EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology, 2025, 26(4), 374–388
https://doi.org/10.12912/27197050/202291
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Received: 2025.02.11
Accepted: 2025.02.25
Published: 2025.03.01

Using phosphogypsum in road engineering: Optimizing materials and structure

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ABSTRACT

The yearly phosphogypsum (PG) production is significant, posing technical and environmental challenges for its permanent stacking. However, within the context of the circular economy, the value-adding of this coproduct in civil engineering, particularly in the construction of roads, is a viable option. Positive mechanical (by deflector) and environmental (by leaching test) evaluations were made possible by the first experimental one-kilometer-long pilot project, constructed at Safi, Morocco in 2017. It included four distinct PG-based formulations with a 7% cement addition. To further assess the feasibility of using PG as a road material, our experimental approach here focuses on material mixture optimization – made of phosphogypsum (maximum content desired) treated with cement (to be minimized to reduce the cost) and sand or steel slag as granular corrector to meet road mechanical requirements. Phosphogypsum made at the Jorf Lasfar plant and other materials were first identified and characterized. The design of experiment (DOE) method is used to simulate the desired mechanical and physical responses and to identify domains that satisfy the requirements for using the mixed material as the foundation layer or as a subgrade layer for roads. Furthermore, using a parametric analysis, we assessed the influences of traffic level, soil bearing capacity, and mechanical performance of treated phosphogypsum mixtures on pavement design for three distinct pavement structures (mixed, reverse, and structure with treated sub-base) and concluded that the pavement structure with sub-base treated with hydraulic binder is the best to adopt for maximizing phosphogypsum recycling.

Keywords: PG, circular economy, road material, optimized mixture.

INTRODUCTION

Phosphogypsum (PG) is a coproduct from natural phosphate rock processing, into phosphoric acid using a wet industrial process. The phosphoric acid wet chemical treatment process, or "Wet Process", is widely used to produce phosphoric acid (up to 90%) and calcium sulfate—mainly in the dihydrate form ($CaSO_4 \cdot 2H_2O$). The reaction is as follows (Equation 1):

$$Ca_5F(PO_4)_3 + 5H_2SO_4 + 10H_2O \rightarrow \\ \rightarrow H_3PO_4 + 5CaSO_4 \cdot 2H_2O + HF \quad (1)$$

The wet process is economical but generates a large amount of PG (5 tons of PG per ton of phosphoric acid produced) (Rutherford et al., 1994). Thus, the world production of PG is estimated between 100 and 280 Mt per year (Weiksnar et al., 2023). Knowing the physio-chemical properties of PG is of great importance to developing technical solutions for the management and/or sustainable use of this coproduct. PG properties depend on the nature of the phosphate ore, the wet process used and the operating efficiency of the plant. In terms of chemical composition, the main component of PG is gypsum, so sulfate and calcium can constitute more than 90% of its chemical composition. Wet process or inheritance from the ore could explain the presence of other elements in PG. From a morphological point of view, PG has, depending on the phosphate rock source, a majority of particle size between 0.045 mm and 0.250 in diameter (Tayibi et al., 2009). PG has a crystalline structure, mainly of rhombic and hexagonal shapes. In terms of physical properties, due to acidic phosphoric, sulfuric, and hydrofluoric residues contained in the porous PG, it is considered an acidic coproduct (pH < 3): this point is to be considered for any further use. The solubility of PG depends on its pH, and PG is very soluble in salt water (4.1 g/L). Its particle density is between 2.27 and 2.40 g/cm^3 (Silva et al., 2022) and its bulk density is between 0.9 and 1.7 g/cm^3 (Vick, 1984). The vertical hydraulic conductivity of phosphogypsum would be between 1×10^{-5} and 2×10^{-7} m/s (Silva et al., 2022).

Road construction, which consumes large quantities of granular materials, appears to be one of the practical and promising valorization ways for PG. Indeed, recycling this type of material could provide interesting solutions to current construction materials shortage, within a circular economy framework. However, this objective needs a rigorous scientific methodology and pilot experiments to demonstrate its relevance. The history of PG's use in road building around the world presented by IFA (Phosphogypsum, n.d.), proved this valorization way meets specific local needs, preserves raw building materials, and has a negligible environmental impact:

- USA ("Phosphogypsum," n.d.) was the first to experiment with it since 1985, PG was used as a binder to stabilize soil in place, in mixtures showing more advantages than those with clay. Indeed, PG mixtures, after compaction, did not absorb large amounts of water, thus minimizing delays due to rainy days. Shrinkage and swelling cracks were also reduced, with a gain in stability and pavement base strengthening over time. For example, a control section with PG built in Florida has proven to show better mechanical properties than the one built with conventional materials, after 21 years of use. In Texas, since 1991, test sections in city streets, shopping centers, truck terminals, parking lots, and loading platforms have been successfully constructed using cement-fly ash-stabilized PG.
- In Russia, in 2014 (Phosphogypsum: Sustainable Management and Use, n.d.), firstly in Moscow and then in Rostov region, the level of measured radioactivity in the experimental roads showed there is no local restriction on PG use in road construction.
- In Finland (Phosphogypsum: Sustainable Management and Use, n.d.) on a rural road in Maanikan, PG-fly ash mixtures worked perfectly in comparison with conventional materials. PG use, as an industrial coproduct, has shown to be environmentally unharmful, as laboratory tests indicate, but more significantly as proven through experimental pilots.
- In 2018, in India (Havanagi et al., 2018), phosphogypsum from Paradeep was used in backfill and subgrade layers. Other works followed in China; in 2020 (Peng et al., 2020), for example, researchers tried to establish pH and particle fineness effects on mechanical properties of PG mixtures for stabilized soil-cement-PG for road construction use.

