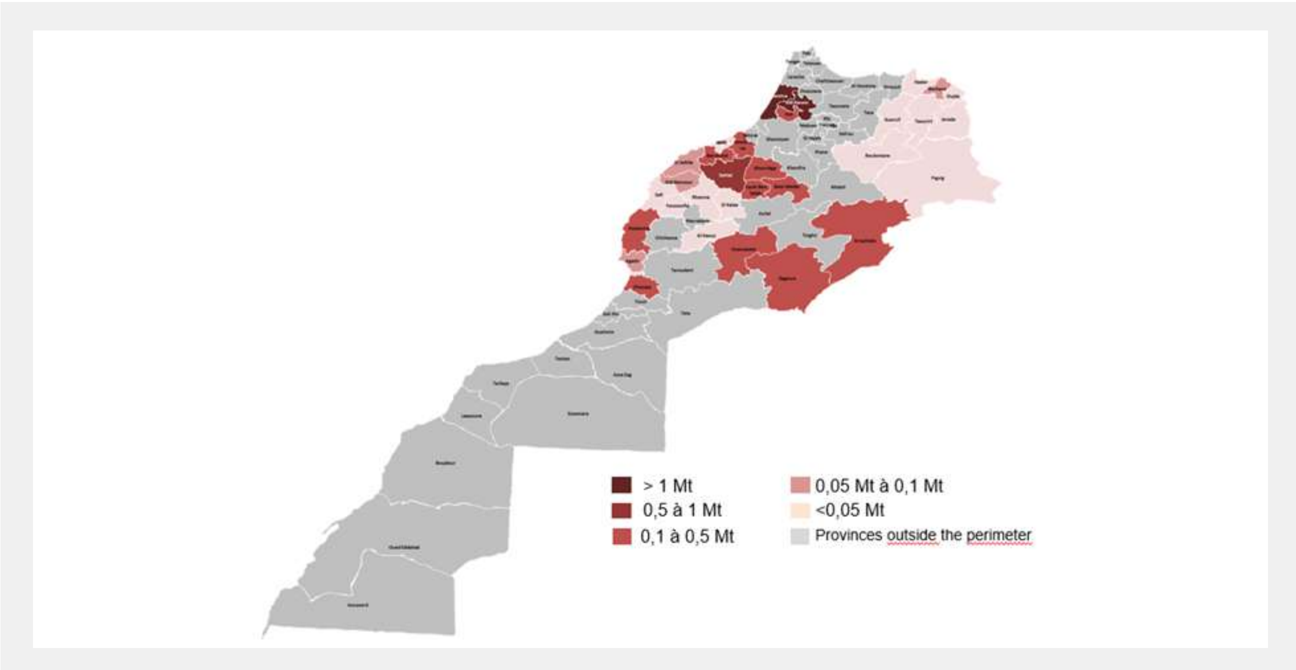


Fig. 107. *Estimated annual PG demand as soil amendment, Morocco*

evaluate the effects of two different Moroccan PG sources as low-cost fertiliser, using four PG different application rates (0, 1.5, 3, and 4.5 t/ha) on soil fertility and barley yield components. The wider objective was to assess PG environmental impacts on soil, in addition to on barley straws and grains.

The findings from pot experiments showed that phosphogypsum application removed a significant quantity of salts from saline soils, especially sodium. Phosphogypsum furnishes soluble calcium to substitute exchangeable sodium, improving soil physical properties: water aggregate stability, total porosity, and bulk density. Applying phosphogypsum was associated with an increase in barley and faba bean straw and grain yields and nutrient uptakes. For the sanitary and environmental aspects, the results showed that phosphogypsum did not engender a significant transfer of heavy metals to straw, and grains. The comparison between phosphogypsum and natural gypsum showed that the two amendments perform equally, assuming they used at the same application rates. The field trial findings revealed that as the rate of phosphogypsum increased, barley yield components were significantly enhanced (number of spikes, tillers, grains, total biomass, grain yield, and thousand grains weight).

When compared to the control, the application of 1.5, 3, and 4.5 t/ha of PG remarkably increased grain yield by 21%, 34%, and 39% respectively under field conditions. The uptake of nutrients by barley straws and grains was significantly enhanced by the PG application rates. Equally positively, applying PG had no discernible impact on the heavy metal content of the soils, straws and grains. It was concluded from this field trial that phosphogypsum application was an efficient amendment for saline/sodic soils as well as a fertiliser without affecting soil and crop sanitary quality (see published articles). However, a thorough investigation of the sanitary and environmental impacts of using phosphogypsum necessitates longitudinal monitoring of soils, plants, and water quality based on heavy metal and radioactive element content as related to the rate and frequency of different crops and applications.

Does Phosphogypsum Application Simultaneously Affect the Leaching of Salts, Nutrients, and Trace Elements From Saline Soils?

A pot experiment was undertaken to evaluate the comparative impact of phosphogypsum (PG) and natural gypsum (G), to successfully remove salts in leachates of water from saline and saline-sodic soils, but which also had the unwanted effect of leaching nutrients and beneficial trace elements at the same time. The purpose of the experiment was to determine the relative efficiency and safety of these amendments as an affordable strategy, for overcoming salinity and sodicity stress.

The PG at 0, 15, 30 and 45 t/ha and G at 15 t/ha were mixed with the upper 9 cm soil in the pot before being leached. The soils were collected from Sed El Masjoune and Sidi El Mokhtar areas of Morocco with ECe of 140.6 mS/cm and 11.7 mS/cm respectively. The highest doses of PG ($\geq$30 t/ha) removed a significant quantity of both salts and nutrients. Calcium sulphate exchanges calcium ions to replace salt ions especially sodium, in the process beneficially replacing the damaging sodium salts which are leached from the soil. The PG was more efficient than natural G in salt leaching. Quantities of trace elements in the leachate for most analysed elements were below the recommended limits of drinking and irrigation water, hence had little negative impact on the healthy growth of the plant. And the experiment's overall alkaline conditions (basic water and soil) reduce the solubility and mobility of trace elements. The amendment application did not affect saturation index (SI) of the main minerals. However, water passing through the soil increased the SI which could potentially result in groundwater mineral precipitation. [118]

Effect of Phosphogypsum on Soil Physical Properties in Moroccan Salt-Affected Soils

The study aimed to evaluate the effect of PG on the physical properties of the soils collected from four regions: Chichaoua, Ras El Ain, Sidi Zouine, and Sed El Masjoune in Morocco. The treatments consisted of different rates of PG (15, 30, and 45 t/ha), natural gypsum (G) (15 t/ha), and control. Their findings revealed that PG application improved soil structure by promoting flocculant action provided by calcium. Linear regression indicated that water aggregate stability (WAS) and PG doses were strongly correlated with a high coefficient of determination ($R2 = 93.41\%$, P value < 0.05). Compared to the control, the overall efficiency of 45 t/ha of PG amendment reached 53%, 95%, and 36%, respectively, in Chichaoua, Ras El Ain, and Sed El Masjoune soils. PG application presented a positive effect on other soil physical properties (soil hydraulic properties, total porosity, and bulk density), especially for the soils of Chichaoua and Ras El Ain regions. The total porosity was increased by 8% with 45 t PG/ha in Ras El Ain soil, and in Chichaoua soil, the bulk density was 5% lower in the pot treated with 45 t PG/ha compared to the control. This study supports the use of PG as an amendment for reclaiming saline/sodic soils through monitoring agronomic and environmental impacts [107].

Effect of Phosphogypsum on Faba Bean Yield and Heavy Metals Content Under Saline-Sodic Conditions

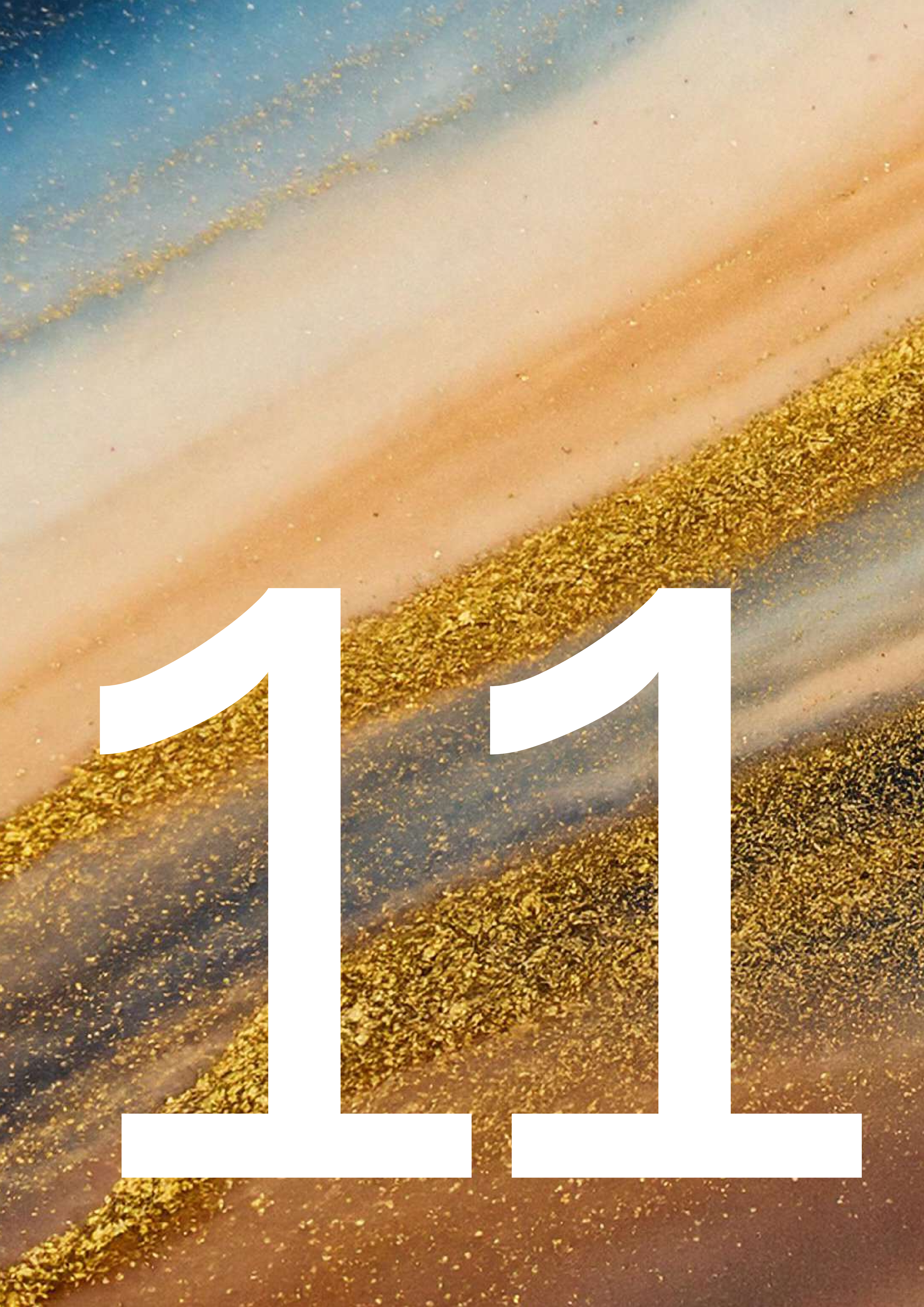
Salinity and sodicity are among the most severe abiotic stresses that cause significant losses to agricultural production, especially in arid and semi-arid areas. In this study a pot experiment was carried out to evaluate PG and gypsum as amendments and their effect on faba bean shoot and grain yield under saline-sodic conditions (Soil ECe=11.17 mS/cm, Water EC=1.5 mS/cm and Water SAR=4.2 meq/l). In addition, the safety of this application was investigated based on assessing the uptake heavy metal content in the harvested grain. Results from this study have shown that applying 30 and 45 t/ha of PG increased grain dry weight by 52% and 62%, respectively, when compared to the control. This supports the hypothesis that PG could substitute for natural gypsum, potentially reducing the pressure on this natural resource and promoting sustainable agricultural practices. Grain heavy metal contents were below the recommended limits and similar across treatments [106].

Evaluating the Effect of Phosphogypsum Source and Rate on Barley Yield Components, Nutrients Uptake, and Heavy Metals Content under Saline-Sodic Conditions

A pot trial was conducted under greenhouse conditions to evaluate the effects of different sources of PG on soil salinity/sodicity mitigation in comparison with G and consequently on barley yield components and heavy metal uptake. Three treatments were tested: two PG sources from two different phosphate industrial sites (PG1 and PG2), applied at four rates (0, 15, 30, and 45 t ha-1) and G at one rate (15 t ha-1). Results showed that the weights and number of spikes and tillers, grain yield, and 1000-grain weight were all improved in the presence of PG application. Remedial PG applications using PG from both source sites, PG1 and PG2, enhanced yields by a remarkable 61% and 59% respectively, across rates compared to the control (0 t ha-1). Shoot and grains nutrients uptake were enhanced by PG addition with no effect on heavy metals contents of barley's grains and shoots. PG and G were equally effective in enhancing barley yield and nutrient uptake. Importantly, the study showed that shoot and grain heavy metals contents were similar, regardless of the treatments [112].

Phosphogypsum as Fertiliser: Impacts on Soil Fertility, Barley Yield Components, and Heavy Metals Contents

A two-year field experiment was conducted using two Moroccan PG products (PG1 and PG2), obtained from two different industrial sites. The PG was applied at four rates (0, 1.5, 3, and 4.5 t/ha). The aim was to assess the impact of PG source and rate on barley crop, including yield component, nutrients uptake and heavy metals content. The study findings revealed that as the rate of PG application increased, so there were significant enhancements in the number of spikes, tillers, total biomass, grain yield, and thousand grains weight. In fact, when compared to the control, the application of 1.5, 3, and 4.5 t/ha of PG led to a marked increase in grain yield by 21%, 34%, and 39%, respectively. Likewise, the uptake of nutrients (N, P, K, Ca, Mg, and S) by the shoots and grains was significantly influenced by the PG application rates, with higher rates resulting in greater nutrient uptake. Notably, the application of PG had no discernible impact on the heavy metal content in shoots, grains, or soil [112].


11

CHAPTER ELEVEN

AFFORESTATION OF PHOSPHOGYPSUM STACKS FOR RECLAMATION AND BENEFICIAL USE IN SITU, CANADA

Author: Connie Nichol, Nutrien

1. Introduction – Closing a Phosphogypsum Stack in Canada

Perhaps because the event is so rare, there are no guidelines or regulation regarding phosphogypsum stack closure in Canada. Traditionally, gypsum stacks are regarded as a waste by-product or phosphoric acid production residue and reclamation involves contouring the piles, covering with soil and seeding to a grass mixture.

In the belief that more satisfactory solutions could be found for managing the end of life of a PG stack, in collaboration with the University of Alberta in 2005 Nutrien began conducting research into alternative methods of reclamation. In the last 18 years, out of the collaboration between university and company, eight students have earned their MSc. degrees working on different aspects of achieving this goal, a significant gain in social capital as well as supporting environmental gains such as CO_2 sequestration and biodiversity enhancement. Little did we realise at the start that the process would literally organically develop into a viable small-scale anthrosol business for planting fast-growing trees in carefully tailored soils suited to the prevailing climatic conditions in Alberta.

1.1 Building the Pathway to Sustainable PG Stack Closure and Reclamation

Initially research projects examined the depth of soil needed to cover the PG stacks and what grasses to seed, but over time it became apparent that it was beneficial to mix soil into the gypsum to create an anthrosol rather than using a barrier approach to reclamation. PG/soil mixes were shown to result in greater vegetation health and biomass over plants grown in soil alone. Once soil was mixed into the gypsum and the rooting depth of vegetation was no longer an important consideration, growing trees could be considered, creating the possibility of reducing long term maintenance costs and sequestering carbon dioxide to combat climate change.

Nutrien then partnered with the Canadian Wood Fiber Center (CWFC)and Natural Resources Canada (NRCAN) to test the possibility of establishing concentrated woody plantations on the PG stacks. Nutrien follows the protocols developed by NRCAN to develop high yield afforestation plantations that maximise biomass and carbon accumulation over the short to medium term. Typically, these types of plantations are established on moderate to high quality land across Canada but have proven to be very successful on the PG anthrosol. Natural Resources Canada has published a handbook entitled Methodology for the Reclamation of Phosphogypsum Stacks in Canada Using Afforestation (see Figure 108) [119].

The goal of this operations guide is to assist those who seek to establish and manage fast-growing, high-yield afforestation plantations for the vegetation of phosphogypsum (PG) stacks. The approach offers an innovative reclamation option that makes beneficial use of PG rather than treating it as waste. CWFC operational researchers envisioned an opportunity to use the industrial waste in situ as a vital input to a favourable environment for the growth of trees. In likely the first effort of its kind, CWFC in partnership with Nutrien Inc. has established and grown a forest on a PG stack[67].

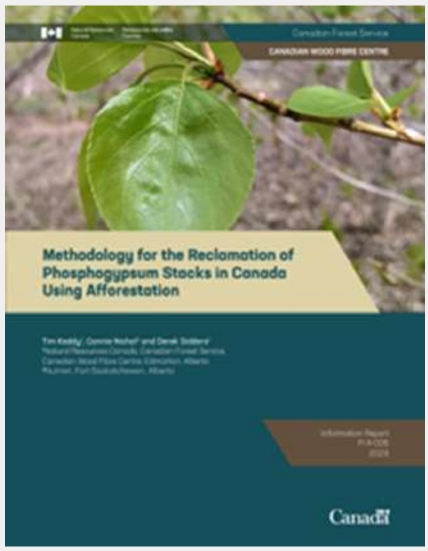


Fig. 108. *Methodology for the Reclamation of Phosphogypsum Stacks in Canada Using Afforestation*

The outcome to a significant extent speaks for itself: "There are multiple long-term benefits of establishing mixedwood forests on PG stacks. These benefits include increasing carbon sequestration, improving long-term ground water quality, increasing wildlife habitat and ecosystem biodiversity, and enhancing long-term sustainability while reducing long-term maintenance costs" [118].