Researches were led in Morocco too, as in 2020 (Amrani et al., 2020), an evaluation of raw phosphogypsum use alone as embankment material and the stabilizing effect of various additives such as clayey soil, fly ash, lime, calcareous material, and a special hydraulic road binder, to use these mixtures as a base material in road pavement, while ensuring a neutralization of PG acidity. Another feasibility study in 2021 focused on the stabilizing effect of fly ash and lime addition on the strength and durability of PG use as road material (Meskini et al., 2021). These research works are exclusively laboratory tests.

In Morocco, OCP Group, a leading global producer of phosphates and their derivatives, processes phosphate rock into phosphoric acid using the wet process at Safi and Jorf Lasfar industrial complexes, which generates a significant quantity of PG. Several valorization ways are being explored for this co-product, among which PG is used as road material. So, in 2013, the OCP group launched a scientific partnership with academic institutions – ENPC (Ecole Nationale des Ponts et Chaussées) and EHTP (Ecole Hassania des Travaux Publics) – and professionals – the CNER (Centre National des Etudes et de Recherches Routières) at Ministère de l'Equipement, du Transport, de la Logistique et de l'Eau (Ministry of Equipment, Transport, Logistics and Water and GTR (Colas subsidiary in Morocco), to lead research works and then develop pilot road sections at Safi site in 2017 then at Jorf Lasfar industrial complex in 2019.

The first experimental pilot road built in the Safi region used as a subgrade layer, four different PG mixes, with either phosphate washing tailings or sand as a granular corrector and a fixed addition of cement (7%), based on literature review (Felfoul et al., 2004). The mechanical assessment, carried out using a Lacroix deflectograph after two years of heavy traffic, proved that PG mixtures gave better results than the control section made up of soil in place. The elastic modulus gave better long-term bearing capacity classes for the four sections (PF3 and PF4) than for the control one (PF2) (Diouri et al., 2022), with a service lifetime of 25 years. Moreover, environmental assessment, based on leaching tests, showed that all measured trace element concentrations were well below national and international limits.

Based on these good results, the objective of the present study is to move on to the multi-objective (environmental and economic) and multi-scale (materials and structures) optimization of the use of PG as a pavement material. This work will focus on the use of the PG produced at the Jorf Lasfar plant. Indeed, the use of this material could provide interesting solutions to the decrease in the availability of primary materials within the frame of a circular economy. This is why we tested steel slag, another local coproduct of the metallurgical industry, as a granular corrector. In addition, to optimize cost, we varied the cement content. To complete the optimization of the materials, we also conducted a parametric study to evaluate different pavement structures according to the bearing capacity of the soils in place, the level of the traffic, and the mechanical properties of the PG-based mixtures.

In the first section of this paper, we carried out a detailed chemical characterization of Jorf Lasfar's PG and all the other materials used in this study as granular corrector (steel slag and crushed sand) or hydraulic binder (cement). We define mechanical criteria for a material use in road construction and explain why raw PG cannot be used alone neither in subgrade or pavement layer, then we detail all factors and responses with the experimental methods used. Then we present methods for material optimization by varying the proportions of the constituents: a mixture design approach allows determining mathematical modeling of needed physical and mechanical properties of phosphogypsum mixtures. The determination of the mechanical properties requires prior knowledge of the optimum water content to determine the density of the mixture. The method we have developed for this purpose is presented. To evaluate the impact of pavement structure, and assess which pavement structure would be the most relevant one to recycle the maximum amount of phosphogypsum at the lowest cost, a parametric study (Diouri et al., 2021), using numerical simulations with Alize-LCPC (2024), design model analyzes the effects of traffic level, soil bearing capacity and mechanical performance of the PG mixtures on pavement conception.

In the second section, results obtained from mixture design experiments are presented, the mathematical modeling of desired responses as well as domains meeting the required criteria for using the mixture material either as road subgrade layer or foundation layer. The effects of soil bearing capacity, traffic level, and mechanical properties of PG-based materials on pavement structures' design are also discussed. We then draw some conclusions and present some perspectives on work continuation.

MATERIALS AND METHODS

Raw materials

Jorf Lasfar PG

In Morocco, different qualities of PG are being produced at the Safi and Jorf Lasfar industrial complexes. The first experiment in Safi having given encouraging results (Diouri et al., 2022), the research study was extended to Jorf Lasfar the largest production site. PG taken from the production unit of Jorf Lasfar has 30% water content. The phosphogypsum consists of 95% dry weight of calcium sulfate dihydrate determined by diffractometric analysis (Moutaouakil et al., 2015). Minerals of quartz, dicalcium phosphate, iron, magnesium, and aluminum sulfates constitute the minority solid fraction. The phosphogypsum is presented in the form of crystals tabular to parallelepipedal elongated crystals (Moutaouakil et al., 2015). This is an industrial coproduct, so according to the road earthworks guide GTR (SETRA – Service d'Etudes Techniques des Routes et Autoroutes, 1992), it is an F5 class material.