1.2 Tree Selection

In the prairie provinces of Canada, the primary tree species to be considered for high yield and carbon sequestration afforestation is hybrid poplar (Populus spp). Hybrid poplar

67 For Methodology for the Reclamation of Phosphogypsum Stacks in Canada Using Afforestation see https://publications.gc.ca/site/eng/9.921583/publication.html

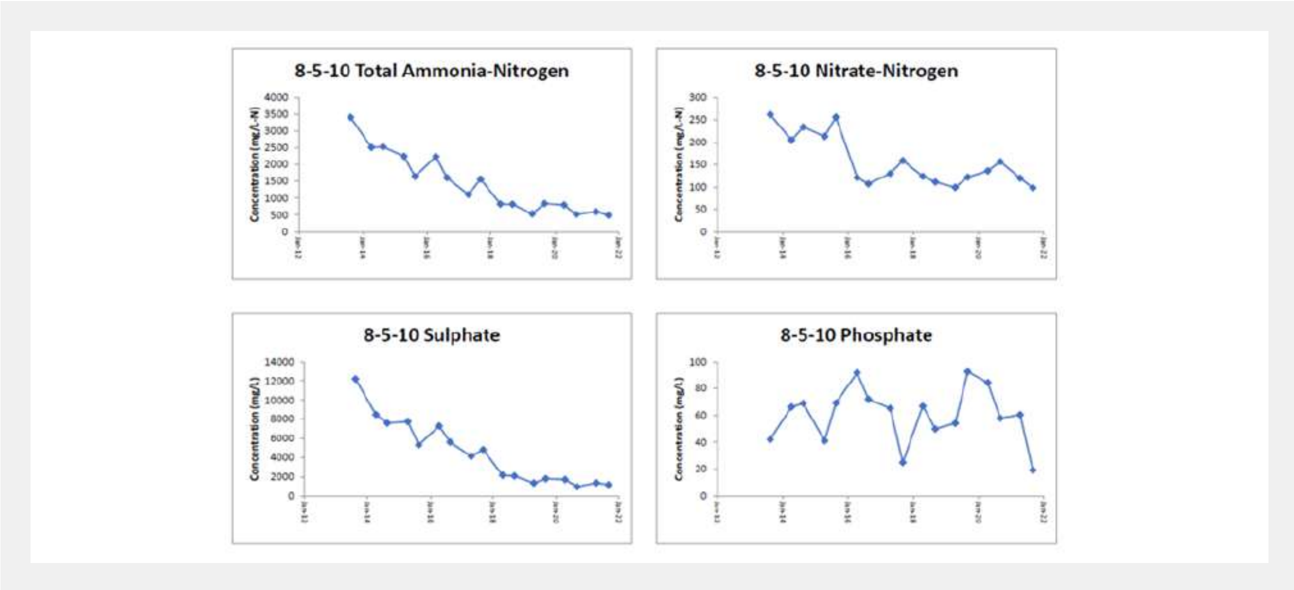


Fig. 109. *Groundwater quality enhancement in PG Plantation area: 10-year time series June 2012 – June 2022 by Stantec Consulting for Nutrien*[71]

plantations of 1100 – 1600 stems/ha produce yields of 13.6 – 20 m^3 or 7.3 – 10.8 ODT (oven dried tonnes) ha/yr of above ground woody biomass. The preliminary assessments of below and above ground carbon budgets estimate potential carbon increase of 500-650 t CO_2 eq/ha over a 20-year rotation, or 25 – 32.5 Mg CO_2 eq/ha/y. Hybrid willows (Salix spp) are also suitable for high yield and bioenergy development. Plantations of 15,625 stems/ha were designed to produce yields of 6 – 12 ODT (oven dried tonnes) ha/yr of above ground woody biomass. Preliminary assessments of below and above ground carbon budgets estimate potential carbon increases of 14 – 28 Mg CO_2 eq/ha/y over 6-7 three year rotations.

1.3 Planting Design for Short and Long Lifecycles

Natural Resources Canada has also designed a mixedwood afforestation plantation [118] using hybrid poplar and white spruce that is designed to maximise biomass accumulation, carbon sequestration and fibre production over both the medium (20 years) and long term (70 years) through the development of both hardwood and softwood crops. Preliminary assessments of below and above ground carbon budgets estimate potential carbon increases of 644-820 Mg CO_2 eq/ha/yr over the 20 and 70 year rotations for the respective hardwood and softwood crops. Establishing a forest on top of PG stacks has many positive impacts on the environment.The afforestation approach to PG stack reclamation will increase carbon sequestration and generate carbon dioxide offsets as well as produce biomass for energy production. Trees are also capable of phytoremediation of any excess nutrients and water within their rooting zone, thereby improving long term groundwater quality (see Figure 109) [120].

Figure 109 shows the steady decline in concentrations of ammonia, nitrate and sulphate in a groundwater well adjacent to a reclaimed gypsum stack. Monitoring under research conditions has shown that there is no water infiltration into the gypsum stack under the concentrated tree plantations in the semi-arid climate of the Canadian prairies. The evapotranspiration rate exceeds precipitation.

2. Building the Plantation – First Cycle

In 2016 and 2017, hybrid poplar tree plantations were established on 20 ha of phosphogypsum (PG) at the Nutrien facility in Fort Saskatchewan, Alberta, Canada[69]. The trees are growing extremely vigorously. After 5 years of growth, the trees are approximately 7 meters in height and 7 cm diameter at breast height. They continue to grow at a rate between 1.5 and 2 meters a year. Crown closure was observed after less than three years. This inhibits vegetation growth beneath the trees, with the site essentially left in a free-to-grow state without any need for maintenance. Trees are observed to be growing much

68 Data provided by Connie Nicholl, Personal Communication to General Editor, September 30, 2024

69 See Local news James Bonnell, Nutrien Fort Saskatchewan expands phosphogypsum reclamation forest June 08, 2023. https://www.fortsaskatchewanrecord.com/news/nutrien-fort-saskatchewan-expands-phosphogypsum-reclamation-forest

faster on the gypsum stacks than the same trees growing on regular soil. This is likely because the PG has excellent water holding capacity and some residual plant nutrients.

2.1 Gathering Carbon Credits

The tree plantations established at Nutrien are predicted to sequester 30 Mg CO_2 equivalents/ha/year. Thus, in 20 years, the gypsum stack area reclaimed to date will sequester 12,000 metric tonnes of CO_2 equivalents. This same area is also predicted to produce 10 ODT/ha/year of above ground woody biomass; therefore, it is estimated that 4,000 green tonnes will be produced in this area over the next 20 years[70]. These numbers will continue to increase as Nutrien continues to reclaim and establish concentrated woody plantations on their PG stacks. The economic benefits of afforestation can be substantial. Carbon credits are worth CA$80/tonne in Alberta as of 2025, a figure rising by 2030 to CA$170/t. Natural Resources Canada estimates in principle that the afforestation protocol using the hybrid poplar planting design at Fort Saskatchewan can sequester 500 – 650 t CO_2 eq/ha over a 20 year period. From this range estimate, it is calculated that the 20 hectares of forested gypsum stack can potentially generate between CA$850,000 and $1.1 million in carbon credits over 20 years (2024-25 CA$ values). The cost of establishing a short rotation woody crop is approximately $3,800/ha, therefore afforestation pays for itself in a few years. If desired, woody biomass could also be sold. According to Index Box, the price of wood pellets in Canada varies by type of pellet and market but can range from $150–$280 per tonne[71].

It is also important to consider that once the trees close canopy, maintenance is essentially eliminated, so the reduction in maintenance and mowing costs compared to a grassed PG stack can be significant. Incorporating trees into the reclamation plan also improves the long-term sustainability and ecosystem diversity of the gypsum stacks. Increased wildlife such as deer, rabbits, foxes, small rodents and many birds have been observed in the forested areas.

2.2 Decommissioning, End of Life, and Renewal

In 2022, Nutrien used the afforestation approach as a strategy to decommission a historical phosphate cooling pond that was highly contaminated with ammonia and metals. The pond was filled with gypsum from the adjacent stacks and compacted. The area was contoured and then 15 cm of soil was mixed into the phosphogypsum to create a good seed bed. Approximately 25,000 hybrid poplar seedlings were planted in the 17 hectare reclaimed pond/gyp stack area the following spring. It is believed (and will be confirmed in the future with university research projects) that the tree roots will act as a 'phyto-cap' and prevent water infiltration into the underlying contaminated pond sediments, thereby improving groundwater quality in the area. The regulator had no objection to this project and accepted it as a risk management strategy. From an economic perspective, trees are much cheaper than purchasing and servicing synthetic liner.

Fig. 110. *Gypsum Stack Reclamation Preparation (Image courtesy of Nutrien)*

On June 8, 2023, the company announced it was expanding the plantation footprint:

> *Through this initiative, Nutrien's Fort Saskatchewan Nitrogen Facility has already planted 44,000 trees on 20 hectares of phosphogypsum. On June 5, in partnership with Project Forest and Trees for Life, the site began expanding on this project, kicking off plans to plant an additional 26,000 hybrid poplar trees over 17 hectares.*
>
> *"We're really pleased to announce that the company has taken a very proactive approach on a lot of our environmental initiatives, a number of projects were pushed through last year, including this one,"* said Ted Sawchuk, General Manager for Nutrien Fort Saskatchewan. *"So, we had a budget of $5 million to regrade, topsoil, and plant an additional 26,000 trees on our gypstack. We're in the process right now of planting those trees, which will bring our site up to over 70,000 trees."* [69]

For a visual synopsis of the evolving Nutrien Afforestation project see Figures 110-116.

70 See Natural Resources Canada, High-yield Afforestation.

71 See Index Box market analysis https://www.indexbox.io/search/wood-pellets-price-canada/#:~:text=The%20average%20wood%20pellets%20export,12%25%20against%20the%20previous%20year.

Fig. 111. *1 year-old Hybrid poplars in May 2024 (Image courtesy of Nutrien)*

Fig. 112. *Historic Phosphate Cooling Pond before Reclamation and Afforestation (Image courtesy of Nutrien)*

Fig. 113. *Phosphate Cooling Pond after being filled with PG and contoured (Image courtesy of Nutrien)*

Fig. 114. *Planting tree seedlings by hand on gypsum filled pond (Image courtesy of Nutrien)*

Fig. 115. *1 year Hybrid poplars in August 2024 (Image courtesy of Nutrien)*

Fig.116. *Hybrid poplar trees on reclaimed gypsum stack after 7 years of growth (Image courtesy of Nutrien)*[75]

72 https://www.nutrien.com/what-we-do/stories/nutrien-transforms-local-industrial-site-17-hectare-forest

CHAPTER TWELVE

REFORESTATION AND COMBATING DESERTIFICATION WITH ANTHROSOLS – AN OCP PATHWAY

Compiled and edited: PG3 General Editor and Specialists from Aleff Group, reviewed and finalised by OCP and UM6P. Original source materials provided in particular by Abdelaziz Nilahyane (ASARI), Dennis Ashilenje (ASARI), Amina Alaoui Soulimani (UM6P), Kamal El Omari (OCP).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1. Introduction

The United Nations Convention to Combat Desertification (UNCCD) was adopted on October 14, 1994, and came into force on December 26, 1996[73]. This was some twenty years before the signature of the Paris Agreement in 2015 and the signing by Heads of State of the UN Sustainable Development Goals (UNSDGs) which came into force January 1, 2017. SDG 13 concerns Climate Action.

Desertification, whether through causes such as poor soil and forestation management, deforestation or overgrazing by livestock, is not just a desert issue, but affects the whole planet. However, the public visibility of the Convention has never equalled that of the Paris Agreement, yet the root causes are identical. Desertification manifests most acutely where perhaps the most critical of all resource nexuses food, energy, and water prevail at intense levels of stress.

Combating desertification at global scale is very challenging as the risks of land degradation and soil infertility are increasing due to climate- and human-related processes. Many innovative policy changes and related intervention programmes have however been undertaken to combat desertification worldwide. For instance, afforestation, reforestation, and desert greening approaches have been adopted to restore degraded lands by improving overall soil health.

One very promising way to enhance soil health status while sustainably promoting circular economy and resilience is by using phosphogypsum (PG) as soil amendment or anthrosol for improving soil fertility and structure. PG offers a range of proven benefits to revitalise degraded soils. As a consequence, PG amendment for example enhances resource use efficiency such as of nutrients and water while contributing to the resilience of vegetation and soil life to climate stress. No doubt, PG use on a significant scale can benefit the source company and country as well as neighbouring regions with pressing needs to mitigate or reverse the effects of climate change across a range of applications. Hitherto, in some countries PG use has been limited due to the general perception that it contains excessive levels of radioactivity and heavy metals. But depending on the appropriate sampling, characterisation and monitoring procedures and applying a graded approach to regulation, PG can be used to scale with full confidence [6].

1.1 Desertification

Arid lands cover 45.4% of the Earth's surface, dominated by poorly formed soil profiles and sparse vegetation. The global trend is towards restoring arid lands through assisted revegetation with selected tree species.

The Sahara is the largest desert in the world. It stretches over a significant area of Africa, occupying over 9,000,000 square km (roughly the size of the United States) and covering some 30% of the entire continent. The arid and desert regions of the Sahara have several constraints such as no/low rainfall (<100 mm annual rainfall), high soil salinity (>25 dS m-1 in many locations), poor soil fertility resulting from low soil organic matter and phosphorus, and gradual degradation of soil quality, primarily due to irrigation using highly saline water. These factors jeopardise the establishment of trees and the production of annual and perennial crops.

Consequently, the Sahara region is entirely desert or barren with no significant vegetation. Massive sand encroachment (especially in the windy coastal region) is causing increasing land degradation and progressive desertification. These pose an existential threat to almost all life, compounded by the high risk of overexploitation without sufficient effort to regenerate natural resources. The large-scale sand encroachment diminishes soil ecosystem services and threatens the viability of agricultural livelihoods in arid lands. The challenge of sand encroachment becomes more complicated by climate change, population growth, overgrazing, wasteful human activities, migration, and urbanisation associated with the conversion of arable land and other fertile soil to housing and industry.

1.2 Morocco – a Net Carbon Sink

While in the south Morocco reaches directly into the Sahara region, the country is increasingly climate stressed, marked by scarce water resources. Rainfall events are rare or ineffective, triggering overdependence on and the threat to water aquifers. Despite these circumstances, Morocco has achieved the remarkable status of a net carbon sink (see Figure 117).

73 United Nations Convention to Combat Desertification, https://treaties.un.org/pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-10&chapter=27&clang=_en#:~:text=26%20December%201996%2C%20in%20accordance%20with%20article%2036(1).&text=Signatories%20:%20114.,Parties%20:%20197.&text=United%20Nations%2C%20Treaty%20Series%20%2C%20vol,force%20of%20Annex%20V)2.&text=The%20Convention%20was%20adopted%20on,York%20until%2013%20October%201995.

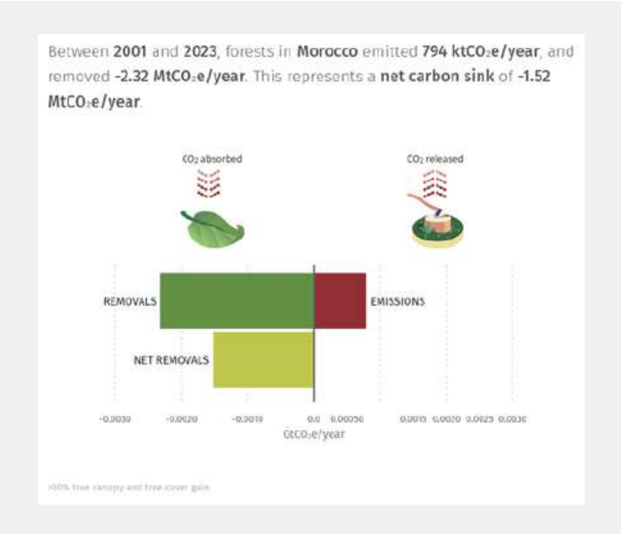

Fig. 117. *Morocco – as net carbon sink*[74]

Safeguarding this status is one of the key responses the country can make to meeting SDG13 Climate Action goals. This is not a simple matter of merely planting more trees and sequestering more organic matter in agricultural land. An integrated holistic approach is needed that relies heavily on the country's institutions of higher learning, including UM6P, with the support of the tangible and intangible resources of OCP.

A popular but underused tangible resource is PG, especially when combined with other such highly valuable secondary resources in the P resource nexus, including beneficiated phosphate sludge (PS) and sewage sludge (SS) rich in phosphorus. In the framework of a circular economy, these products are rapidly being absorbed into the overall nutrient economy making positive contributions to the balanced, integrated management of the national and regional P budgets[75].

1.3 Surprise Discoveries Breed Sustainable Solutions

In the particular field of (re)forestation, two unrelated fertiliser production site remediation projects associated with PG use were started in 2015 – the first in India and the second in Alberta, Canada. In India, the goal was to rehabilitate a PG storage area causing dust issues, while in Canada, the plan was to neutralise a high-pH ammonia pond using PG. Both projects led to the planting of trees, initially for landscaping purposes, with unexpected results.

1.3.1 Redwater

In Alberta, Canada, in the context of highly rainy region, the trees showed rapid growth, which a study found was linked to the PG content in the soil. The trees thrived in a soil mix of 80-90% PG, leading to enhanced growth and carbon sequestration, which generated profitable carbon credits. This approach has since been considered a model for large-scale carbon farming projects[76].

1.3.2 Paradeep

In Paradeep, India, growing conditions were initially challenging for the tree species planned for landscaping the remediated PG storage area. However, with the use of an inoculant during establishment, the trees took root and began to grow with vigour. Two seasons later, a severe monsoon struck the area, causing residents to be evacuated and the site to be submerged in seawater. When returning to the site, it was expected that the trees would be uprooted by stormy winds or killed by the seawater. Neither of these outcomes occurred. The trees were still standing, thanks to the strong growth of their root mass, and they likewise tolerated saline water.

The trees were able to tolerate the saline water, thanks to the modifying effect of PG-amended soils. A subsequent controlled irrigation of the trees with saline water confirmed that the conditions were conducive to the growth of certain native species. In fact, these positive attributes of PG application are now regularly observed in other parts of the world, such as Brazil, where trees have shown similar resilience.

1.3.3 Case Studies presented at IFA Delhi March 2016

Both case studies, from Canada and from India were presented to the fourth IFA PG Working Group meeting in Delhi, March 2016 and event also marked by the first of IFA's PG reports. Both reported unexpected but highly significant results, which have redefined the way in which we now approach using PG as a high-performance anthrosol component for use in reforestation and combating desertification worldwide.

Building on this knowledge and its own research and development in Morocco at the same time, OCP developed a complementary knowledge base, focused on mine site remediation and combating desertification. But as the options for storing and using large quantities of PG on land (including costs) are carefully weighed up, the anthrosol envelopment strategy looks highly promising. The drive is on to extend the range of applications from remediation and restoration to creating extensive

74 See Global Forest Watch https://www.globalforestwatch.org/dashboards/country/MAR/?category=climate&location=WyJjb3VudHJ5IiwiTUFSIl0=&map=eyJjYW5Cb3VuZCI6dHJ1ZX0=

75 For the concept of the Phosphate Budget, see European Soil Data Centre (ESDAC): https://esdac.jrc.ec.europa.eu/themes/phosphorus-budget-topsoils#:~:text=The%20main%20P%20inputs%20are,P%20inputs%20with%20manure%20application.

76 See case studies in both IFA PG1 and IFA PG2.

stretches of new growing media, which have the added financial advantage of saving significant levels of CAPEX investment in creating new PG storage facilities.

1.4 Mine Site Remediation

Phosphogypsum use per se, as was the case for Canada and India, was not the initial driver of change towards the use of PG-based anthrosols for reforestation in Morocco. It was rather the motivation to test a new approach to mine remediation. This was premised on reestablishing ecosystems in mined out areas, and bringing the land back overall into socially, environmentally, and economically viable development.

For several years, OCP began a major reforestation drive around the inland phosphate mines (Figure 118).

Fig. 118. *Mine remediation through forestation (Image Courtesy OCP)*

By 2023 a total of some 6,110 ha of trees had been planted (3,905 ha by 2018 (Figure 119)) which at a planting density of 850 trees/ha, a standard forestation planting metric in Morocco, equates to 5,193,500 trees. From 2018, new soil mixes started to be tested using secondary resources such as PG and rock beneficiation residues, to very good effect (Figure 120).

> *This mechanism of restoring plant cover encourages reforestation and tree planting and promotes best sustainable agricultural practices around rehabilitated mining fields. It also creates a multiplying effect through demonstration platforms that display in field conditions the impact of plant cover encourages reforestation and tree planting and promotes best sustainable agricultural practices around rehabilitated mining fields. It also creates a multiplying effect: through demonstration platforms… demonstrating in field conditions the impact of such mixed on rehabilitation and improvement of low quality soils*[77].

This opens up a very fruitful approach to land management using soil amendments across a spectrum of applications which, taken together, create and "recreate new spaces giving life to future projects, creating economic value (to the land) and creating jobs for the surrounding communities and villages".

Through the mining rehabilitation program, the OCP Group is preparing the ground upstream, for the development of future production & industrial projects"[79].

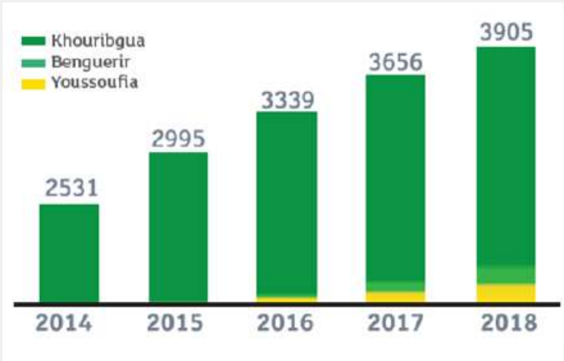

Fig. 119. *Hectares of phosphate mine land rehabilitated per year (2014-2018)*[78]

Soil management	2019	2020	2021	2022	2023
Hectares of rehabilitated land	864	305	204	342	**490**

Fig. 120. *Hectares of rehabilitated land 2019-2023*

With the pending availability of much higher volumes of PG for such applications there will be no shortage of feedstock.

77 See OCP Fact Sheets, Land Use, April 2020, https://ocpsiteprodsa.blob.core.windows.net/media/2021-06/H_OCP%20Lande%20use_ENG_HD.pdf

78 For OCP Sustainability Integrated Report (2023), see https://ocpsiteprodsa.blob.core.windows.net/media/2024-07/OCP_Sustainbility_Report_2023_0.pdf

1.5 The Moroccan Context for PG Use in Reforestation and Combating Desertification

Morocco is the world's largest phosphate exporter and out of the total PG produced commercially globally, it accounts for around 18%. In the context of reforestation and combating desertification, OCP has responded favourably to the opportunity of using phosphogypsum, mixed as needed with other components to make substrate/anthrosol (man-made soil) to improve soil health, vegetation growth and surface cover and prevent sand encroachment and wider desertification.

1.5.1 The Developing Knowledge Base

By 2021, the scientific basis of using secondary raw materials from different stages of the P resource value chain was being actively studied and reported in the peer-reviewed literature, led by UM6P on behalf of OCP. By 2024 it was evident that proper value-added application of this coproduct has economic, environmental, and social benefits.

The positive effects of PG in ameliorating soil properties and increasing crop yields are well documented [14][6]. It contains phosphorus, a significant amount of calcium, sulphate, and other plant nutrients and has the potential to improve soil health [120]. It contains components such as calcium oxide, silicon, iron, titanium, magnesium, aluminum, and manganese and can be used for the reclamation of saline and sodic soils. Its optimal application (as a substrate/anthrosol and soil amendment) boosts plant growth, prevents desertification, and improves agricultural production by enriching soil nutrients. PG application rates and mixing ratios with soil and sand vary with soil and sand type, application site, and crop or tree species.

1.5.2 Complementary Secondary Phosphate-Bearing Raw Materials

Phosphate mining and processing generates large quantities of by-product such as phosphogypsum (PG), phosphate sludge (PS) and phosphate tailings (PWR) that currently in Morocco are simply stored rather than valorised [120][121]. In complement to the mining process, urban wastewater treatment generates large amounts of nutrient rich sewage sludge (SS) the volume of which is rapidly increasing with population growth in cities and related industrial development. As the circular economy gathers momentum and supply-chain security for P features more and more in government policies recovering and reusing all potential sources of secondary phosphate becomes essential [79].

Various methods have been adopted either to use or to dispose of phosphate by-products and sewage sludge, such as landfill, selective combustion, sea disposal and farmland application. All these methods, however, have their limitations, such as requiring expensive and extensive landfill sites or having various unfavourable environmental impacts.

1.5.2 PG Anthrosol as Soil Ameliorant

The development of anthrosols has been proposed as a new environmentally friendly approach to ensuring the successful revegetation of phosphate mining sites. Phosphate industry by-products such as phosphogypsum (PG), phosphate tailings or "waste rock" (PWR), phosphate sludge (PS), together with plant nutrients containing sewage sludge (SS) and topsoil (TS) can all be valuable resources in restoring the ecological balance of soils from mined out sites. Of the challenges faced during site rehabilitation, the extensive physical disturbance to the site through mining coupled with the inherent environmental challenges posed by the arid/semi-arid climate, make land rehabilitation under such circumstances particularly difficult.

Against that background, the development of anthrosols has been proposed as a new environmentally friendly approach to ensuring the successful revegetation of former phosphate mining sites. So, the main objective of the anthrosol study carried out jointly by OCP and UM6P was to evaluate various combinations of readily available PG, PS, and PWR, with SS and TS as growing media first in pot trials under glass and then, if successful, in field trials at the mine site to be rehabilitated itself.

1.5.3 Greenhouse Pot Trials with Italian Rye Grass

First steps were taken using PG from Jorf Lasfar with combinations of all five components to grow Italian Ryegrass over a four month period under glass [122].

1.5.3.1 Rye Grass: Trial 1 – PG for Mine Site Reclamation

As potential growing medium ingredients for mine site reclamation, all five components demonstrated value, at different performance levels in different combinations. From a PG perspective 65% PG performed consistently well, especially with 5% SS mixed in. The PG demonstrated excellent moisture retaining properties at between 15% and 26% showing "the addition of PG was responsible for the high values of water holding capacity observed" [121]. Heavy metal content was found to be low and the chemistry of mixes tended also to immobilise some elements indicating that these could be regarded as non-polluting.

79 See https://www.linkedin.com/company/um6p-asari

The proportion of 65% of PG enriched the substrate in phosphorus and hence improved the crop yield. The addition of 5% of SS contributed to a significant improvement of rye-grass aerial biomass. In the absence of SS application, the addition of nitrogen is required to maintain crop growth. For large-scale application, topsoil from mine overburden (T) can be mixed with PS, SS and PG for mine site reclamation.

1.5.3.2 Rye Grass: Trial 2 – PG for Remediating Soil Sodicity

Using the same experimental structure and resources, rye-grass growing under glass in a variety of soil mixes, a complementary analysis was undertaken as to the value of PG and other anthrosol ingredients tto controle soil secondary salinisation/sodification [123]. In that respect the best performing anthrosol mix is 65% PG + 30% PS + 5% SS. Of course, that mix is also effective in preventing sodification of mining soils when low quality water is used: "phosphogypsum associated with sludges can be used as an amendment to reclaim mine soil affected by sodicity" [122].

1.5.4 Field Trial with Trees – 1. Argan, Carob and Olive

Building on the knowledge and experience gained from the ryegrass studies, a three-year field trial was undertaken at the Ben Guerir mine site using three selected species of tree: Argan, Carob, and Olive. These were planted in a 50cm deep layer of the 65% PG, 30% PS and 5% SS anthrosol successfully tested on Italian ryegrass. The planting design employed a randomised block layout design with six replicates. [124]

1.5.4.1 Objectives – Science

The scientific objective was to evaluate the interaction dynamics of the three selected species in the moisture-retaining PG based soil-plant system of nutrients and heavy metals.

The three axes of investigation are summarised as:

i. Growth parameters determination (height and diameter) of different fruit trees (argan, olive, and carob).
ii. Evaluation of the dynamic of nutrients (N, P, K, Ca and Mg)
iii. Evaluation of the dynamics of heavy metals (Pb, Cd, Cr, Cu, Ni and Zn)

Achieving the objective of this study will make it possible to assess the degree of effectiveness of this new approach in arid and semi- arid climates, with a view to adopt it as a new rehabilitation technology for large scale application in rehabilitating phosphate mining sites [123].

1.5.4.2 Objectives - Policy

The OCP policy frame is also the reference point for the strategic business case for these PG Anthrosol trials:

> *OCP adopts circular growth for its environment, and its communities, while minimising the environmental impact. Rehabilitation of mining sites and valorisation of phosphate by-product as well as wastewater treatment are at the heart of OCP strategies. Thus, the development of anthrosols from phosphate industry by-products and sewage sludge could be a sustainable strategy" to minimise rehabilitation costs by using available secondary raw materials and risks of either rehabilitation failure or negative environmental impact [123].*

PG-based growing media are proving a cost effective alternative for improving plant-growing conditions on degraded mine site soils, but close attention was to be paid in the trial to the potential of the new anthrosol mix to leaching any contaminants from the mix to the environment.

1.5.4.3 Findings – Argan "Best of Breed"

After three years of growth, the results of the study showed that the PG/PS/SS mix supported the growth and development of argan, olive and carob (Figure 121) trees which could be used for successful revegetation of the phosphate mine site.

Fig. 121. *Carob Tree - 3 year growth*

Because of its ability to grow despite its low water content and its ability to withstand drought stress, the Argan tree [123] is the species with the best results.

Each of the three species independently had a bioconcentration factor (BCF) less than 1, demonstrating a low transfer

Fig. 122. *False Pepper- 3-year growth*

Fig. 123. *Eucalyptus - 3-year growth*

of heavy metals. Nutrients and heavy metals were monitored in soil-plant system by analysing soil at different depths and soil samples. Soil samples were taken at the beginning of experiment and two years later at 0-10, 10-20 and 20-30 cm. The movement of heavy metal in the soil was very low and did not constitute any hazard for groundwater pollution. Microbial load was also evaluated and showed a diversified microflora similar to that of trees grown in conventional soil.

1.5.5 Field Trial with Trees – 2. Pistachio, False Pepper and Eucalyptus

Wholly complementary to the study on Argan, Carob and Olive and on the same PG/PS/SS mix is the simultaneous study of Pistachio, False Pepper (Figure 122) and Eucalyptus (Figure 123) [125].

1.5.5.1 Findings – 2. Pistachio, False Pepper and Eucalyptus

In general terms, False Pepper and Eucalyptus outperformed Pistachio in terms of growth, and in respect of the contribution the two better performing species can make to the mine remediation and rehabilitation objective, the results are very promising. For the ingredients of the mix, PS is available on site, but PG and SS would have to be trucked to site.

As specific findings, [124] difficulties for restoring soil quality and fertility on mined out sites include chemical limitations such as low organic matter (OM) content, low cation exchange capacity, low levels of available nutrients and, in some cases, the presence of potentially toxic elements above those tolerated by the soil biota and plants For phosphate-mined areas, the P content is significant still, but not in plant-available form, while the available carbonate and calcium sources may not be well tolerated by some plant species. Against that background, the PS/PG/SS combination represents a sustainable practice of reuse of secondary raw materials designed to support the successful revegetation of mine sites in a range of ways enhancing planting and growth conditions for trees at planting or establishment (especially root matter), significantly higher moisture retention in semi-arid soils, offering a range of plant nutrients, and increased carbon capture in both the trees and their soil.

Heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), copper (Cu), and zinc (Zn) may accumulate at the surface of mine sites represent another limiting factor for plant growth while also impairing rapid establishment. The findings from this experiment at Ben Guerir suggest that providing the young trees with the PG, PS, and SS complexes reduces root contact with heavy metals, improves tree root formation and delays any potential toxicity level build-up in plant tissues at an early growth stage.

1.6 Combating Desertification with Innovative Anthrosols

Phosphogypsum from different OCP production facilities in Morocco has been successfully trialled as substrate (mixed with other components, see section 1.5 above) for establishing native trees to restore existentially damaged eco-systems, restore biodiversity and enhance carbon sequestration. In particular the PG fraction of the anthrosol ameliorates the arid saline soils for efficient use of mineral nutrients and water, a benefit of high significance in Morocco itself.

Against that background, and from the strong evidence base that has now been assembled nationally in Morocco and from studies of a similar kind around the world, the logical next step on the pathway to a commercial-scale delivery process focuses on developing scalable technologies/solutions to combat desertification and restore degraded soil in sand-encroached sites of Southern Morocco and further afield.

1.6.1 Parameters and Questions for the Next Stage of Development

Two parameters are key to designing the next steps towards scale-up:

- PG characterisation and attributes vary across rock source or beneficiated source rock mix and cannot be assumed to perform uniformly.
- PG valorisation has to be adapted both to specific tree species grown in a range of semi-arid/ arid conditions.

With these factors in mind the development phase is designed to find long-term solutions for combating desertification by addressing the following questions:

1. What is the influence of phosphogypsum substrate formulations (anthrosol/man-made soil) on soils and selected tree species establishment/survival and growth in typical arid conditions of the Sahara Desert, as in the goal to contribute to the Great Green Wall initiative?
2. What are the optimum levels of phosphogypsum substrate formulations to keep heavy metals below acceptable limits and maximise soil health and tree species growth?
3. What are the impacts of phosphogypsum substrates on tree species ecosystem services including desalinisation, carbon sequestration and forage production?
4. How can best practices of phosphogypsum valorisation be integrated into a techno-economically scalable model that enhances the social and economic wellbeing of a resource stressed population as a deliverable to the Great Green Wall Initiative?

1.6.2 A Two-Stage Approach

These questions are addressed in a 'two stage' experiments in the greenhouse and field conditions and empirical phosphogypsum substrate optimisation models.

The specific objectives of this project are to:

1. Develop phosphogypsum-based optimal substrates under different climate and soil conditions to improve tree species growth for 'Great Green Wall' development.
2. Strengthen the technical capacity of local stakeholders, local community, partners, and farmers.
3. Develop a techno-economic scaling strategy to deliver an integrated desert greening technology/solution for the 'Great Green Wall Initiative' regions of the Sahara.

1.6.3 Adding Farmyard Manure to the Reusable Resources for Anthrosols

It is expected that a combination of salt tolerant tree species, phosphogypsum and phosphate tailing, combined with farmyard manure[80] as available, will enhance soil nutrient supply, tree species growth, and ecosystem services relevant to the desert greening initiative in southern Morocco and beyond into the GGW. While the "big picture" reaches towards the Great Green Wall Initiative, the national social, environmental and economic gains feature equally prominently in the business rationale.

2. Convergence of OCP Approach and UNCCD Science Policy Framework

A systematic alignment has been undertaken between OCP's approach and the science policy framework recommended by the UNCCD, the key aspects of which are set out below.

2.1 Land Degradation Neutrality

A fundamental objective for UNCCD in Combating Desertification is to reach Land Degradation Neutrality (LDN). The procedure is set out in the UNCCD document, **Integrated Land Use Planning and Integrated Landscape Management for Land Degradation Neutrality**[81] [126]. The anchor policy aspects are:

1. Science-based evidence on the potential contribution of integrated land use planning (ILUP)
2. Integrated landscape management (ILM) to positive transformative change

80 See case study in PG1 from Canada on successfully combining PG and FYM on a dairy farm in Canada

81 For UNCCD text see https://www.unccd.int/sites/default/files/2023-09/UNCCD Integrated Land Policy Brief.pdf

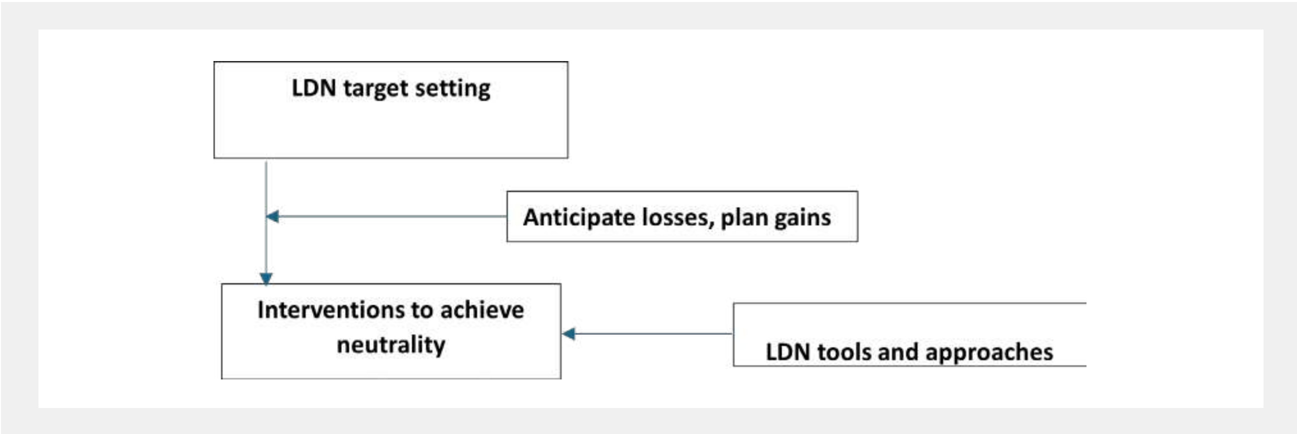

Fig. 124. *Land Degradation Neutrality model, UNCCD [132]*

3. Achieving Land degradation neutrality (LDN)
4. Addressing desertification, land degradation, and drought issues (Decision 18/COP.14).

The UNCCD Science-Policy document further states: "The neutrality principle - also known as the zero net principle - requires landscape planning and management efforts that go beyond a consideration of individual land parcels and sustainable land management practices to embrace national planning. This allows unavoidable losses to be compensated and enhance landscape diversity (e.g., socioeconomic, ecological, and cultural) to optimise the LDN response hierarchy (i.e., avoiding, reducing, and reversing land degradation)" [125].

2.2 UNCCD Implementation Guidelines

The model suggested by UNCCD1 is shown in Figure 124. The following guide principles are set out by UNCCD [125].

- National land use planning systems provide the immediate context in which LDN targets are set and implemented. The relationship between these national planning systems and how LDN is being pursued in a country will determine the suite of ILUP-ILM tools and approaches most suitable for LDN target setting and implementation.
- The integration of LDN into the land use planning system of a country must be achieved through a national, long-term vision that integrates the interests of multiple sectors with different demands for land resources. This vision requires sufficient financial support and a land governance system that is designed to enable the achievement of LDN.

The overall goals may be summarised as follows:

- integrate LDN target-setting and implementation into national and subnational ILUP and ILM processes
- strengthen cross-sectoral governance and land use planning for transformative change to support efforts to address desertification/land degradation and drought and to achieve LDN
- incentivise collaboration between academic/research and practitioner communities specialising in land use planning to develop new or tailor existing tools and approaches
- promote national knowledge generation and sharing of approaches and tools to support ILUP and ILM to achieve LDN.

There are five generic phases of cyclical ILUP-ILM planning processes:

1. description and assessment,
2. visioning,
3. planning,
4. implementation
5. monitoring and evaluation.

Achieving LDN requires more than just scaling up sustainable land management. Realising the neutrality principle is most effective when it is integrated into existing national planning systems that govern the use of natural resources for development.

When implementing LDN, the monitoring and evaluation phase contributes to learning so that mid-course adjustments based on lessons learned can be made. Thus, the results from the monitoring and evaluation phase of LDN should feed into subsequent planning processes in the form of new knowledge and understanding, contributing to future land use planning decisions.

In this context, the Action Plan and its policy anchored business strategy, as formulated by OCP for implementing the project 'Combating desertification in the Southern regions of Morocco' is fully consistent with the UNCCD Science Anchor Policy approach.