Cement

It is a composite Portland cement rated CEM II, coming from Lafarge-Holcim Bouskoura's plant near Casablanca (Morocco). The chemical characteristics are listed in Table 1. Its loss on ignition at 1,000 °C (%) is 3.0%, insoluble residue

14.2%, Blaine specific surface 3,908.7 cm²/g, mixing water 30.8%, expansion 1.2 mm, start of setting time 229.7 min, end of setting time 330.9 min. In terms of mechanical resistance, simple compression strength (measured according to NF EN 13286-41) at 2 days is 14.3 MPa, 33.2 MPa at 7 days, and 41 MPa at 28 days.

Steel slag

In metallurgy, especially steel, slag is a solid by-product of smelting, refining, treating, or shaping metals at high temperatures. It is a various oxides mixture that floats on the molten metal or is detached from it when it is processed at high temperature. Our steel slag comes from Sonasid, a steel industry, adjacent to OCP's Jorf Lasfar industrial complex. Its water content is about 0.03%, so it is a dry material. Its impact resistance is determined at LCC by(SETRA, 1992):

- Micro deval index: MDE (NF P 18-572) = 7,
- Los Angeles index: LA (NF P 18-573) = 16.

They are therefore very hard aggregates. GTR Class (SETRA, 1992): this is an industrial by-product, so according to the road earthworks guide it is an F8 class material.

Sand

It is a crushed siliceous sand, of a 5 mm maximum diameter. Its fine element content (< 80 µm) is about 9%, almost zero water content. The apparent density is about 1.60 g/cm³.

Characterization methods

For chemical characterization of both PG and steel slag, Plasma emission with optical detection (ICP OES) is the method used to quantify sulfur trioxide SO_3, calcium oxide CaO, phosphoric anhydride P_2O_5, alumina Al_2O_3, potassium oxide K_2O, silicon dioxide SiO_2, magnesium oxide MgO, iron oxide Fe_2O_3, and sodium dioxide Na_2O by continuous flow.

PH measurement was done after 5 min agitating of 10 g dry sample in 100 mL distilled water, then using a direct pH-meter.

Table 1. Raw materials characterization

	PG	C	SS
pH	2.85		11.22
SO_3 (g/100g)	39	2.8	0.26
CaO (g/100g)	26	47.7	26
Al_2O_3 (g/100g)	0.16		8.52
K_2O (g/100g)	0.06	1.2	0.16
SiO_2 (g/100g)	0.02		0.52
MgO (g/100g)	0.02	2.2	4.73
Fe_2O_3 (g/100g)	0.01		24
Na_2O (g/100g)		0.4	

Raw materials properties

Table 1 shows some of the raw materials' chemical composition and their pH.

Mechanical criteria for use as road materials

The objective is to evaluate the effect of the variation of the proportions of the constituents of the various mixtures on the physical and mechanical characteristics that allow mechanical dimensioning and stability monitoring, as defined by road design guides. The criteria for subgrade layers and foundation layers are presented hereafter.

Mechanical criteria for subgrade layer

Mixture criteria for subgrade layer use are (Schaeffner et al., 2000):

- Californian-bearing ratio after 4 days of water immersion CBR-4d>20 and CBR-4d/IBI>1,
- simple compressive strength Cs28d>1MPa,
- diametral tensile strength (Ts360d), and Elastic modulus (E360d) at least in zone 5 of the classification chart (Fig. 1).

Mechanical criteria for pavement layer

Mixture criteria for foundation layer use are similar to those above, except (CFTR, 2007):

- Cs > 1.2 MPa to take into account average site traffic,
- (Ts360d, E360d) at least in zone T1 of the classification chart (Fig. 2).

Material optimization procedure

Bearing capacity of PG

Load-bearing tests are conducted on raw PG (according to NF P 94-078) the results of which, shown in Table 2, proved that raw PG does not meet the mechanical criteria of road use from GTS 2000 (Schaeffner et al., 2000; CFTR, 2007). For this reason, a cement treatment is necessary, for stabilization and required resistance achievement. This cement addition also

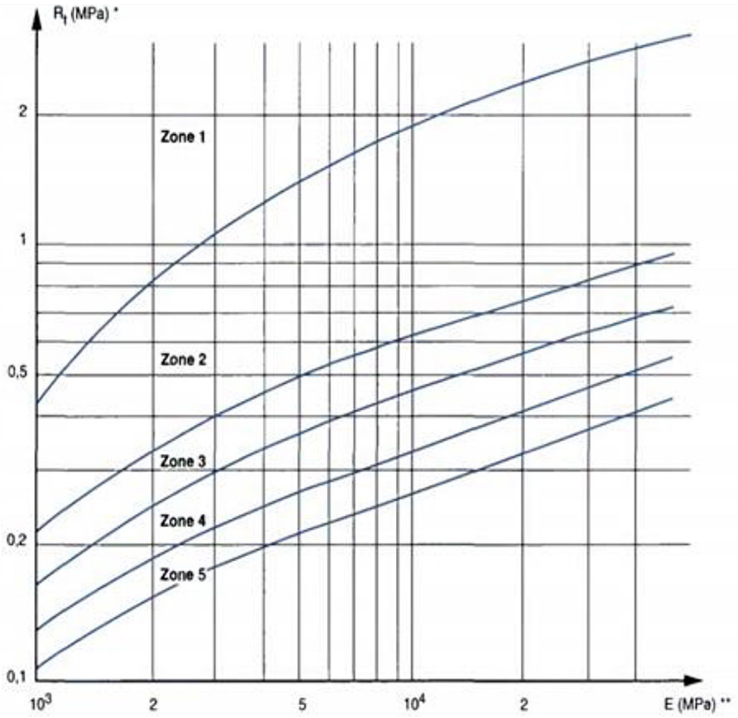

Figure 1. Classification chart of treated materials for subgrade layer

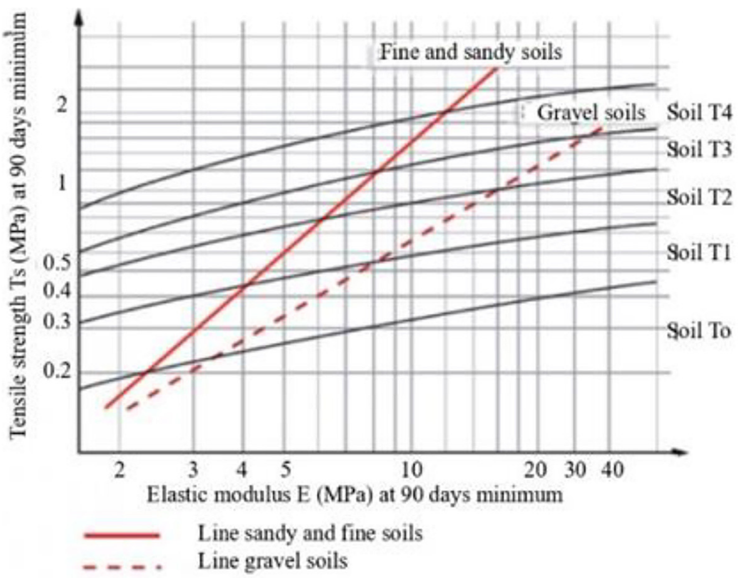

Figure 2. Classification chart of treated materials for the foundation layer

neutralized the acidity due to the PG. Moreover, a granular correction using conventional materials (sand, aggregates) is also recommended to achieve a better granular skeleton and thus higher density. To remain in a circular economy approach, other available by-products (steel slag (SS), and washing tailings (T) have been considered. In this article, steel slag (SS) and sand (S) have been chosen for the 1st and 2nd formulations respectively.

Design of experiment method

To evaluate the variation effect in constituents' proportions on the responses, and to derive mathematical models of the responses, the design of experiment (DOE) method is adopted (Goupy, 2016.), which is a statistical approach offering several tools that make it possible to control a multi-parameter problem, while following an experimental program.

Table 2. Bearing test results of raw PG

	IBI	CBR-4d	CBR 4d/IPI	G_V (%)
PG	68	46	0.67	0.10

It aims to:
- minimize experimental measurements' number compared to a classic approach, while ensuring a quality of results, if not better, at least identical,
- put the focus on expected results, before experimenting with them,
- determine key factors in a new product design.

It is therefore an effective tool in the case of this study where experimentation is associated with a modeling objective. We are dealing with a 3-component mixture in which the sum of proportions is equal to 100%, therefore the mixture design under constraints (Goupy, 2016) turns out to be the best design suited for this study.

Responses

The responses targeted throughout this study are those defined in section 2.4:
- IBI: Immediate bearing index according to NF P 94-078 (Fig. 3),

Figure 3. Immediate bearing index (NF P 94-078)

Figure 4. Californian bearing ratio after 4 days of water immersion and vertical swelling after 4 days of water immersion with overload (NF P 94-078)

Figure 5. Simple compressive strength (NF EN 13286-41)

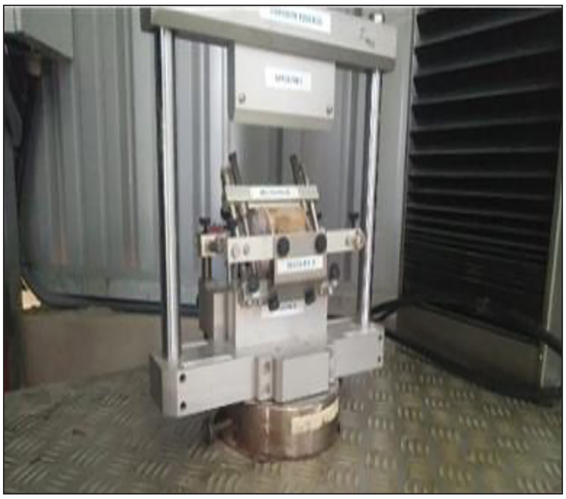

Figure 6. Diametral tensile strength and elastic modulus (NF P 98-232-3)

- CBR-4d: Californian bearing ratio after 4 days of water immersion according to NF P 94-078 (Fig. 4),
- Gv: The vertical swelling after 4 days of water immersion with overload (%) according to NF P 94-078 (Fig. 4),
- Cs7d, 28d: Simple compressive strength at 7 and 28 days (MPa) according to NF EN 13286-41 (Fig. 5),
- Ts28d: Diametral tensile strength at 28 days (MPa) according to NF EN 13286-41 (Fig. 6),
- E28d: Elastic modulus at 28 days (MPa) according to NF P 98-232-3 (Fig. 6).