2.3 Anthrosol Mixtures and Their Suitability for Selected Plant Species

2.3.1 Greenhouse Study

The Greenhouse stage involves chemical characterisation of different formulations of phosphogypsum, phosphate tailing, desert soil and farmyard manure and test their influence on substrate chemical elements and establishment (survival/growth) of tree saplings. The process started in 2023 and uses PG from Jorf Lasfar production plant 5 (JLV).

Based on the results of this process, empirical models that identify phosphogypsum substrate ratios that maximise nutrient supply can be derived. The objective is to identify the most appropriate substrate (anthrosol) compositions that alleviate salinity and heavy metals while maximising tree sapling establishment and growth.

2.3.2 Field Testing

In the second step, field experiments to test the influence of the best phosphogypsum substrate mix combined with irrigation regimes on establishment, survival and growth of selected tree species and ecosystem services in, or on the margins of, the Sahara Desert will be conducted. Based on the findings, local communities will be engaged in capacity building to develop and adopt a technoeconomic scalable model for desert greening as a pioneer GGW initiative in Morocco.

2.4 Capacity Building, Participation and Involvement of Local Communities and Stakeholders

To develop and deliver suitable training, wider capacity building and dissemination of information but also to facilitate a smooth progressive roll-out of the PG-based anthrosol technology in GGW countries, the project also envisages hands-on knowledge transfer workshops in Laayoune, Morocco. At least two representatives from neighbouring countries, Mauritania and Senegal, will be invited to attend the workshops in person and five to 10 further participants from these partner countries will take part virtually.

The workshops are expected to be complemented by two farmer training courses, combining field visits, group discussions and workshops with involvement from local communities, co-operatives and other stakeholders.

3. PG Substrate Formulation Project for Combating Desertification

3.1 Establishment

A greenhouse experiment was set up in March 2023, at the UM6P African Sustainable Agriculture Research Institute (ASARI)[82]. The objective of the study was to identify the most appropriate substrate (anthrosol) compositions that alleviate salinity and heavy metals while maximising tree sapling establishment and growth. The study included sixteen different phosphogypsum substrate formulations tested in a randomised complete block design [120]. These substrate mixes were applied to one selected tree species Tamarix aphylla. The substrate formulations were mixed at different ratios of phosphogypsum, phosphate tailings (ST), desert soils, and farmyard manure (FYM) and respective treatments were in propagation pots with 20 × 20 cm top dimensions and 30 cm height.

Follow-on field experiments are designed to test the influence of the best phosphogypsum substrate mix combined with irrigation regimes on establishment, survival and growth of selected tree species and ecosystem services in or on the margins of the Sahara Desert.

3.1.1 Sources of Substrate Components

The local soils are predominantly loose xerosol obtained from Foum El Oued, Laayoune. Cow farmyard manure composted for ~2 years was obtained from a farm near the Sakia El Hamra Dairy Cooperative in Foum El Oued. Phosphogypsum was sourced from the OCP Jorf Lasfar Fertilizers Company V production plant (JFCV). Phosphate tailings were obtained from the OCP facility in Laayoune.

3.1.2 Seedling Procurement

Seedlings of Tamarix were obtained from the National Forestry Nursery in Foum El Oued. All trees were irrigated using tap water every two days until established followed by weeks of stabilisation when irrigation treatments were varied. Irrigation treatments for PG formulations (treatments) 1 to 15 were composed of tap water with low salinity (EC value of 3 dS m-1). Trees in treatment 16 were maintained on saline water with EC of 10 dS m-1. A uniform irrigation regime of 700 ml twice per week was administered such that there was no excess drainage.

82 See https://www.linkedin.com/company/um6p-asari/

Fig. 125. *Tamarix saplings without phosphogypsum (T2) and those with phosphogypsum (T16, saline water), T12 and T13 from the greenhouse study.*

3.2 Data Collection and Analysis of PG Mix Anthrosols

Data was collected between March and October 2023, including initial characteristics of substrates, tree sapling survival, growth, and dry matter. Each sample was collected from individual anthrosol mixes of PG, phosphate tailing, soil and manure substrates [120].

Salinity and pH were determined using an EC/pH meter. The substrate pH and salinity values were measured again in October 2023. Plant height was measured in May and October 2023 and growth was determined as the incremental height during this period (see Figure 125 for graph of greenhouse grown plants in varying PG-anthrosol mix and Figure 126 for greenhouse building).

The Dickson Quality Index (DQI) was included as a measure of sapling performance. This metric was computed as indicated in Equation 1: [127]

$$\mathbf{DQI = TDW/ [(SH/CG) + (SDW/RDW)]} \qquad \text{Eq. 1}$$

where, TDW is total sapling dry weight (shoot and roots), SH is shoot-height, CG is crown girth, SDW is shoot dry weight and RDW is root dry weight. Dry weights were obtained after oven drying plant samples at 60°C for 72 hours.

Substrates were analysed at the UM6P-AITTC soil labs using the Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) to detect the concentration of heavy metals.

Substrate properties and sapling growth parameters were subjected to ANOVA to determine treatment effects ($p < 0.05$). The ANOVA was based on the general linear model procedure of statistical package, in R software version 3.6.3. (R Core Team, 2022). Treatment means were compared in the post-hoc test using Fisher's protected LSD test ($\alpha = 0.05$).

Model parametrisation and optimisation was conducted in the Design Expert software version 13. [128] The initial multivariate included the independent factors phosphogypsum, phosphate tailing and soils with variants of 5% and 10% manure. Model iterations were performed to find outputs that maximise phosphogypsum in the substrate and keep salinity and levels of heavy metals below the acceptable thresholds.

Along with these, the aim was to realise the best range of substrate organic matter and bulk density that maximises Tamarix sapling DQI. To realise this, the mixture design of experiment was conducted in the following steps:

1. Setting model constraints to maximise phosphogypsum while phosphate tailing, and soil were left unbound. In any scenario the mixture added up to 100%.
2. A screening analysis of variance to determine significant regression model and coefficients ($p<0.05$) for each response variable. The linear, quadratic, cubic, and two factor interactions were explored to determine significant fit to the data set.
3. Model fit and validation using QQ plots and contour plots.

4. Graphical optimisation to identify domains for optimal combinations.
5. Numerical optimisations with preset constraints of response variables and identification of the most desirable combinations of factors.

Fig. 126. *Greenhouse interior ASARI Experimental Farm (Courtesy UM6P)*

3.2.1 Phosphogypsum Substrate Mix Properties

As indicated in Table 14, after nine months of Tamarix growth in substrates amended with phosphogypsum and phosphate tailing, salinity reduced by a range of 0.6 to 5.3 dS m^{-1}. PG in a mixture with soil and manure with less saline water slightly salinised the substrate by a range of 0 to 2.9 dS m^{-1} unlike 2.2 dS m^{-1} increase in salinity of the substrate irrigated with saline water with EC of 10 ds m^{-1}.

Phosphogypsum is known to have acidifying effects on propagation media immediately after application. This was the case initially after phosphogypsum amended substrates with 5% manure developed acid to slightly acidic (pH of 5.7 to 6.4) conditions (Table 14). But nine months later, phosphogypsum tended to moderate pH in these substrates under Tamarix saplings to a slight to moderately alkaline range (7.6 to 8). The same scenario was witnessed in the media with phosphogypsum, soil and 10% manure in which pH increased from 6.6 to 7.5. The rating of substrate pH is according to FAO soil classification. [129] The final slightly alkaline conditions are most favourable for the availability of most nutrients particularly nitrogen, phosphorus, potassium, calcium, and sulphate. This range of pH also tends to optimise microbial enzymes activity [130] with implications for nutrient cycling and most importantly for substrate bioremediation against heavy metals. [131]

3.2.2 Growth Monitoring

After ~ 9 months of growth, there were no significant variations in the quality of Tamarix saplings or Dickson Quality Index in response to varying formulations of PG substrates. The range of DQI of Tamarix was 1.8 to 3.1 and 1.4 to 3.9 on substrates amended by 10% and 5% manure, respectively (Table 15). It is worth noting that saplings grown on substrates without PG and non-saline irrigation water had generally the least DQI. Same applied to phosphogypsum supplemented saplings irrigated with 10 dS m^{-1} water.

Radiological measurements are ongoing.

3.2.3 Phosphogypsum Substrate Optimisation Models

Figure 127 displays graphical optimisation overlay plots for phosphogypsum, phosphate tailing and soil formulations with 5% and 10% manure against the dependent variables of soil physical and chemical properties, heavy metals, and Tamarix sapling quality (Dickson Quality Index). The domains for optimisation of respective substrates are marked by the region shaded yellow. While constrains for various dependent variables were set according to the maximum tolerable levels in the soil set at 3 ppm [132], 100 ppm [133], 60 ppm [134], 20 ppm [131], and 100 ppm [131] for cadmium, chromium, barium, arsenic, and lead, respectively. Response variables, whose maximum tolerable levels were outside the range of our data set, were excluded from the optimisation criteria.

Using these tools, we found the domain that kept the levels of Cd and Ba in phosphogypsum substrates with 5% manure content below their maximum tolerable limits respectively of 3 and 60 mg kg^{-1}. The rest of the heavy metals had a range of values all below the maximum permissible limit. With this accounted for, and an allowance for maximum possible inclusion of phosphogypsum in the substrate mix with 5% manure, the model predicted DQI levels as high as 4. Likewise with constraints for maximum phosphogypsum in substrates of 10% manure, the domain for optimisation predicted levels of heavy metal below the maximum permissible limits. Unlike the substrates with 5% manure, DQI optimisation extended to relatively lower values of 3 in the graphical optimisation of the PG substrates with 10% manure.

Further optimisation of the analytical models will help identify the optimum substrate compositions associated with minimised heavy metal content and optimum growth of saplings.

Table 14. *Variation of salinity (EC) and pH March - October 2023*

Treatment	PG	St	Soil	Manure	EC1:5			pH	
					Initial	Final		Initial	Final
	%				dS m-1				
PG	100				5.2			2.5	
St		100			3.2			7.8	
Soil			100		0.7			8.5	
Manure				100	16.2			8.3	
T1	0	50	50	10	3.0	1.8		8	8.3
T2	0	0	100	10	2.1	2.7		8.5	8.5
T3	75	0	25	10	4.9	6		6.6	7.5
T4	75	12.5	12.5	10	5.6	5.5		6.7	7.6
T5	37.5	0	62.5	10	4.4	3.9		6.9	7.5
T6	0	25	75	10	2.5	3.4		8.3	8.2
T7	37.5	50	12.5	10	8.5	4.4		7	8.3
T8	37.5	25	37.5	10	5.1	3.9		6.9	7.8
T9	18.75	25	56.25	10	4.7	5.2		7.1	7.7
T10	56.25	16.25	27.5	10	4.4	5		6.9	7.6
T11	0	50	50	5	2.6	1.7		8.1	8.6
T12	37.5	0	62.5	5	3.5	4.7		6.2	7.6
T13	37.5	50	12.5	5	5.3	4.7		5.7	8
T14	37.5	25	37.5	5	3.9	4.5		6.1	7.9
T15	56.25	16.25	27.5	5	4.1	3.5		6.4	7.7
T16	56.25	16.25	27.5	10	4.9	6.3		6.4	7.7

Table 15. *Dickson Quality Index (DQI)* [138] *of Tamarix aphylla sapling nine months after establishment on PG substrates*

Treatment	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16
DQI	2.5	1.8	3.1	2.7	3	1.8	2.6	2.4	2.5	2.6	1.4	3.6	3	3.2	3.9	1.4

3.2.4 Stakeholder Engagement and Confidence Building

To date, no replicate experiment along these lines has been conducted elsewhere. Third party review and verification of these findings is welcome and will reinforce the credibility of the results obtained. This will help convince stakeholders in Morocco and surrounding countries that there are no issues of concern with either radionuclide content or other trace quantity constituents in the particular PG used for developing innovative PG anthrosol mixes. To this end, eventual support of IAEA accredited PG experts and certified laboratories recognised by national authorities, ISO and participating in IAEA NORM materials ring-testing will also be beneficial.

The planned to-scale deployment phase will be accompanied by a detailed monitoring programme of both soil and plants. Such a programme will keep all stakeholders informed as to progress and findings and in the process set a baseline for future evidence-based protocols for regulating and monitoring the use of PG in a wider range of target climate stressed agro-environments and soil conditions.

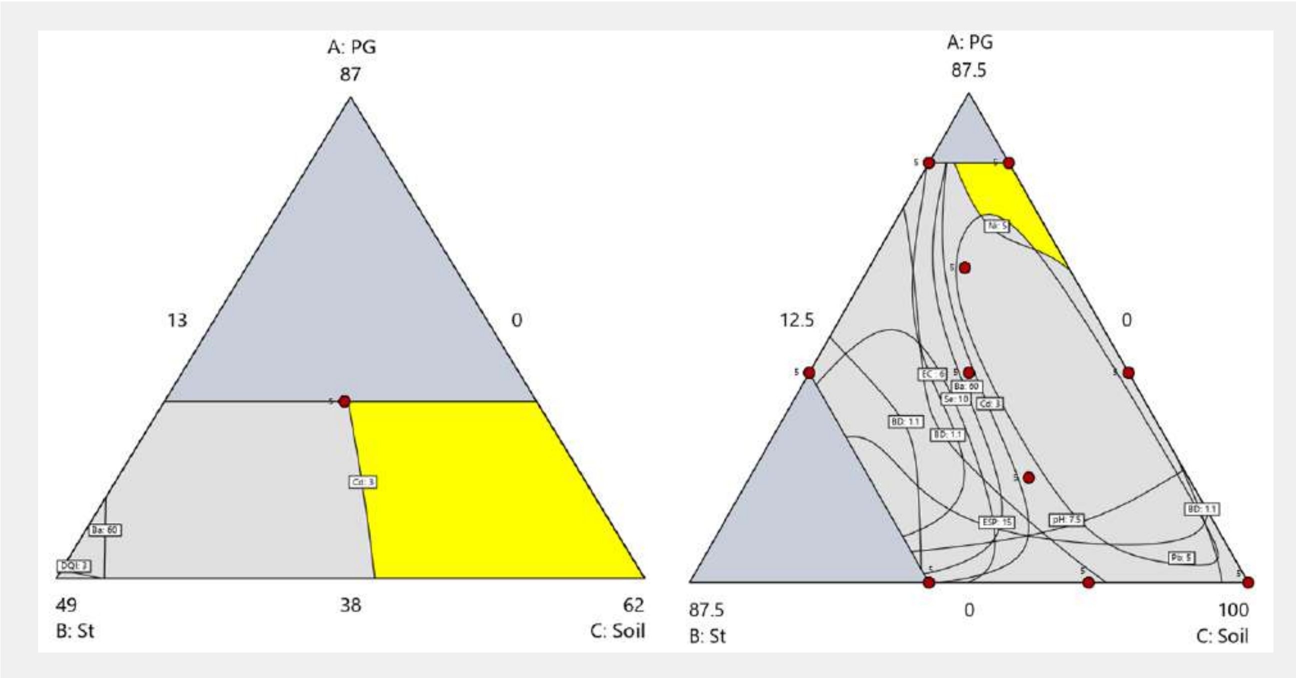

Fig. 127. *Overlay plot showing the graphical optimisation of phosphogypsum, phosphate tailing and soil formulations with 5% manure (left) and 10% manure (right) against the dependent variables of soil physical and chemical properties, heavy metals, and Tamarix sapling quality (DQI)*

3.3 Comparative Findings - India using PG from Moroccan Rock

Use of PG in agriculture in India was permitted unrestricted under the Graded Approach from late 2008 by the Atomic Energy Regulatory Board[83] and the Central Pollution Control Board[84] after extensive laboratory and field testing. In particular, both radionuclide and heavy-metal content were assessed and found to be below regulatory limits. As a comparative data set it has direct relevance to the situation in Morocco as the PG produced in India is largely derived from Moroccan rock concentrate.

At a commercial scale, Paradeep Phosphates Limited (PPL) has supported thousands of field trials and demonstrations on various crops across all states in India based on locally grown crops. These studies have been conducted both by independent agricultural universities and by PPL's own agricultural experts and with the active participation of farmers. The specific goals were to:

1. measure the effect of PG on the growth, yield, and the yield characteristics of different crops,
2. determine the residual effect of PG on succeeding crops,
3. assess the effect of PG application on soil, groundwater, and crop quality especially with respect to fluorine,
4. undertake adsorption and leaching studies in the laboratory to assess the extent of adsorption and rate of leaching of fluorine,
5. establish PG as safe fertiliser for agricultural use,
6. compare the relative efficiency of PG as a source of sulphur against mineral gypsum and single super phosphate.

The application of S to S-deficient soils using PG increases the yield of oil-producing seeds, paddy, wheat, pigeon pea and mung bean, a clear farmer-centred business case as the lead beneficiary. The results have demonstrated that PG is most affordable and best source of S available in India, points also made in IFA PG2 [14].

Field trials were conducted across India on a range of crops studying the effect of PG on crop productivity, crop quality and environmental impact.

As an example, general observations of the renowned Odisha University of Agriculture and Technology (OUAT) were that:

1. PG helps to improve crop quality especially oil and protein content in oil seed and pulses

83 For AERB Directive No. 01/09 see https://www.aerb.gov.in/english/acts-regulations/safety-directives

84 For CPCB Guidelines for PG Use see http://www.indiaenvironmentportal.org.in/content/395562/guidelines-for-management-and-handling-ofphosphogypsum-generated-from-phosphoric-acid-plants-final-draft/

2. gypsum can be used to improve the quality of acid soils
3. doses of PG for growth enhancement vary from crop to crop
4. PG does not significantly lower the soil pH[85]
5. combined application of a lower dose of lime with PG showed better results for acid soils
6. PG is a good, affordable source of S. Its efficiency is as high as other sources of S
7. PG contains radionuclides, notably 226Ra, but its use in agriculture is not restricted by AERB as these limits are well in line with naturally-occurring background levels
8. no significant impact of fluorine is found with the use of PG.

The findings of such studies clearly contributed to the general conclusion of the Indian regulatory authorities that PG may be used in Indian agriculture without restriction.

3.4 Steps Forward Towards Commercial Scale Application

Results from the greenhouse study at ASARI indicate that PG can modulate substrate properties providing an ample range of salinity and pH for nutrient availability to tree saplings. Against this background, Tamarix aphylla was identified as a more resilient species with potential to maintain high survival rates in Morocco when exposed to increasing intensity of substrate salinity. The results also suggest that manure use should be limited relative to PG and that irrigation needs to be sequenced in a manner to avoid soil surface crusting and detrimental buildup of salts in the field. The careful ratio of PG versus manure can also help avert substrate consolidation and allow for free distribution of water across the profile.

Tests will be continued to determine Tamarix, Prosopis, and Acacia uptake of heavy metals and nutrients from different phosphogypsum formulations in the greenhouse and fields. Consequently, correlations between substrate and plant accumulation of heavy metals and their critical levels in test tree species for safe use as forage will be determined. With these data, specific guidelines for phosphogypsum substrates in the context of resources and conditions in the Sahara Desert will be developed. Several substrate mixes are being used in the treatments to test the establishment of tree species in two sites of Southern Morocco.

4. The Great Green Wall

The Great Green Wall initiative for Africa is a flagship project for UNCCD[86].