Factors and fields of study

Factors considered throughout this research are the principal components necessary for the mixture formulation: phosphogypsum, steel slags or sand, cement, and more precisely their content in mixtures. Choosing ranges of study for all factors was determined in such a way as to maximize the use of PG and minimize the cement use:

- 45% < PG < 70%,
- 4% < C < 7%,
- 23% < SS or S < 48%.

The optimal matrix of experiments (mathematically) is defined to achieve reliable and efficient results while minimizing the number of tests(Goupy, 2016.). Our experimental matrix is represented in Table 3, and the field of study on the simplex in Figure 7. The granular envelope of the 9 experimental points in Figure 8 turns out to be continuous and well distributed.

Table 3. Table represents experimental points

Formulation	PG (%)	SS or S (%)	C (%)
1	70.000	26.000	4.00
2	51.625	42.125	6.25
3	58.250	36.250	5.50
4	64.125	29.625	6.25
5	70.000	23.000	7.00
6	53.125	42.125	4.75
7	48.000	48.000	4.00
8	45.000	48.000	7.00
9	64.125	31.125	4.75[1]

Sample preparation and water content

Simple compression test Cs is carried out for a material density set at 98.5% of Proctor dry density (NF P 98-230-1), while tensile strength test Ts is set at 96% of Proctor dry density (NF P 98-230-3) (Fig. 9). It is therefore necessary to determine optimal Proctor density of experimental mixtures before studying targeted responses.

Proctor test requires density determination of at least five points at different water contents. Performing these tests for each of the nine experimental mixtures requires 45 experimental points. To save time and gain productivity, we opted for mathematical modeling, which would make it possible to obtain Proctor results based on the DOE method. We worked on the mixture (PG-S-C). The modeling consists of taking a sample of 15 points with different water contents to build a mathematical model that predicts Proctor densities and Proctor water content values.

The chosen model should establish an equation considering PG, sand, and cement dosages as factors, in addition to water content to give the mixture dry density. Then, this equation is used to obtain optimal dry density and Proctor water content for each mixture processed.

Targeted results, Proctor optimum dry density, and water content are shown in the next section.

Pavement structure optimization

In order to determine the optimal type of pavement structure allowing better road use of phosphogypsum, a parametric study was carried out on 3 types of pavement structure (Fig.

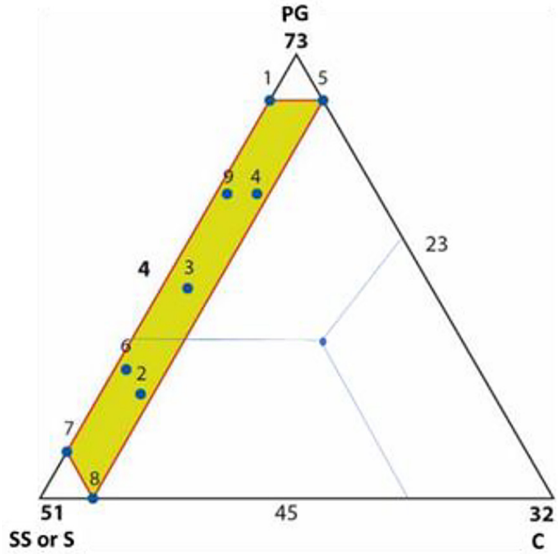

Figure 7. Graphic representation of the 9 experimental points in the study area

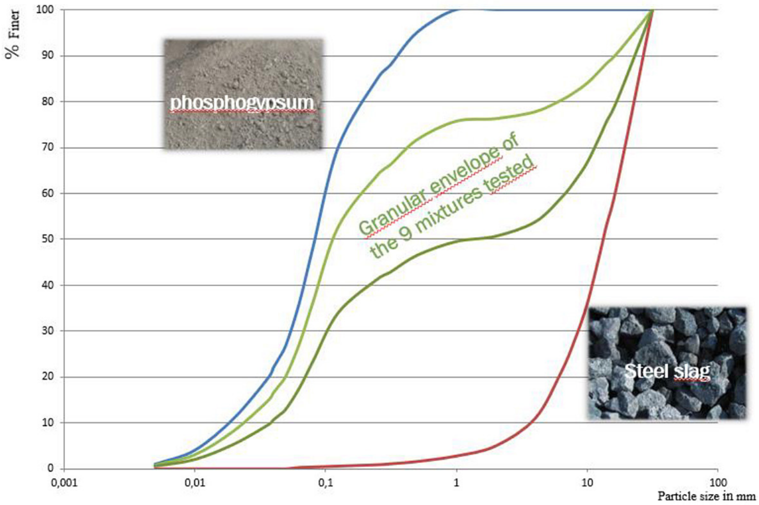

Figure 8. Particle size distribution of PG, SS, and the 9 mixtures of the PG-SS-C formulation

Figure 9. Moulding-demoulding of simple compressive strength test tubes

10), varying three factors: bearing capacity of the soil (BC), traffic level (Tr), and mechanical performance of phosphogypsum mixes (Diouri et al., 2021).

- 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 (itech, n.d.) (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 annual average daily traffic TMJA, the class T, and the number of axles NPL of 13 tons of heavy goods vehicles soliciting the roadway refer to the values from the middle of the traffic class T2 and T3 of PNM 2019 (Projet de Norme Marocaine PNM 13.1.219 (2019) Dimensionnement Structurel Des Chaussées Routières: Application Aux Chaussées Neuves., n.d.) (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).