85 This finding is not the case in regions with high pH soils, eg 8.2 and higher where PG has been observed to lower pH values to 6 or even lower depending on dose.

86 For the Great Green Wall Initiative - UNCCD, see https://www.unccd.int/our-work/ggwi

The GGW initiative's ambition, to which OCP will contribute new options, is to restore 100 million hectares of currently degraded land; sequester 250 million tonnes of carbon and create 10 million green jobs by 2030. This will help communities living along the Wall to grow:

- one of humanity's most precious natural assets: fertile land
- economic opportunities for the world's youngest population
- food security for millions in the GGW region that go hungry every day
- climate resilience in a region where temperatures are rising faster than anywhere else on Earth
- a new world wonder spanning 8,000 km

Eleven countries are officially taking part Burkina Faso, Djibouti, Eritrea, Ethiopia, Mali, Mauritania, Niger, Nigeria, Senegal, Sudan, and Chad. Fortunately, Morocco, which was not a founding member of the GGW project, is now taking a lead to inject new momentum into the project by creating linkages with Mauritania and Senegal.

Progress on GGW establishment has to date been slow with only Senegal achieving a major breakthrough in recent months where the first self-propagated seedlings have taken unassisted from the first generation of planted trees. The commitment of Morocco to contribute to the next stages of the GGW, and thereby bridge through Mauritania to link up with Senegal is a decisive advance to regional scale. In fact, an agreement between the OCP Foundation and the Senegalese Agency for Reforestation and the Great Green Wall (ASERGMV) was signed in June 2022 in Dakar, to support the project and the preservation of biodiversity[87]. It may be anticipated that PG-based anthrosols will be a critical advantage in making that link at a regional scale.

4.1 GGW Strategic Axes

The activities under the GGW are structured around five major strategic axes, which are equally applicable to Southern Morocco:

1. Sustainable land management and green economy (SLMGE)
2. Climate change, socio-economic development and governance in the localities (CCSEDG)
3. Support research and development (R&D)
4. Communication, marketing and advocacy (CMA)
5. Information system, observatory, early warning and response (ISOEWR).

87 See https://afrique.le360.ma/maroc-senegal/societe/2022/06/27/38520-senegal-le-groupe-marocain-ocp-offre-14-milliard-fcfa-la-grande-muraille-verte-38520/

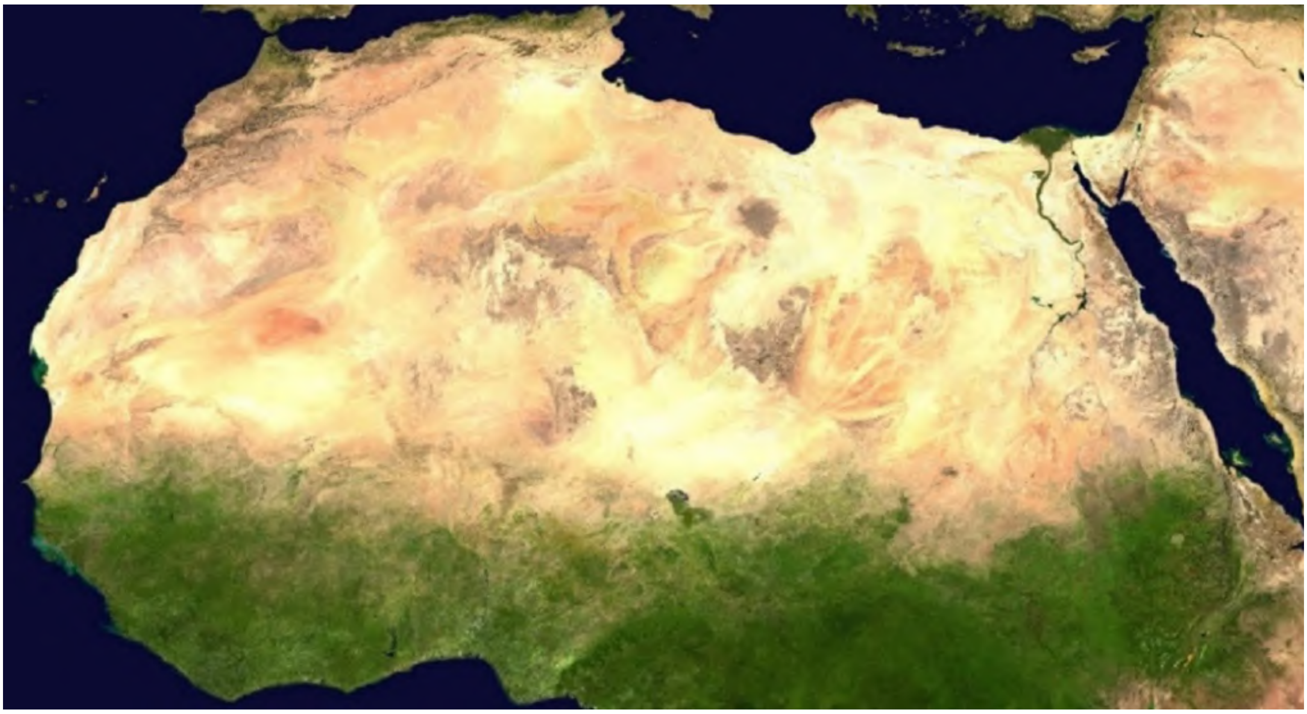

Fig. 128. *Satellite view of desertified land in the Sub Saharan Africa*

Desert greening and control of sand encroachment might bring several opportunities to rehabilitate the degraded land and prevent desertification, both in the South of Morocco and in the wider Great Green Wall region countries of SSA. To achieve this goal, collective action and unified policy on sustainable land management are required.

Further, the protection and growth enhancement of tree species (tree, shrub, and bushes) that are well-adapted to local conditions is the key to fight against desertification, restoring and regreening the desert (see Figure 128). Development of integrated good agronomic practices (especially irrigation and fertiliser) and soil amendment with PG improves the growth of dominant tree and annual crop species which ultimately helps in combating desertification, improves fertility of the desert soil and increases economic, environmental, and social sustainability in the desert. Native tree species with drought tolerance and multiple purposes (fruit, fodder, forage, medicine and construction) have more hope of restoring the original ecosystem and have the potential to contribute to the achievement of objectives of the Great Green Wall Initiative of the UNCCD [126].

5. Conclusions

The need for combating desertification through tree establishment (survival & growth) in desert conditions can be addressed by formulation of phosphogypsum substrates (mixes to be used as man-made soil/anthrosol) that optimise tree establishment without adverse effects on the environment.

To contribute to this goal, OCP's approach is fully aligned with that of the UNCCD. The studies conducted by OCP indicate that substrates (anthrosols) containing phosphogypsum, phosphate tailings, soils from the Sahara Desert and FYM have low profiles of heavy metals. The results identify formulations that maximise the survival rate and growth of planted trees, keeping the heavy metal concentrations in the soil below the maximum permitted levels. Since the optimisation is based on initial substrate chemical properties, the substrate interaction with plants could further invigorate tree establishment in arid conditions.

More widely, strengthened involvement of Morocco in the GGW project will potentially allow the high-volume use of PG and other secondary resources as anthrosols to the major strategic cause of combating desertification, aligned nicely to UNCCD scientific guidelines and values [125]. Benefits are diverse and include:

- Boosting global implementation of forestation and soil amendment for food, fibre and crops production (cash)
- Water and other nutrient use efficiency from anthrosol use
- Forest cover / commercial (re)forestation with high performance anthrosol

- Offset of urban development forestation land loss with anthrosol which grows trees
- Carbon sequestration
- Biodiversity and habitat enhancement, microclimate modification
- Social capital enhancement - science and technology capability for climate action intervention
- Assistance to regional neighbours with reforestation and overland woodland management
- Bridge along the Great Green Wall between neighbouring countries.

SECTION C

BREAKING OUT


1

CHAPTER ONE

THE GREAT REVERSAL – FROM POTENTIAL HAZARD TO ALPHA THERAPEUTIC: DMT PILOTS PHOSPHOGYPSUM INTO THE PHARMACEUTICAL MARKET

Author: Michael Haschke, DMT Group, Essen, Germany

1. Introduction

The radionuclide content (mainly Radium as Ra-226) of phosphogypsum (PG) is among the main challenges when recycling PG as main fertiliser by-product. Various radiation limits (e.g. U.S. EPA limit 10 pCi, equating to ~ 370 Bq/kg for PG reuse) has prevented PG recycling on a larger operational scale, and therefore also prevented reduction of the vast stockpiled PG volumes, for instance exceeding 1 billion tonnes PG in Florida alone.

Recent research has, however, demonstrated that both the billions of tonnes of legacy holdings of PG stored across the planet - and estimated to be of the order of 4-5 billion tonnes globally and still accumulating - and the hundreds of millions of fresh PG produced each year, actually hold a highly sought-after raw material for oncological cancer (alpha) therapy, (Figure 129) — its radionuclide content, mainly Radium as Ra-226 is a very low concentration, very high value component, measured in grams, contained in a very high volume co-product measured in millions of tonnes [135].

2. The Challenging Ra-226 Supply Chain

Ra-226 is scarce and among the most sought-after naturally occurring radioactive materials from which to derive radiopharmaceuticals such as Actinium (as Ac-225). To date there is no established and secure raw material supply chain for Ra-226, resulting in the USA alone in an estimated 50,000 cancer patients each year currently going untreated.

2.1 Demand for Ra-226

The known U.S. demand for oncological alpha therapy is currently about 10 Ci per annum (equivalent to 10 grams of Ra-226 per year), but it is expected to multiply when considering the increasing global demand for cancer treatment. The extreme demand for Ra-226 is also reflected in its current price tag of US$ 3.7-6 million dollars for 1 gram of Ra-226 (source: U.S. Dept of Energy).

2.2 Feedstock Sources

The main challenge facing a dependable supply chain for Ra-226 supply chain lies in the extraction of Ra-226 from a wide range of sources and recovery procedures to generate a reliable flow of suitable raw materials for radiopharmaceutical suppliers to process. Sources of Ra-226 to date include electronic instruments, recovered bearing coatings, lightning rods and uranium mine tailings. How then, does the fertiliser by-product PG find its natural place in the unlikely field of feedstock options for leading-edge pharmaceuticals?

3. Extracting Ra-226 from PG: Reshaping the Phosphate Fertiliser Industry Business Model

A group of German geologists and U.S. radiopharmaceutical manufacturers has recently pooled their resources to demonstrate that Ra-226 can be efficiently extracted from PG (>70%) as raw material for production of Ac-225 for cancer medical diagnostic and therapeutic applications (alpha therapy). It is the resulting registered patent (Figure 130), and the vast availability of PG, that now has the potential to turn PG into the main inventory for raw material for production of radiopharmaceuticals for oncological therapy worldwide.

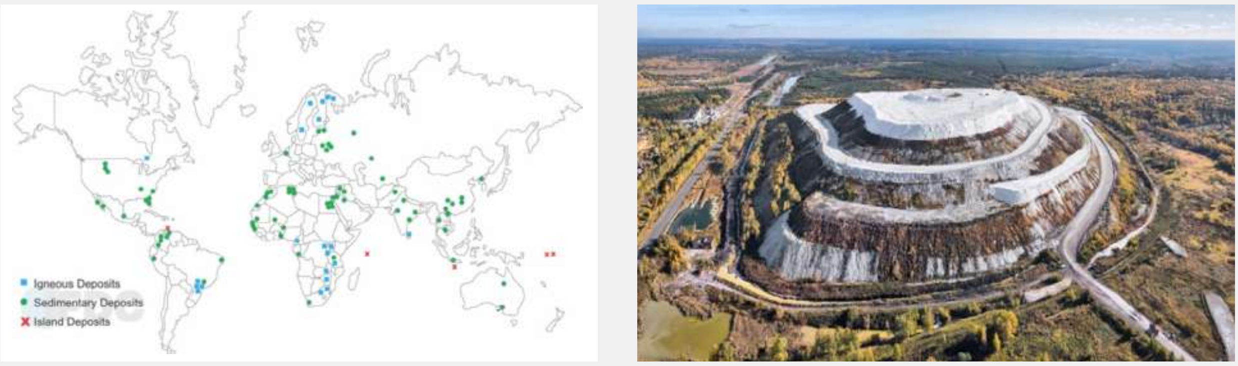

Fig. 129. *World phosphate rock resources and typical PG stockpile (sources: International Fertilizer Development Center IFDC[91] [142]*

88 International Fertilizer Development Center, https://ifdc.org

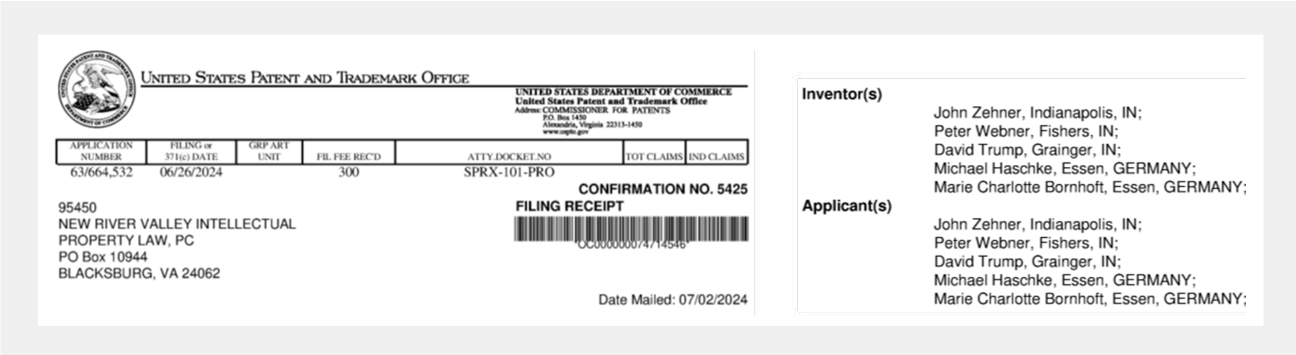

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Fig. 130. *Registered patent no. 63/664,532 United States Patent & Trademark*[92]

Legend: Barite (green) is associated to anhydrite/gypsum (purple), quartz (pink) and Fe/Ti-oxides (red)

Fig. 131. *Line up of detected Ba-phases in QEM Scan false colour image. (Image courtesy of Alpa Powder Equipment*[93]*)*

Their work has demonstrated that PG stockpiles in Florida/USA, Serbia, Bulgaria, Spain, and in due course Morocco, are among the main available sources of Ra-226. These have typical activity concentrations of ~ 600-1,200 Bq/kg depending on the source and region (Figure 131). This suggests that Ra-226 from PG has the potential to supply sufficient Ra-226 for cancer (alpha) therapy indefinitely across the globe.

The benefit of Ra-226 extraction and commercialising Ra-226 from PG is to create a high value-add pre-treatment option for eliminating the potential real or perceived risks that may in certain conditions accompany PG use, for example as a soil amendment. This approach, if adopted worldwide, would very likely set off a downstream cascade of sequential added value options for managing PG as a secondary raw material across a standardised value chain. At the start of this value chain would come profitable recovery of materials such as Ra-226 and certain rare earth elements (REEs), such as for electric vehicles and renewable energy, steps which would further enhance regulatory, market and social acceptance for existing PG applications in agriculture, construction materials and road building.

89 The US Patent is also registered by the patent Corporation Treaty (PCT, valid in 158 countries).

90 See Alpa Powder Equipment, https://www.alpapowder.com, last accessed Mar. 22 2025.

3.1 High-Value, Low Volume

On a larger scale, the global oncological demand for Ra-226-based radiopharmaceuticals holds potential to further accelerate the fertiliser industry into a game-changing sustainability and circular economy champion, extracting maximum social, environmental and economic benefits from PG as a secondary raw material of high value. At the high-value, low volume end of the PG value chain are critical raw materials such as REE e.g. for Nd-Dy-Pr magnet production, and now Ra-226 recovery as raw material for production of radiopharmaceuticals (Ac-225) for oncological therapy of cancer patients urgently awaiting alpha therapy.

3.2 High Volume, Lower Unitary Value

At the high-volume, lower value end of the PG value chain are the established but growing market demands for PG as a soil amendment — in particular where PG strengthens the phosphate industries' capacity in climate-stressed regions to enhance food security by boosting yield in degraded soils — but also the enhanced security of supply of high-performance building materials in populous markets, by offering products such as alpha wallboard and cement production.

PG is already starting to fill the rapidly growing gap in the supply- chain into the construction materials feedstock market from declining flue gas desulfurisation gypsum (FGD) availability as coal-combustion energy is phased out. Substituting PG for FGD protects natural gypsum stocks while securing production of cement and gypsum board products for certain markets struggling to meet their rising demand for affordable, energy efficient housing (see B 8).

3.3 Pharmaceuticals

Numerous large radiopharmaceutical companies worldwide require a steady Ra-226 supply for maintaining and expanding on ongoing oncological clinical trials and manufacturing of radiopharmaceutical medical products. The anticipated steady supply of Ra-226 from PG is expected to support the growing abundance and variety of radiopharmaceutical (Ac-225) manufacturers and related start-ups, mainly in the USA and Asia. These businesses have already started negotiating Ra-226 supply contracts to stabilise Ra-226 supply chains, in the expectation that the first fertiliser companies will enter the market to meet rising demand for Ra-226 feedstock.

From an investment risk assessment and financial reporting perspective, such a coherent, integrated high-value and sustainable value-additive sequence across the PG and Ra-226 supply chain has high potential to be ESG-certified. This step in turn will likely generate additional competitive advantage, with potential to uplift the fertiliser industry into a global ESG champion and circular economy role model for other industries producing high-yield value chains from hitherto neglected secondary raw materials.

CHAPTER TWO

ACHIEVING 100% PHOSPHOGYPSUM UTILISATION IS NOW WITHIN REACH

Author: Hari Tulsidas, Economic Affairs Officer, United Nations Economic Commission for Europe


2

1. Context – From Waste to Inventory

Five years ago, I contributed a section to the second IFA phosphogypsum report [16] under the title **Value creation and compliance with UN Sustainable Goals: the pathway to 100% Phosphogypsum Use?** It was intended as a long-term horizon-setting question, i.e. to be achieved between 2030 and 2050. As I write this update, on the evidence of what I read in this report, a pathway to 100% use is coming rapidly into view, much ahead of my then optimistic schedule. Since 2019 in some major producing and consuming markets for phosphogypsum, 100% use has either become (e.g. Brazil) or is fast becoming (e.g. Indonesia) a profitable market reality, or it is now national policy (China), with major cost savings resulting from of 50% use of current annual production.

Phosphogypsum (PG), a co-product of phosphoric acid production, is generated in substantial quantities, with annual global production exceeding 230 million tonnes and rising due increased global demand for phosphate fertilisers for food security. As Julian Hilton points out earlier in this report, this means that PG management and use has to be rethought. It is no longer primarily a waste management issue but has instead become a long-term, secondary raw material use opportunity.

1.1 Circular Economy Integration for Sustainable Resource Management

In its seminal 2013 report on the management of NORM residues in the phosphate industries [6], one of the primary conclusions of the IAEA publication team (of which I was a member), is that safe, beneficial use is preferred to disposal as an end of life solution for PG, whether disposal is to land or to sea. Either option brings with it significant environmental challenges. Discharge to sea is now limited to a small number of producing countries, with a generally shared commitment to stopping the practice in compliance with a range of different treaty obligations not to discharge wastes to seawater. Disposal in large stacks on land has also a questionable track record of losses to sink-holes, slope failures with discharges of low pH process water to rivers and seas, but with chronic consequences leading to land degradation and potential contamination of the wider eco-system. In terms of financial cost, there is concomitant loss of income from alternative economically productive uses of the land, and indefinite maintenance costs for the oversight of the landfill facilities themselves.