RESULTS

Proctor model optimization

The actual Proctor test points are presented in Table 4. For each experimental point, Proctor optimum dry density has been measured.

The quadratic model is judged to be the most suitable for our case study since it has a larger adjusted correlation coefficient (Goupy, 2016). Moreover, its *p*-value (Goupy, 2016) is less than 0.05, which proves that this model is statistically valid. It has an adjusted R^2 coefficient (Goupy, 2016) of 88%. A verification of the model for our experimental points shows that the difference between actual results and density obtained through the model does not exceed

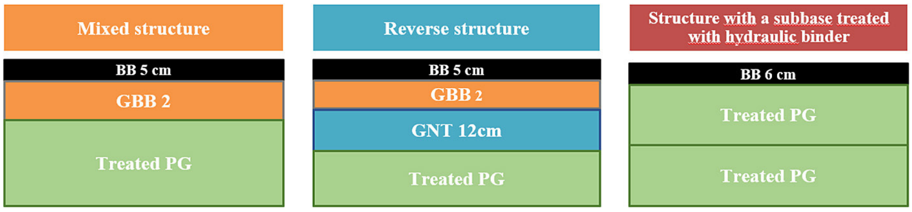

Figure 10. Types of pavement structures considered in the parametric study (Diouri et al., 2022)

Table 4. Experimental points of Proctor test modeling

No.	PG	S	C	w (water content)
1	0.7	0.26	0.04	0.064
2	0.7	0.26	0.04	0.085
3	0.51625	0.42125	0.0625	0.08
4	0.5825	0.3625	0.055	0.086
5	0.5825	0.3625	0.055	0.115
6	0.64125	0.29625	0.0625	0.12
7	0.7	0.23	0.07	0.16
8	0.53125	0.42125	0.0475	0.127
9	0.53125	0.42125	0.0475	0.14
10	0.48	0.48	0.04	0.09
11	0.48	0.48	0.04	0.102
12	0.45	0.48	0.07	0.08
13	0.45	0.48	0.07	0.07
14	0.64125	0.31125	0.0475	0.06
15	0.64125	0.31125	0.0475	0.1

0.01 t/m^3 on average.Based on regression equation, and fixing the other parameters (PG-S-C) for each mixture, we go back to a second order polynomial equation we can solve to determine the couple (w_{opm}, D_{opm}):

$$D(w) = aw^2 + bw + cte \quad (2)$$

$$W_{opm} = -b/2a;\ D_{opm} = D(w_{opm}) \quad (3)$$

DOE results

Bearing and swelling test

For each of the studied formulations, we carried out an immediate bearing test IBI, a CBR after 4 days of water immersion and measured vertical swelling Gv. PG-SS-C and PG-S-C mixtures'

Table 5. IBI and Gv for PG-SS-C and PG-S-C formulations

Mixture	PG-SS-C		PG-S-C	
Response	IBI	Gv (%)	IBI	Gv (%)
1	80	0.7	160	0.1
2	138	0.4	191	0.3
3	121	0.2	124	0.1
4	111	0.6	145	0.4
5	102	0.8	138	0.5
6	119	0.2	133	0.1
7	128	0.09	158	0.03
8	140	0.6	149	0.2
9	98	0.4	101	0.2

results are shown in Table 5. CBR-4d data can be requested from the author, and range between 100 and 278 for PG-SS-C and between 115 and 322 for PG-S-C.

Mathematical response models

Now that all experimental results are available, DOE method is proceeded, to mathematically model each of the targeted responses, continuously over the entire study area.

Thus, responses of mathematical models for PG-SS-C mixture are shown in Table 8, and for PG-S-C in Table 9.

Model verification example: E28d

E28d response model is drawn in Figure 11. Module increases with cement content, and at a fixed one, it increases with steel slag content, and decreases with PG content.

An experimental verification 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 Equations 4 and 5. It is clear that relative deviation (less than 8%) remains acceptable (Table 10). 360 days value is the sizing value, since it will be reported on the classification chart mentioned above (Fig. 11).

$$\frac{E_{28days}}{E_{360days}} = 0.65 \qquad (4)$$

$$\frac{E_{90days}}{E_{360days}} = 0.7 \qquad (5)$$

DISCUSSION

Proctor optimization

The main effects diagram (Fig. 12) defines each factor (PG, S and C) and each process variable (*w*) main effect on density values: to have a

Table 6. Experimental results of the simple compressive strength of the PG-SS-C and PG-S-C mixtures at 7 days

Mixture	PG-SS-C		PG-S-C	
Response	Cs 7d (MPa)	Cs 7d (bis) (MPa)	Cs 7d (MPa)	Cs 7d (bis) (MPa)
1	0.18	0.16	0.22	0.20
2	0.27	0.26	0.29	0.32
3	0.24	0.22	0.44	0.45
4	0.27	0.27	0.37	0.37
5	0.21	0.21	0.86	0.96
6	0.22	0.21	0.48	0.62
7	0.21	0.215	0.55	0.53
8	0.35	0.35	0.79	0.89
9	0.2	0.19	0.40	0.37

Table 7. Experimental results of tensile strength and stiffness modulus for PG-SS-C mixture at 28 d

Mixture	PG-SS-C		PG-S-C	
Response	E 28d (MPa)	E 28d (bis) (MPa)	E 28d (MPa)	E 28d (bis) (MPa)
1	1,263.6	1,300	1,098	1,053
2	1,048.4	1,100	1,349	1,166
3	1,046.5	1,050	1,861	1,812
4	919.1	950	708	726
5	785.8	801	1,376	1,359
6	806.6	810	600	590
7	1,358.5	1,415	530	535
8	1,302.6	1,298	1,155	1,042
9	910.6	899	647	601

Table 8. Responses mathematical models for PG-SS-C mixture

Mathematical models of the responses of the PG-SS-C mixture (the dosages are 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
E28d = 150×PG - 598×SS + 193,016×C + 33×PG×SS - 2,152×PG×C - 2,146×SS×C	92%	0

Table 9. Responses mathematical models for PG-S-C mixture

Mathematical models of the responses of the PG-S-C mixture (the dosages are in %)	Adjusted R^2	*p*-value
Gv (%) = 1.06×PG + 18.57×S - 3,222.45×C – 0.79×PG×S + 35.44×PG×C + 34×67×S×C + 0.034×PG×S×C	99%	0
IBI (%) = 22.75×PG - 125.31×S + 37,753.13×C + 6.72×PG×S - 420.44×PG×C – 420.26×S×C	99%	0,01
Cs7d (MPa) = -0.92×PG - 13.45×S + 2,271.59×C + 0.57×PG×S - 24.94×PG×C - 24.36×SC×C - 0.0267×PG×S×C	95%	0
E28d (MPa) = -7,645.4×PG - 136,430×S + 23,774,900×C + 5,851×PG×S - 261,479×PG×C - 255,924.2×S×C - 252.25×PG×S×C	97%	0

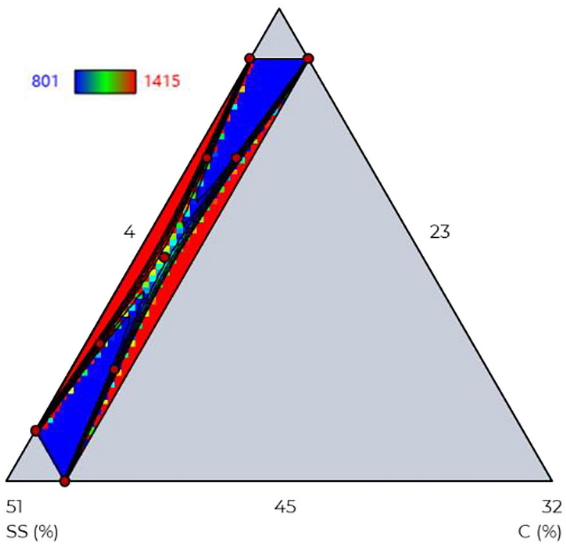

Figure 11. Elastic modulus E28d modeling for PG-SS-C mixtures

high Proctor density it is practical to seek a compromise between PG average values, S maximum values and water content mean values. Cement effect can be considered as negligible compared to those of other factors. The coefficients *a* and *b* obtained are low, which means that dry density curves as a water content function are relatively flat nearby Proctor optimum. This is a material positive characteristic which allows an easy implementation on site.

The cement treatment allows a significant reduction in the water content of the mixture. Sand has a positive influence on increasing dry density. The mixture optimum water content is relatively low, which contributes to durability improvement of pavement layers. Thus, the results of this Proctor mathematical modeling led to water optimum values w_{opm} ranging between 8.44% and 9.55% whereas associated optimal Proctor densities D_{opm} ranged between 1.61 t/ and 1.82 t/.

The addition of cement and steel slag considerably improves the immediate bearing capacity, as well as after 4 days of water immersion.

For mixtures with the same cement dosage (i.e., mixtures 1 and 8) the IBI goes from 102 to 140 and the CBR-4d from 159 to 278, which shows steel slag has influence on bearing capacity, which is clearly improved after 4 days of water

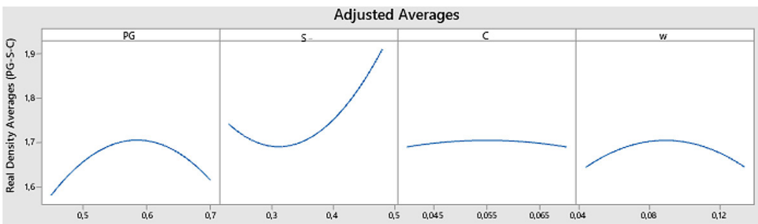

Figure 12. Main effects diagram, Proctor modeling

immersion. The CBR-4d/IBI ratios are all greater than 1, which is a criterion for the treatment durability (Schaeffner et al., 2000)

The vertical swelling Gv varies between 0.094% and 0.84%, which represents acceptable values for subgrade layer use. Indeed, the GTS 2000 (Schaeffner et al., 2000) and CFTR 2007 (*CFTR*, 2007) guides tolerate a maximum swelling of 5%. The results of the PG-S-C shown in Table 5, prove that a high dosage of sand gives greater bearing indexes in addition to increased dry densities. However, sand alone does not have a dominant effect.

Compressive strength

The simple compressive strength values at 7days for PG-SS-C and PG-S-C mixtures, carried out twice, are shown in Table 6. Based on these results, we conclude that at the age of 7 d, all mixtures' simple compressive strength does not exceed 0.4 MPa, which means that time for circulation exceeds 7 d. According to GTS 2000 and CFTR 2007, the simple compressive strength should exceed 1 MPa at the age of circulation.