In the context of the circular economy and energy transitions, in parallel with efforts to reorient from disposal to use, innovative applications are emerging that transform PG into valuable resources, aligning with the principles of the United Nations Resource Management System[91] (UNRMS). UNRMS is a comprehensive framework integrating sustainability into global resource management practices. It provides a principles-based and structured approach for governments, industries, and communities to manage natural resources efficiently, aligning with the United Nations' Sustainable Development Goals (SDGs) and the Paris Agreement. UNRMS emphasises transparency, equity, and sustainability across all stages of resource management, from extraction to consumption, ensuring that resource use contributes to economic growth, environmental protection, and social well-being.

By integrating PG into circular economy frameworks, we can address environmental, social and economic concerns, promote sustainable development, contribute to global resource efficiency and encourage investment in ESG-compliant projects to valorise and use PG, such as outlined by the European Bank of Reconstruction and Development (EBRD) in the first section of this report. Some countries to expedite comprehensive utilisation are favouring pretreatment of all PG to eliminate potential risks from radionuclides and/or heavy metals that may be present, while others apply the graded approach, aligning regulatory requirements to the risk/benefit profiles of each application type and environmental context.

Whichever pathway to use is taken, integrating PG into a circular economy framework is essential for sustainable resource management. Of the significant tonnages the phosphate fertiliser industry generates of PG annually worldwide, as of 2024 only ~35% is recycled – the remainder still being stored in environmentally – detrimental stockpiles or discharged. This underutilisation represents a significant waste of potential resources and poses environmental hazards.

2. The Growing Range of Use Options

To address this continuous and growing cost burden, already many innovative applications of PG have been successfully explored and progressively explored worldwide [6] [14] [16]:

- Construction materials: PG can be processed into building materials such as cement, plasterboard, and road-based materials, reducing the demand for natural gypsum and promoting sustainable construction practices.
- Agricultural applications: PG improves soil structure and fertility, controls salinity and enhances crop yields through soil amendment.
- Environmental restoration: Utilising PG to create artificial

91 For the United Nations Resource Management System (UNRMS) see https://unece.org/circular-economy/press/ecosoc-endorses-unrms-paving-way-implementation-sustainable-resource

reefs and constructed wetlands supports marine biodiversity and aids in wastewater treatment.
- Anthrosols for land rehabilitation: PG can be utilised in creating anthrosols – engineered soils designed to rehabilitate degraded lands.
- Rare Earth Elements (REE) Recovery: PG contains significant amounts of REEs and other critical raw materials, and research is ongoing to develop economically viable methods for their extraction, contributing to the supply of critical minerals.

Aligning these applications with UNRMS principles – such as circularity, comprehensive resource recovery, and value addition – can transform PG from an environmental liability into a valuable resource. This approach mitigates environmental risks and contributes to economic development and resource efficiency, embodying the essence of a circular economy.

2.1 Addressing Environmental, Social and Economic Challenges

Effectively utilising phosphogypsum addresses several environmental, social, and economic challenges as delineated here:

2.1.1 Environmental Benefits

- Waste reduction: Repurposing PG minimises the accumulation of waste by-products, reducing the phosphate industry's environmental footprint.
- Resource conservation: Incorporating PG into construction materials conserves natural resources by substituting secondary for primary raw materials.
- Ecosystem restoration: Using PG to create artificial reefs and wetlands supports biodiversity and rehabilitates degraded environments.

2.1.2 Social Benefits

- Health improvements: Proper management of PG reduces potential exposure to hazardous substances, enhancing community health.
- Employment opportunities: Developing industries around PG utilisation generate jobs in processing, manufacturing, and environmental restoration sectors.
- Community Engagement: Involving local communities in PG projects fosters social cohesion and empowers stakeholders.

2.1.3 Economic Benefits

- Cost savings: Utilising PG as a raw material in construction and agriculture reduces production costs.
- Market development: Innovative PG applications open new soil amendments and building materials markets.
- Sustainable growth: Aligning PG use with circular economy principles promotes long-term economic resilience.

These available and tested solutions align well with the principles of UNRMS, promoting sustainable development and resource use efficiency.

3. Future Prospects and Research Directions

Advancing the utilisation of PG necessitates innovative research and development to unlock its full potential. Emerging applications could include:

3.1 Advanced Climate Solutions

- Carbon mineralisation: Develop processes to react PG with CO_2, forming stable carbonates. This would contribute to carbon capture while producing usable materials like construction fillers or soil conditioners.
- Geoengineering applications: Explore PG use in geoengineering, such as for reflective ground covers in arid regions to mitigate local heat effects.

3.2 Enhanced Waste-to-Resource Applications

- Co-processing with industrial waste: Combine PG with other industrial by-products (e.g., steel slag, fly ash) to create composite materials for construction or landfill covers, i.e. secondary raw materials.
- Geopolymer cement: PG blends are used to produce geopolymer cement, which has lower carbon emissions than traditional cement.
- Fertiliser co-products: Extract residual phosphorus and sulphur from PG for high-value agricultural fertilisers.

3.3 Bio-innovation and Ecosystem Restoration

- Microbial soil enhancement: Inoculate PG-amended soils with beneficial microbes to accelerate bioremediation and improve soil fertility.
- Biocrust development: Use PG to support growth in arid or degraded lands, stabilising soil and promoting biodiversity.
- Habitat engineering: To enhance aquatic ecosystems, design PG-based substrates for artificial wetlands, mangrove restorations, or fish spawning beds.

3.4 Energy Innovations

- Energy storage systems: Research PG-based composites for thermal energy storage, particularly in renewable energy setups like concentrated solar power.

- Biochar integration: Mix PG with biochar derived from agricultural residues to improve soil nutrient retention and carbon sequestration.

3.5 Urban and Industrial Applications

- Urban agriculture: PG-based anthrosols can be used for rooftop gardens and urban farming, enhancing cities' green infrastructure and food production.
- Smart materials: Research PG's potential as a base material for developing smart building materials with thermal or acoustic insulation properties.

3.6 Disaster Risk Reduction

- Flood mitigation: Use PG to reinforce levees or construct permeable barriers to control water flow during floods.
- Post-disaster land recovery: Deploy PG-based soil amendments to rapidly rehabilitate lands damaged by natural disasters like floods or wildfires.

3.7 Circular Economy Innovations

- Zero-waste industrial ecosystems: Integrate PG into closed-loop systems, continuously recycled or repurposed for multiple industrial uses.
- Rare earth and trace element recovery: Advanced technologies for extracting trace elements like uranium and thorium from PG, transforming it into a resource for clean energy technologies.

3.8 Food and Water Security

- Irrigation system enhancements: PG can be used as a substrate in controlled irrigation systems to improve water distribution efficiency and reduce soil salt buildup.
- Aquaponics: Develop PG-based substrates for aquaponic systems, which will support plant growth and water filtration in integrated food production systems.

Focused research in these areas, aligned with UNRMS principles, can transform PG from an industrial by-product into a valuable resource, contributing to global sustainability goals.

3.9 Strengthening Global Resource Governance and UNRMS Alignment

Aligning PG utilisation with UNRMS enhances global resource governance by promoting sustainable practices and international cooperation. UNRMS emphasises integrated resource management, transparency, and stakeholder engagement, which are crucial for effective PG management. Implementing standardised guidelines for PG applications, such as in construction and agriculture, ensures environmental safety and public health. International collaboration facilitates the exchange of best practices and technological innovations, optimising PG use.

Engaging stakeholders — including governments, industries, and communities — in decision-making fosters equitable benefit distribution and addresses social concerns. By adhering to UNRMS principles, PG utilisation contributes to the SDGs, particularly those related to responsible consumption and production, climate action, and life on land. This approach transforms PG from an environmental challenge into a valuable resource, exemplifying effective global resource governance.

4. 100% Utilisation Now Within Our Reach

Achieving 100% utilisation of PG presents a transformative opportunity to convert industrial co- and by-products into valuable resources, aligning with the UNRMS principles. Innovative applications such as carbon mineralisation, co-processing with industrial waste, microbial soil enhancement, and energy storage systems exemplify forward-looking strategies that can drive sustainable development.

We can unlock PG's full potential by investing in applied research and development, fostering international collaboration and standards and implementing supportive resource management and environmental policies focused on stimulating markets in secondary raw materials. This collective and collaborative approach addresses environmental challenges and contributes to economic growth and resource efficiency, paving the way for a sustainable and resilient future.


3

CHAPTER THREE

DEFINING THE FUTURE: SHAPING A MAJOR HUB IN THE NEW GLOBAL MARKETS IN SECONDARY RAW MATERIALS, SAUDI ARABIA

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Ma'aden Phosphate Company with Malika Moussaid,
Julian Hilton, Aleff Group

Industrial Mineral Diversification of the National Economy - Phosphate as Energetic Resource

A key priority of the diversification of the Saudi national economy is counter-balancing the dominance of the oil and gas sector with major industrial minerals and precious metals sourced from within its national borders. Ma'aden Phosphate Company[92] (MPC), a subsidiary of the national mining company Ma'aden[93] has played a leading role in meeting that objective since it started industrial production of diammonium phosphate fertilisers at Ras al Khair Industrial City (RIC), Eastern Province in 2011 (see Figure 132).

Phosphate is perhaps the most natural bridge from KSA's established strength in oil and gas industries to mineral resources such as phosphate, not least in the way it functions in the soil, as an energetic resource.

Fig. 132. *Ras al Khair Industrial City[94] (Image courtesy Ma'aden and Google Earth)*

MPC's success led to the founding of a second Ma'aden phosphate company based in Wa'ad al Shamal, in the Northern Province of Saudi Arabia, a joint venture with the US company Mosaic. This enterprise flourished as global demand grew for phosphate fertilisers. As of Jan 2, 2025 Mosaic has however, fully divested itself of its ownership stake to Ma'aden. Meanwhile in the freshly integrated Ma'aden phosphate business segment, growth at Wa'ad al Shamal is now being complemented by a third phosphate company within Ma'aden, this one located both at Wa'ad al Shamal and at Ras al Khair.

Unsurprisingly, this growth in phosphoric acid production actual and planned has been accompanied by a rapid surge in the quantities of Phosphogypsum (PG) produced across Ma'aden phosphate sector in general. In parallel, as internal awareness within MPC grows regarding the potential value of a phosphogypsum business, MPC is emphasising that its current phosphogypsum management approach is one of storage for use, not disposal. Consequently, the case for making this approach a strategic commitment to comprehensive use is gaining momentum. From a purely financial point of view it is as much for potential CAPEX and OPEX savings that storage for use has such support as for revenue generation purposes, not to mention these benefits combined. Such a business approach aligns well with the evident Ma'aden business trend towards "Materiality"[95] and "Double Materiality"[96].

The Ma'aden position on materiality as a whole is set out clearly in the 2023 Ma'aden Sustainability Report [136]:

> *Ma'aden defines materiality as topics both in which Ma'aden's activities create the most significant impacts on the environment and society (i.e., outward impact) and that have the most significant financial impacts on Ma'aden's business (i.e., inward impact). To this end, we have been applying a double materiality assessment approach, considering both dimensions of impact materiality and financial materiality, to identifying and prioritising our material ESG topics[97].*

Investment materiality assessments by Ma'aden now combine the direct financial dimensions with the related environmental and social consequences, hence use of the term "double materiality", reflecting the influence of circular economic thinking and the alignment to ESG compliance standards. With cost saving in mind, it is clear why the "impact materiality" case currently leads the reasoning, and understandably so. But once the "impact materiality" has created momentum for use, it is clear – not least from evidence of continuously profitable PG business cases in other countries such as Brazil, Belgium, Canada and Indonesia - that "financial materiality" considerations are equally, or even more, compelling.

At a business strategic level, this leads directly to the emerging business case for utilisation of phosphogypsum and other secondary available materials (such as red mud) as offerings on a dedicated processing and trading hub at RIC, focused on monetising PG. This is to be done in two complemen-

92 See https://www.maaden.com.sa/en/business/phosphate

93 See https://www.maaden.com.sa/

94 For RIC Special Enterprise Zone see https://www.raksez-info.com/en

95 Ma'aden Sustainability Report 2023 p. 50

96 Ma'aden Sustainability Report 2023 p. 55

97 Ma'aden Sustainability Report 2023 p. 55

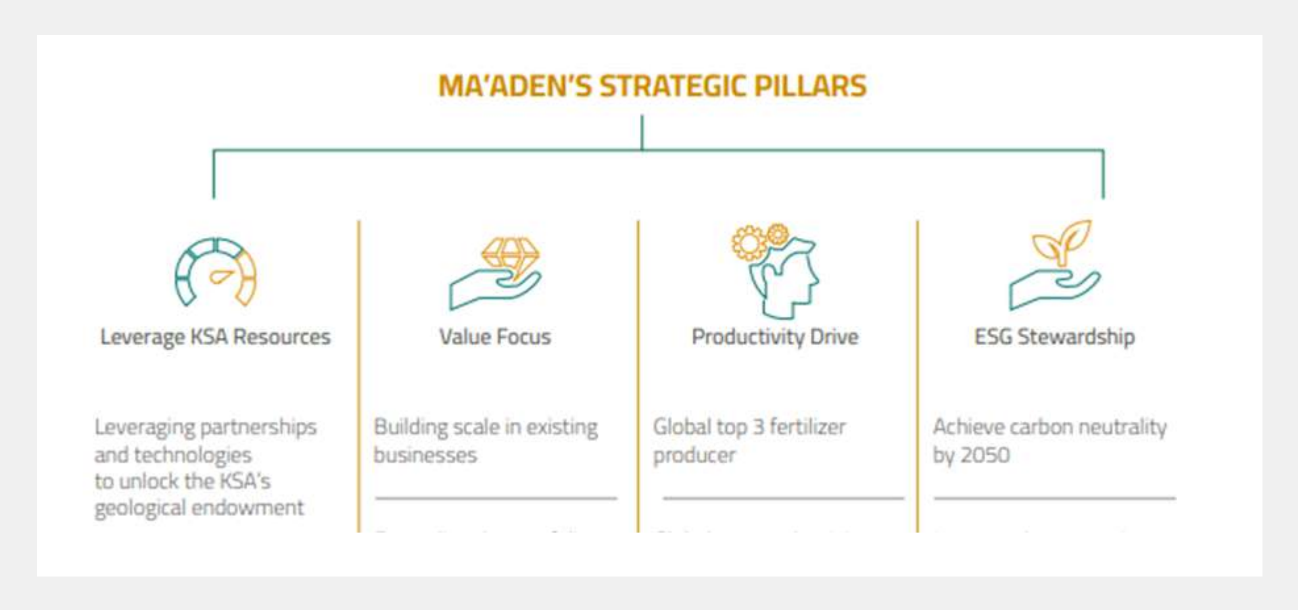

Fig. 133. . *The four Strategic Pillars of Ma'aden business practice (Image courtesy Ma'aden)*

tary ways. First, there are considerable and continuous cost savings, both CAPEX and OPEX, to be made from high volume use of PG as compared with stacking in open land. For as long as the wet process is used to generate PG as a by-product, yielding at least 5x the quantity of phosphoric acid production, the business case should be that PG should contribute positively to the MPC bottom line rather than weakening the balance sheet through the overhead of storing PG at high and steadily accumulating volume, at high cost. But secondly, in terms of double materiality assessment, in pivoting from PG as a waste management overhead, to PG use as a high-value feedstock, the environmental and social "material" impacts mirror the positive financial materiality consequences with sustainability and resource use efficiency as the business outcomes: win/win.

The alignment with the objectives of the Ma'aden four strategic pillars (see Figure 133) is also compellingly innovative as well as yielding high financial rewards, both through indefinite cost savings and through complementary revenue generation - win/win.

At a suitably ambitious aspirational level applying these pillars is to challenge the secondary raw materials (SRM) hub at RIC to create all-round double materiality benefits as:

- A hub for talent, creativity and expertise
- A magnet for investment and innovation
- A really rewarding place both to work and to visit
- A place to take pride in.

1. Policy Context

1.1 Circular Economy Principles and Practices

The 2023 Ma'aden Sustainability Report [136] makes a direct connection between attitudinal changes as to how the development of new technologies for recovery of value from ores such as bauxite and phosphate is both materially and financially aligned with the principles of the Circular Economy (CE):

> *Sustainable development includes circular economy-based models, and mining presents an opportunity to integrate materials and waste management solutions into business functioning by increasing the share of renewable materials used, minimising the generation of waste while maximising the recycling of waste*[98].

At a meta-level CE values are very simple:

1. Maintain value – never destroy value = zero waste
2. Add value wherever possible

When these values apply to operational practice, they focus on objectives such as:

- Resource use efficiency (RUE) for all resources
- Lower energy intensity
- Decarbonisation material substitution: modify product design and materials to comply with CE values (recycling, upcycling)...

98 Ma'aden Sustainability Report 2023 p. 88

- Foster innovative business models that extend product lifespans.

Taken together, they naturally lead to Ma'aden's four strategic pillars of current business practice, as shown in Figure 133.

1.2 Leverage KSA Natural Resources

The KSA natural physical resources (the natural endowment) to be leveraged are found in the mines that service the two, soon to be three phosphoric acid production facilities that drive the MPC product stream, Al Jalamid and Al Khabra[99]. But the double materiality approach balances direct financial capital accumulation with social and techno-scientific capital, a triple bottom line return:

a. **financial capital** — the allocation of capital resources to fund and motivate these outcomes and the recovery of the return on these investments for maintaining the achievements of the national economy.
b. **social capital** — the capabilities of the organisations that partner with each other to locate, characterise, quantify and valorise the geological endowment
c. **techno-scientific capital** — the expertise, knowledge and drive for innovation that crystallises in the course of the release and delivery to stakeholders and beneficiaries of the value that the natural resources embody.

1.3 Building Scale

Including PG resources as an asset not a liability adds immediate scale to the MPC business, in tonnage terms a five-fold amplification. In a native state, used as a soil amendment, a bulk PG per tonne price of $25-50 USD is being achieved in markets such as Brazil on a regular basis (see case study — Section B. 8). When OPEX savings for maintaining PG stacks and revenue losses from sterilised land are also taken into account, the financial impact is at least doubled, which must necessarily positively affect the investment case. "Double Materiality" win/win impact is an apt way to describe this. The large and continuous benefits from taking a double materiality view of how to include secondary raw materials such as PG in a positive manner in strategic investments in the minerals processing sector are becoming increasingly clear. As new forms of product and service are being developed from PG it is clear the knowledge acquisition process is generating social and techno-scientific capital — i.e. significant investment in human creativity and ingenuity are the true drivers of revenue growth from this class of materials.

99 For further details of the phosphate mines see https://www.maaden.com.sa/en/business/mines

1.4 Productivity

Productivity enhancement is as much an outcome from raising worker morale by regarding PG as an asset not a polluting waste, as in investing in more efficient PG pre-treatment technology. In the case of both Ma'aden Phosphate company and Ma'aden Aluminium Company at RIC, as per the new international OECD terminology the classification of both PG and RM as secondary raw materials of significant value is completely changing the way in which members of both companies see their future feedstocks and the way they valorise them. This in turn has pivoted sentiment about RIC as a place of work from one seen by staff as polluting and generating waste, to a creative place where release of value from all resources is seen and practiced as an ethical imperative to be proud of. For the rising generation of the expanding RIC workforce this is of decisive significance. "Of course we come to work to be paid, but the type of job we really want is something that is inherently interesting and challenging and gives us a sense of value that is beyond the financial"[100].

1.5 ESG Stewardship

As a mark of the seriousness with which Ma'aden is committed to ESG stewardship is the fact that the term appears 68 times in the 2023 Sustainability Report. The rapid uptake of the Environmental, Social and Governance (ESG) approach to resource stewardship, including financial investment, shows how profoundly CE values have impacted the mining and processing sector, focused on eliminating the highly damaging negative externalities that have proven to be the legacies of previous approaches, to recovery value from the natural endowment. The connection to the powerful underlying case for investing heavily in developing secondary raw materials markets is clearly drawing the inference, where better to focus this investment than at RIC?

1.6 Holding Ourselves to Account

But if reinforcement of an explicit kind were needed, the Ma'aden 2023 Sustainability Report comments as follows:

> *In 2021, we established our sustainability footprint system which is a set of key sustainability metrics upon which we*

100 The quotation genericises a number of versions of this opinion heard by both the lead author and the Aleff Group team while working together on both the case study at Ras al Khair and on a joint keynote speech to open the Arab Fertiliser Association Technical Workshop, Jeddah given November 26, 2024. It captures nicely the change in sentiment towards working with phosphogypsum now being heard worldwide, expressed by operational staff, research personnel and investors alike.

have set long-term quantitative targets (2040) for, a baseline (2020), and annual progress tracking obligations.

The ultimate purpose of these targets is to enable Ma'aden to become a local industrial role model in Saudi Arabia while contributing to the Kingdom's ESG objectives.

Additional targets are still being developed, including increased renewable energy sourcing, Scope 3 GHG emissions reduction[101], where we are currently developing Scope 3 Baselining Activities and investigating appropriate targets, and closing any gaps in social- and governance-related performance compared to global mining industry best practices[102].

2. Mineral Diversification

RIC is the only facility in the world where phosphate and aluminium are produced in the same industrial complex, meaning that the primary residue from bauxite processing, red mud, is also produced in close proximity to phosphogypsum – just a few hundred metres separating the bauxite from the phosphate processing and manufacturing facilities. Bauxite processing for aluminium production actually predated phosphate production by three years; Ma'aden Aluminium (MA) starting operations in 2012 as a joint venture with Alcoa. It is located in close proximity to MPC (see Figure 134), and like phosphate operations, MA is now scheduled to expand by adding a new bauxite processing line from late 2025.

A third major industrial mineral, steel, is now in the process of establishment at RIC, as part of a further economic diversification push towards offshore industries. These include ship-building and the construction of oil production rigs, exploration rigs and offshore service vessels, hosted at the King Salman Marine Yard (KSMY). This expansion is accompanied by the establishment of a new "offshore cluster" of specialist businesses at RIC signaling both diversification and consolidation of RIC activities into a fully integrated industrial platform and resource eco-system with downstream industries included in its scope.

This means both oil and gas and mineral industries – such as copper, zinc and lead in future, all of which produce significant quantities of residues – are anticipated. But unlike phosphates and aluminium, this time the recycling and reuse of residues, scrap and recycled materials is planned into the model, not grafted on afterwards.

2.1 The RIC Secondary Raw Materials Hub: SRMs and the KSA Policy and Investment Context

Recycling and reuse of residues, scrap and recycled materials has the following attributes that determine the double materiality context within which investment in the SRM hub at RIC will work:

1. ESG principles-based
2. Approach to PG and RM scalable to other secondary resources in RIC Master Plan such as steel, copper, zinc, lead, tin etc.
3. Excellent opportunity for investment in high-growth PG and RM downstream industries, such as construction material industries (cement, gypsum board, roads, etc.).
4. SRMs central to the integrated industrial platform model for RIC and King Salman Marine Yard.
5. Aligned fully with KSA Waste Management National Regulatory Framework and related SRM market development objectives.

3. The Great Transformation: A Fully Integrated, Circular Industrial Eco-system at Ras al Khair

What sets this initiative apart is its recognition that a circular economy begins to leverage the geological endowment with valorising and revalorising secondary raw materials before reaching for primary resources. So, what are secondary resources? And which are currently of immediate interest to Ma'aden?

3.1 Secondary Raw Materials – What are They?

As defined by OECD secondary raw materials (SRMs) are reusable or recyclable materials[103]. They are best managed in a balanced, integrated industrial ecosystem of primary and secondary resources.

- SRMs enable reusable and recyclable resources to continuously enter, and re-enter, the production value chain.
- Continuous recycling reduces dependency on primary resources. (UNSDG 12)[104]
- SRMs can be used in manufacturing processes as substitutes for or combinable with virgin (primary) raw materials.

101 For further definition of Scope 3 emissions see USEPA https://www.epa.gov/climateleadership/scope-3-inventory-guidance#:~:text=Scope%203%20emissions%20are%20the,its%20upstream%20and%20downstream%20activities. "Scope 3 emissions are the result of activities from assets not owned or controlled by the reporting organisation, but that the organisation indirectly affects in its value chain. An organisation's value chain consists of both its upstream and downstream activities."

102 For Scope 3 Baselining Activities see Ma'aden Sustainability Report 2023 p. 44

103 See OECD https://www.oecd.org/en/topics/sub-issues/material-resources.html

104 See United Nations overview of SDG 12, https://sdgs.un.org/goals/goal12

- SRM markets based on recognised product specifications and service and trading standards are crucial for sustainable resource management.
- Flourishing SRM markets are a key sign of a healthy circular economy.

3.2 Secondary Raw Materials – Which are of Current Interest to Ma'aden

Of immediate interest to Ma'aden are the high volume residues, phosphogypsum and red mud (RM), as part of the core business of both Ma'aden Phosphate and Ma'aden Aluminium companies.

Fig. 134. *Colocation and accumulation of secondary raw materials at RIC (Image courtesy Ma'aden)*

Uniquely in the world, both these secondary raw materials are produced in the same industrial complex, Ras al Khair, only a few hundred metres apart (see Figure 134).

3.3 Annual PG & RM Secondary Raw Material Accumulation at RIC 2014-2024

The quantity of secondary raw materials available at RIC as of year-end 2024 are summarised as follows:

PG accumulation: 7 + million metric tonnes per year stored in stacks

RM accumulation: 2+ million metric tonnes per/year – stored in cells

Total accumulated legacy secondary raw material at RIC (PG and RM): ~90m tonnes (2024)

These secondary raw materials are available to valorise and use now (see Figure 134).

3.4 Developing the KSA Domestic Market for SRMs in a Favourable Market Entry and Investment Context

A transformational approach to PG and RM management and use at RIC is now being developed for adoption at RIC, grounded in the double materiality framework set out in the Sustainability Report 2023. This approach will set a benchmark for valorising secondary resources produced at RIC, which will be usable well beyond the RIC facility.

To give some direction to the approach, strategic options for both PG and RM, and possible mixes, are set out in detail in two internal reports assembled for the Royal Commission as regulator of and investor in the RIC site. Based on the Waste Options Report (2015-16) and Detailed Feasibility Study (2016-17), Ma'aden Phosphate Company commissioned the PG-Access to Market study, completed along with an accompanying environmental impact assessment[105].

The expected outcomes from this double materiality approach are:

- New projects using secondary raw materials from RIC set the standard for valorisation and use of residues from current and future minerals processing at RIC, in the wider KSA markets, but also with global impact accessed through RIC Port.
- The process credentials RIC as a global leader in sustainable minerals and secondary raw materials processing and zero waste from a trading hub at RIC.

4. Towards a Sustainable Tomorrow

Ma'aden's vision and mission for a sustainable tomorrow ('The Sustainable Tomorrow') is converted into action, through the circular economy and green transition as described in Figure 135.

'The Sustainable Tomorrow' summarises in one sentence: "the case for consolidating all activities into a secondary raw materials hub, both for production and trading, fits exactly the profile anticipated in the Vision 2030 and Vision 2040 diversification programmes" and now confirmed as MPC's (Ma'aden's) Strategic Pillars as described.

105 Reports referenced for Royal Commission and MPC were produced by Aleff Group

Fig. 135. . *The Sustainable Tomorrow (Image courtesy of Ma'aden)*

In the process of assembling and deploying natural, social and financial capital, the strategic plan has set up Ma'aden to become a national ESG role model. To this end, MPC has:

- built an ESG investment strategy with defined goals and targets
- identified environmental targets and its contribution to the circular economy
- defined a carbon neutrality pathway
- developed a secondary raw material valorisation and use policy and practice that anchors the mineral diversification strategy in circular economic values and practices (see Figure 135).

4.1 Conclusions

A wide range of sustainability benefits can be predicted from these policy and strategic goals such as:

4.1.1 Market Potential

a. KSA domestic market has a clear potential for high-volume uses across agriculture and construction
b. KSA domestic market uptake will stimulate export market and external investor interest

4.1.2 Climate Action: CO_2 Capture, Water Use Efficiency, Reversing Desertification and Soil Erosion

a. Significant opportunity for CO_2 sequestration in Forestation and build-up of Soil Organic Matter
b. Up to 70% increase in Water Use Efficiency
c. Major enhancement potential for soil physico-chemical stabilisation, reducing erosion and risk of desertification

4.1.3. Crop Yield Increase

a. Brings yield increase of up to 270% by reversing build-up of salinity in soil from poor irrigation practices

4.1.4 Operating Lives of PG Pads and RM Cells Extended by Reduced Rate of Accumulation

a. Using legacy and current PG and RM resources extends PG stack and RM cell- lives, potentially indefinitely
b. Eliminates or reduces CAPEX and OPEX expenditures for future residue storage (no sunk costs – PG Stack CAPEX $200million per stack; RM Cell CAPEX $100 million per cell)

4.1.5 Primary Resource Conservation

a. Substituting PG and RM for primary filler resources (sand etc.) conserves millions of tonnes of primary resources – e.g. sand and aggregates. Global experience indicates that primary resource conservation substituting PG for natural gypsum (calcium sulphate) is in the range of 40%-89%, with typical values between 53% and 60%.

4.1.6 Land-loss Offset

a. Land loss in KSA to urban development can be offset by land reclamation at RIC, e.g. for the plots of land designated in the master plan for development for use in the Marine Yard Off-shore Cluster, or RIC Port
b. Land loss offset - a key objective for UN SDG 11: Sustainable Cities and Communities

4.1.7 Reduced Costs and Emissions from Handling and Applying Secondary Raw Materials for Fill

a. Lower materials costs/ per tonne
b. Significant reduction in tonne/km haul distances
c. Major reductions in CO_2 and NOx emissions

4.2 Alignment with Saudi Green Initiatives

These benefits all converge in the major national strategic project known collectively as the Saudi Green Initiatives (SGI).

As summarised by the Ma'aden Sustainability report 2023: "SGI[106] employs a whole-of-society approach to action on and invest in climate change, energy security, and economic prosperity through offsetting, reducing greenhouse gas (GHG) emissions, and using clean energy. By making sustainability a priority in the activities that Ma'aden does, we combine the efforts of the government and of the private sector to support and leverage opportunities for collaboration and innovation to accelerate the green transition"[107].

The most direct SGI alignment concerns a well-advanced plan to apply the new anthrosols that have been developed to support forestation and agriculture, as part of the tree plantation initiative close to the Ras al Khair manufacturing complex. Varieties of tree that perform well in the Eastern Province both in PG alone and PG/RM mix with local soils have been piloted successfully since 2018 at RIC, and in companion pot trials conducted under protocol based laboratory conditions. These findings are now the basis of a significant planned scale-up in afforestation as set out in the Saudi Green Initiative [108].

One plantation project is to be established in close proximity to RIC but also by establishing new tree growing sites along the highways between RIC and Jubail, where the logistics of supplying these PG-based anthrosols from the PG repositories at RIC to the designated planting locations is straightforward. Localised EIAs are currently being completed prior to starting the implementation, but all materiality findings and impacts hitherto are positive.

This greening initiative is of course closely tied to other SGI goals, such as offsetting and reducing emissions. The offset comes from CO_2 sequestration in the organic matter to be nurtured in the new PG and RM soils, which in themselves sequester CO_2, notably RM and of course in the trees planted themselves; but emissions are also reduced by the eliminating that fraction of the carbon load which is generated currently at RIC by using the material rather than disposing of it to landfill. That fits doubly with the national waste management policy by converting waste industrial residues into cost-saving, revenue generating products such as timber (directly) and new soils (indirectly), by sequestering carbon in the soil organic matter and significantly boosting crop yield and water use efficiency in agriculture.

Beyond that, the SRM approach leads directly to promoting the circular economy transition in action as well as policy; and not disposing of residues while lowering emissions protects the whole environment, particularly on the eco-sensitive Gulf coast and around the Port of Ras al Khair. This is collaboration and innovation of the highest calibre between private and public sectors and should be accelerated before MPC and its partners (including the Royal Commission) risk losing the window of opportunity they have so carefully opened for themselves.

106 Saudi Green Initiatives (SGI) see https://www.greeninitiatives.gov.sa/about-sgi/

107 Ma'aden Sustainability Report p. 50

108 Greening Saudi, https://www.sgi.gov.sa/about-sgi/sgi-targets/greening-saudi/#:~:text=Saudi%20Arabia's%20journey%20to%2010%20billion%20trees&text=A%20comprehensive%20framework%20is%20steering,to%20be%20planted%20by%202030.

CHAPTER FOUR

LEAVE NO RESOURCE UNUSED: THE FUNDAMENTAL LAWS OF NATURE FOR AN ENTERPRISE OR VALUE CHAIN

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4

1. Introduction

Two key maxims define any successful resource production and management enterprise: first, be profitable and safeguard and cherish the value efficiency of your feedstock. Secondly, do that and you are well placed to develop and also satisfy the needs and standards of your era – even define them. Without exception, the phosphate industry, like any other, must obey these fundamental laws of nature by which any value chain operates and delivers value.

Thinking of profitability and feedstock use efficiency there are three aspects to consider:

The Value Indicators

Be guided by these key indicators: output, profit, tax revenue (return to government and society), jobs created and employment.

Dynamic Business Rule

Marginal output is greater than marginal input.

Criterion One

To create the target value gain with as little resource consumption as possible.

The level to be reached of profitability and feedstock consumption efficiency is determined by the combination of productive forces assembled and the enterprise's collective management capability to harness them. Looking across industrial history, it breaks naturally into three eras, first, the age of steam, second, the era of electricity and third, the era of artificial intelligence – AI. Now in our era, AI, what are the standards we expect and are expected of us?

- High requirements of industrial health, safety and environmental protection.
- Conformity to the green economy and low carbon emissions.
- People-centred belief: trust your workforce.

How can we map these to phosphorus resources and their many value chains?

2. The Phosphorus Value Chains

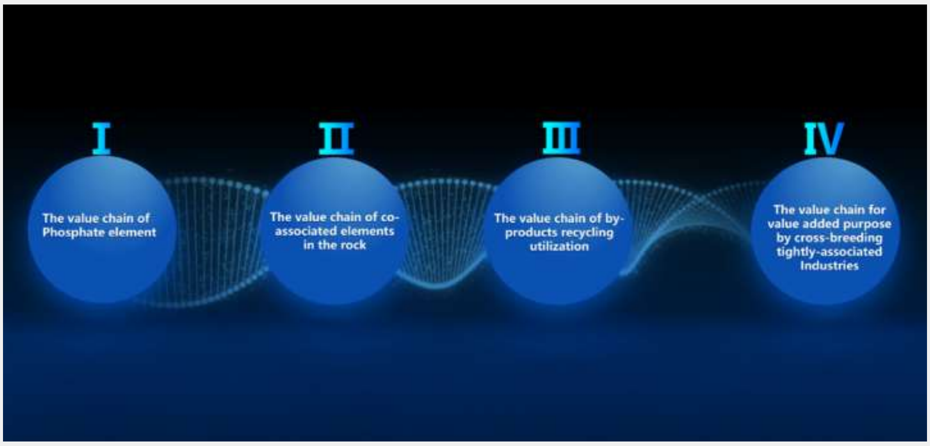


Fig. 136. *The Phosphorus Value Chains*

As shown in Figure 136, to promote the global phosphate fertiliser industry we must drive the phosphate endowments of the earth deep through the four dimensions of their value chains, in whatever form they take. These value chains are comprised of:

1 **The phosphate element**

2 **Co-associated elements in phosphate rock**

3 **By-product recycling and reuse**

4 **Disruptive new perspectives and added purposes forged by tightly crossbreeding industries we never dreamed before could pair.**

2.1 The Phosphate Element Value Chain

Fig. 137. *The Phosphate Element Value Chain*

At the heart of the phosphorus element value chain is P itself (Figure 137). But the roots of that value chain in China date back at least to 1600 as a team of researchers at Nanjing University showed very clearly in their 2016 study [137].

2.2 The Value Chain of Co-Associated Elements

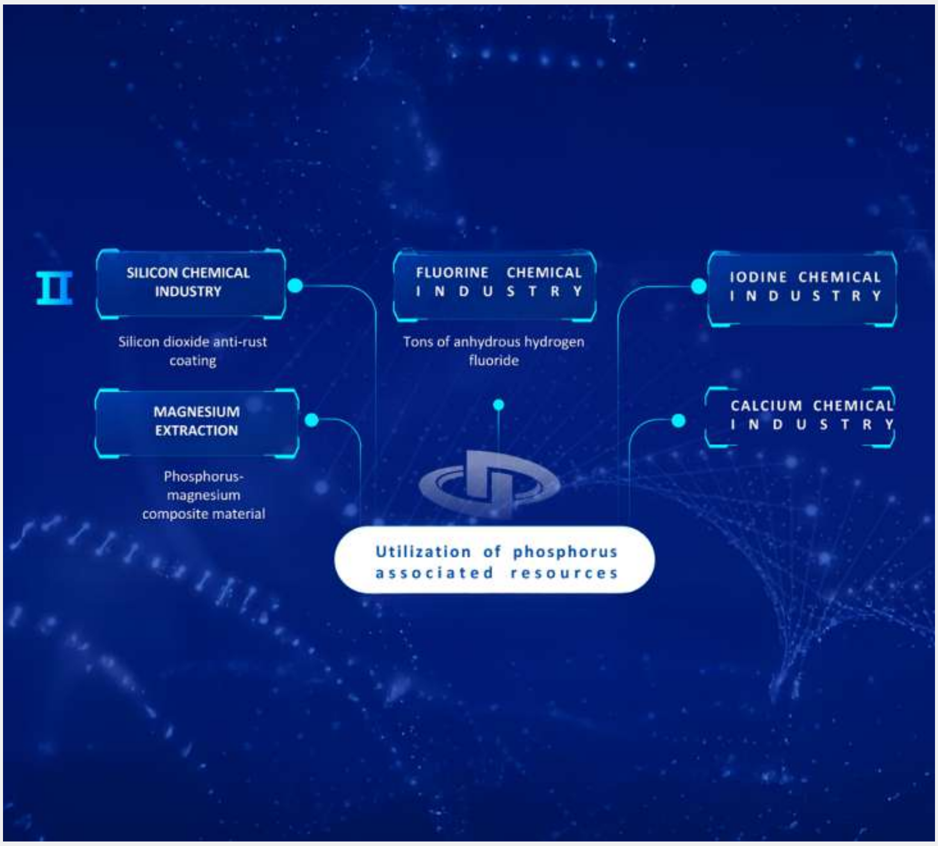


Fig. 138. *The Phosphate Element Value Chain*

The associated industrial resources of P include F, Mg, Si, Ca and I etc, but when one considers the agreed wisdom concerning the chemistry of P rock that "it may contain almost the entire Periodic Table", in the longer term "associated industrial P resources" has a future rich in potential new value chains (Figure 138).

2.3. The Value Chain of By-Product Recycling and Reuse (P and any Secondary Resources)

Fig. 139. *Co-associated Elements*

Early indicators of the speed at which the P-associated resources are spawning new uses, and with them new value chains, (see Figure 139) are well illustrated in this IFA PG report. Guizhou Phosphate Chemical Co. is proud to be one of the leading pioneers in the field. First place is given in this respect to PG, both as a product in its own right and as a multi-use feedstock, in its way as precious as P itself. Managing the inventory of this resource in an optimal way, both fresh from the filter and as legacy, is at the heart of building the new PG value chains.

2.4 Crossbreed Value Chains

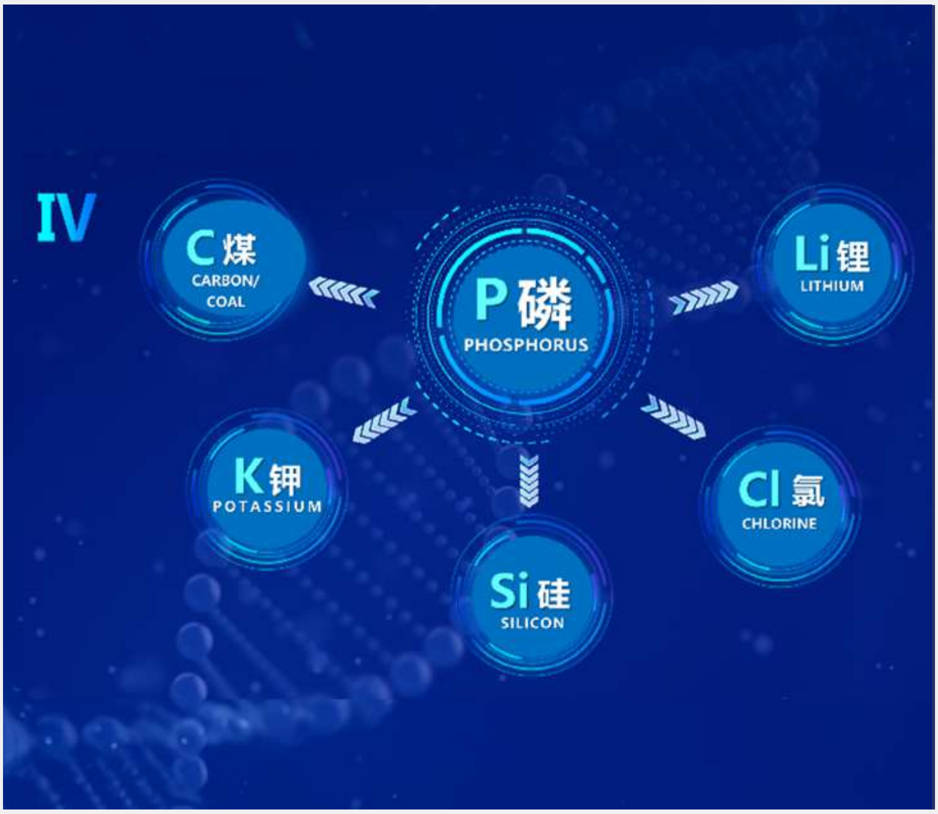


Fig. 140. *The Crossbreed Nexus*

When the field of vision of the entire phosphate resource nexus (Figure 140) is re-plotted in terms of the new industrial era into which we are transitioning, remarkable breakthroughs occur. But they do not drop ripe from the tree. These require creativity, dedication, hard work and strategic levels of investment. Most of all, new value chains begin with people. Two examples for many of the newly expanded GPCG product inventory, high precision building blocks and biodegradable packaging are shown in Figures 141 and 142.

Fig. 141. *High precision blockwork*

Fig. 142. *Biodegradable polymer packaging*

3. The GPCG Growth Curve

What can be clearly seen in the key business metrics 2019-2028, shown in Figure 139, is that after a period of strategic revision and intense investment in innovation at its peak in 2019, a new unifying strategic goal came sharply into focus for GPCG, to recover significantly higher revenue from significantly lower quantities of resources. Success at this is now driving our growth. In the four years from 2019-2023 source rock use had dropped by 23.3% while gross output increased by 70% representing a very significant breakthrough in resource use efficiency, which is mirrored by the quantum jump in trading margins and profitability.

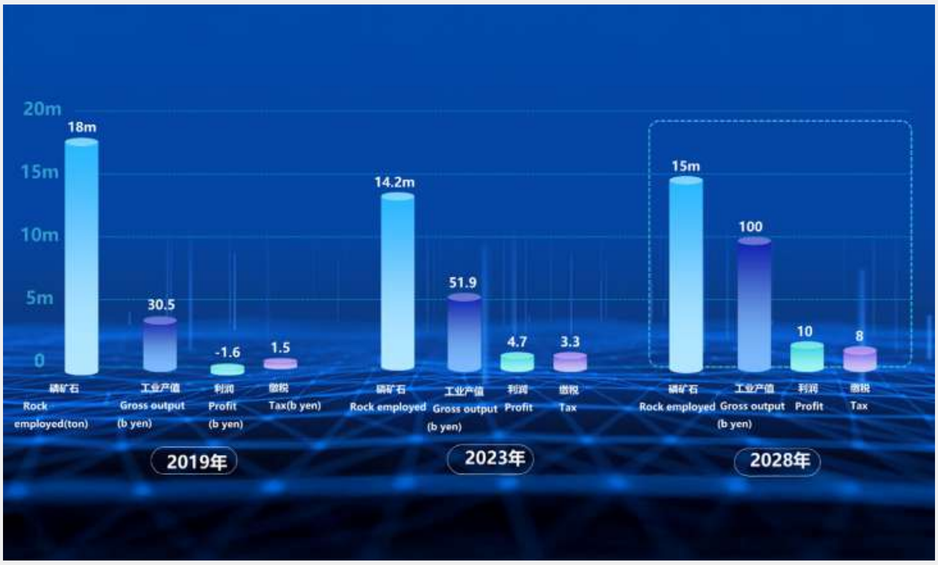


Fig. 143. *The Mid-point Ten Year Transformational Business Model – 2019-2028*

From a business case perspective, Figure 143 also plots the transition pathway that GPCG is now on, in which PG features front and centre as part of the national and global push to reach the goal of 100% PG use. The first major national milestone is now in our sights, to reach 65% by the end of 2026. This in itself is remarkable. But perhaps even more significant is that by turning PG from a costly externality into a valuable feedstock, PG has become a fundamental internality.

The forecast for 2028 is also shown; it demonstrates further the impact of transforming PG from externality to internality, or in terms of this report, from waste to inventory. By 2028 the value returns to the company, society and government are forecast to have fully rebalanced in a highly satisfactory way, meeting the three self-imposed goals:

3.1 The Value Indicators

Output, profit, tax revenue (return to government and society), jobs created and employment.

3.2 Dynamic Business Rule

Marginal output is greater than marginal input.

3.3 Criterion One

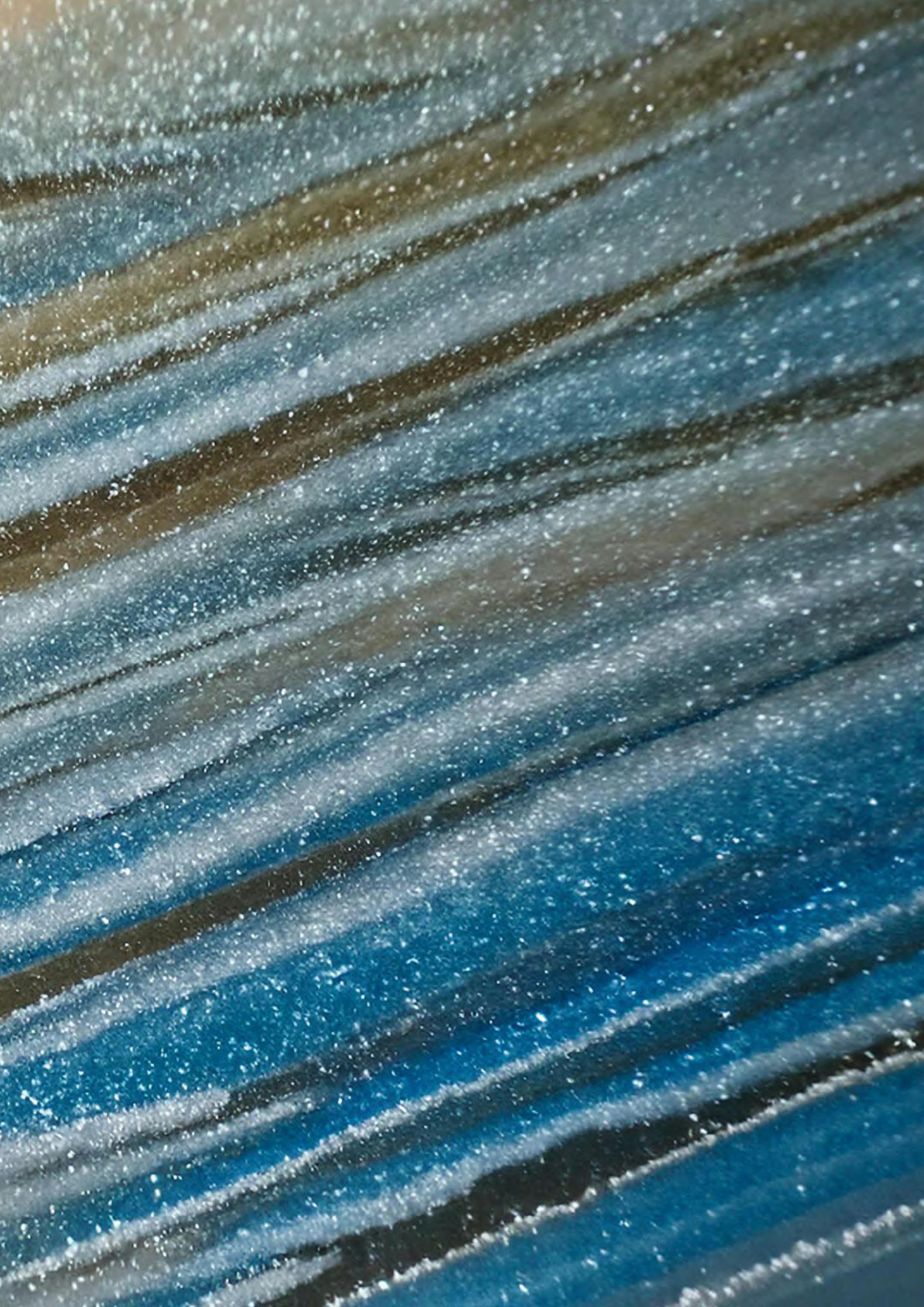
The target value gain has been achieved with as little resource consumption as possible.

4. Postscript - Bracing Forces for these Business Strategies and Goals in the AI Era

Powering the AI era revenue growth curve in the phosphate fertiliser industry will be the unexpected crossbreeds such as PG and its derivatives, polymer hybrids, and new pharmaceuticals, which in the circular economy are both are simultaneously drivers and passengers. Follow the path of comprehensive utilisation in which any resource coming from the wider phosphate resource endowment is of use and value. And if a use has not yet been found, resist taking the easy way out and discarding it. A use will be found if you are determined enough to find it.

AI endows us with a new energetic resource to power the imagination. Make good use of it, the new era productive force, at each new stage in the coming times to seek continuously the optimal solutions to the industry's chemical, technical and management challenges.

Leave no resource unused to the full.



So, what have we learned from PG3?

As compared with the PG2 report (2020), the case studies in PG3 exhibit the attributes of a worldwide, strategic and generational change. The change is not evident everywhere at the same pace and the early adopters of change are now benefitting significantly from first-mover advantage.

PG Business Case Analysis

In greater detail:

1. All companies contributing to this report demonstrate that at least two of the business drivers identified in Section B are strong motivators in their specific business models: policy, values/ social responsibility, innovation, profit and environment.

2. The companies trading consistently profitably in PG (Belgium, Brazil, Canada, Indonesia) and the one at breakeven point, about to turn a profit (China) exhibit beneficial influence of all five drivers. The change-driving investment case is typically anchored in policy rather than a response to market forces. The policy makes the market.

3. Good policies and constructive regulations make for success. Bad policies and rigid regulations erode or destroy value, demotivate and disincentivise innovation. Policy makers must set conditions for success in the regulatory approach as well as among investors and operators.

4. Each company on the path to profit has found a different way to construct a highly resilient circular economic value chain, sometimes by sheer chance and observation, as suits their size, market offering and location.

5. Profitability derives from quality and premium products, not from commoditised bulk.

6. Double materiality works for profitability.

7. The success factors on the supply side are the same as those foregrounded in PG2 – leadership, innovation, partnership – but the x factor is demand-side meeting an ongoing local or business sector or need. Does it remedy deficiencies in your soil or enable greater water retention and use efficiency to carry crop growth across dry seasons? Does it make your trees grow faster and sequester carbon in those trees and soils? Does it act as a substitute for natural gypsum? Does it provide a biodegradable substitute for plastic packaging? Does it contain precious quantities of high performance materials such as those that treat cancers? Does it support the creation of new soils – anthrosols – to offset land lost to urbanisation or desertification? Does it provide a superior performance in roadbed or mine backfill to conventional materials, and are there other SRMs it can combine with to like effect? Unless you look and unless you observe both natural and chemical processes very carefully and over time, you will not find out.

8. Policy compliance is the clear anchor for motivating and underwriting the fundamental pivot from waste to inventory, from PG as waste and liability to PG as a feedstock and asset. But a policy of comprehensive utilisation, without strong social and environmental values at company, professional and personal levels will not drive innovation and creativity and not attract investment.

9. The next major step forward will be the formulation of internationally accepted standards in the provision of PG-based products and services, enabling regional and eventually global trade in PG based products, support services and investments in downstream derivatives. This goal of standards to support trade in products and services is now within reach.

The PG Business Case

TAKEAWAYS

Reclassifying PG from waste to co-product or by-product:

- Recentres the role of management from controlling waste disposal costs to leveraging feedstock revenues.
- Marks a quantum jump for environmental responsibility in the phosphate sector.
- Unlocks innovation, reduces environmental harm and opens doors to new science and technology.
- Releases new PG-based remedial products and services to rehabilitate exhausted mines across a range of minerals, not just phosphates .
- Galvanises the phosphate fertiliser value chain to become circular, sustainable and resource-efficient, opening new investment opportunities.
- Benefits both the environment and surrounding communities.

PG success stories are mounting up:

- They are about real PG businesses from across the world: scalable, decarbonising, profitable for the long term.
- They highlight industry leadership and creativity, smart regulation, collaborative public-private investments and stakeholder engagement.

Devolving financial incentives for PG use in China to local level:

- Promotes building new community assets with PG from abandoned stacks.
- Recovers land from landfill for urban redevelopment.
- Drives comprehensive PG utilisation at national level.
- Shows why and how Environmental, Social and Governance investment works.

Postscript – Ending the Externalities

It has been a great honour and pleasure to work with Volker Andresen, IFA Sustainability Director, the IFA leadership and team and the IFA Phosphogypsum / NORM Working Group since 2015 to assemble now three Phosphogypsum Reports – 2016, 2020 and 2025. These have each been conducted under terms of full editorial independence and peer review, but with all the support – administrative and financial – required from individual contributors and reviewers, IFA member companies, third party public and private sector organisations, academic and scientific organisations, regulators and policy makers to enjoy high levels of approval from the global readership. And while these are IFA reports, they are made available at no cost and are easily accessible online. My heartfelt personal thanks go to all concerned.

One outcome of this process gives me particular satisfaction and has its origins in 2005 not 2015, with IFA support from the outset. In that year, the same year I first started exchanging views on PG with IFA, I was appointed one of the Principal Investigators of an evidence-based review of the impact of the policy of mandatory stacking of phosphogypsum on land. The review was supported by the Florida Institute for Phosphate Research (FIPR) under my wonderful mentor, the Research Director Mike Lloyd. The project title was "Stack Free by '53". Later in 2005 a meeting at the International Atomic Energy Agency, Vienna aligned certain aspects of the project to a Safety Report IAEA had independently launched on Management of NORM Residues in the Phosphate Industry. As FIPR was publicly funded no conflict of interest was seen in the collaboration, so a joint scientific programme between FIPR and IAEA was started, including two major weeklong working meetings held in 2006 and 2007 at the then FIPR HQ at Bartow, Florida. If there was ever a PG world capital, that was surely it.

My particular satisfaction about where PG3 records the industry now to have reached in 2025, makes good on a claim made in late 2006 in a report published by the International Fertiliser Society under my name - "Phosphogypsum – management and opportunities for use: Resolving a conflict between negative externality and public good", Proc. No. 587, International Fertiliser Society, Leek, UK, (2006). The sections of the PG3 report show that that externality conflict can be and is being rapidly resolved, with significant social, environmental and economic benefits.

Quite independently of one another, five remarkable figures Dr. Malika Moussaid and I have worked with over many years on PG illustrate exactly the Nelson Mandela approach to meeting challenges of the type we signed on to with FIPR in 2005, turning negative externalities into positive internalities. These are: Mike Lloyd Jr. former Research Director, Florida Institute of Phosphate Research, Dr. Denys Wymer, sometime technical officer, International Atomic Energy Agency, Esin Mete, former President, IFA, Volker Andresen, Sustainability Director IFA, and He Guangliang, Chairman, Guizhou Phosphate Chemical Group.

Thank you to them and the countless others who have helped, cajoled and inspired us along the way, and who would take another report this long simply to list by name…

Post Postscript

In the course of assembling PG3 for publication it has been a pleasure to work with the graphic designer Federico Anastasi and the 50A team.

Early on in the publication process, I asked Federico to develop a graphical representation of what the current state and future direction of the Phosphogypsum Industry looked like, capturing the mood of excitement, innovation, and pride in collective achievement I increasingly sensed as I received the chapters of this Report.

The result is on the opposite page to this one.

At its simplest, a **Phosphogypsum Renaissance** is well underway, the outcome of which is the birth, or rebirth, of a global Phosphogypsum industry.

Long, barren years of wandering in a seemingly sterile and hostile wasteland are coming to an end, not by leaving a Phosphogypsum wasteland behind but by first understanding it, learning from it and then restoring and transforming it, for the benefit of People, Planet and Prosperity.

As is shown in the final four chapters, for all the brilliant reasoning, scientific and technical prowess captured in the three IFA PG Reports without a shared and concerted vision of change, a sprinkling of Aha moments and dogged, irrational and courageous determination on the part of many the PG desert would still not be turning green... but now it is, as we learn to appreciate the precious resource that it is.

"It always seems impossible until it's done".

Julian Hilton,
General Editor

PHOSPHOGYPSUM RENAISSANCE

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