Elastic modulus

Elastic modulus E28d results for PG-SS-C and PG-S-C mixtures at 28 days are presented in Table 7, whereas tensile strength at 28 days can be requested from the author.

Table 10. Values verification of the mathematical model E28d for a specific mixture PG-SS-C

Modulus	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%

Note: ** Extrapolated from E28d (Equation 4);
* Extrapolated from E360d (Equation 5).

Mixtures verifying mechanical criteria

Having modeled all needed responses, we can graphically determine domains where materials' properties verify the criteria.

Mixtures for PG-SS-C formulations verifying criteria either for subgrade or foundation layer are represented in Figure 13. It shows that a wide area respects all criteria mentioned above, that can be combined, if needed, with economic, environmental and radiological criteria.

Pavement structure optimization

Factors effect

For the three types of pavement structures (Fig. 10), soil bearing capacity has an important effect on pavement total thickness (Fig. 14), in particular that of the treated phosphogypsum layer, which decreases when going from a low level of soil bearing capacity () to a high level (). 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 of this by-product. Indeed, this type of pavement can consume up to twice more phosphogypsum than pavements with a mixed structure, and up to 2.3 times more phosphogypsum than pavements with an inverse structure.

For the three types of pavements, the total thickness of the pavement and that of the treated phosphogypsum layer increase with heavy traffic. In this particular case, inverse pavement structure can be more interesting (Fig. 14). In general, the total thickness of the pavement and that of the

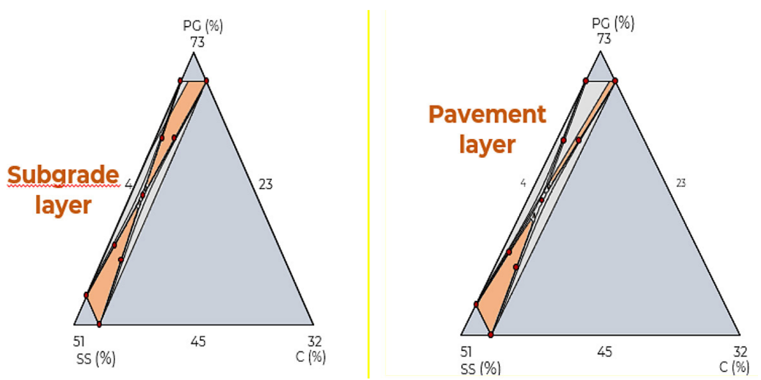

Figure 13. PG-SS-C: suitable domain either for subgrade or foundation layer

treated phosphogypsum for mixed structures tend to decrease by increasing the rigidity of the phosphogypsum mixture.

The total thickness of inverse pavement structure increases by increasing the rigidity of the PG based material, but it is not the case of pavements with sub-base treated with hydraulic binder. For a softer phosphogypsum mix, inverse pavement structure tends to be thinner than the one with hydraulic binder treated sub-base, for a more rigid phosphogypsum mix, the first is thicker than the second.

It can be gained up to 15 cm in total thickness by adopting a mixed structure compared to an inverse one, and this difference is particularly noticeable when the phosphogypsum mixture is more rigid.

There is also a gain 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 (Fig. 14).

The substitution by PG layers allows preserving conventional resources (gravels, sand). Actually, PG layer in a mixed structure can constitute from 53% to 60% of total pavement thickness, whereas in inverse structure, it represents from 40% to 54%, and in a treated PG sub-base from 87% to 89%.

Economic gain

It has been carried out, on the basis of the Moroccan market prices, a basic cost analysis, based on the following hypothesizes:

- price calculation is relative to the most used conventional structure in the Moroccan context, which is the thick bituminous [22], considered equal to 100%;
- the price is that of materials implemented on site excluding transport costs;
- we assume a local availability of materials;
- we consider the price of PG as zero;
- we take ref. (Diouri et al., 2021) as the basis of prices on the Moroccan market.

Pavements with a sub-base treated with hydraulic binder have an undeniable cost advantage (Fig. 15) compared to other types of structures. Indeed, this type of pavement can be up to 52% less expensive than mixed pavements, and up to

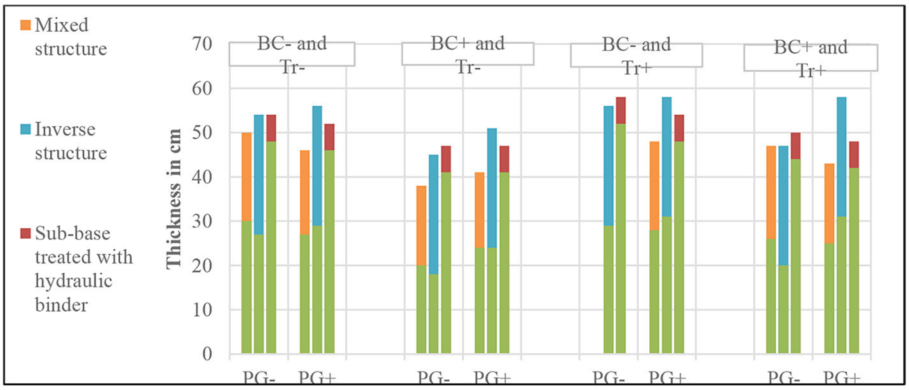

Figure 14. Effect of each factor on PG layer thickness and total pavement thickness

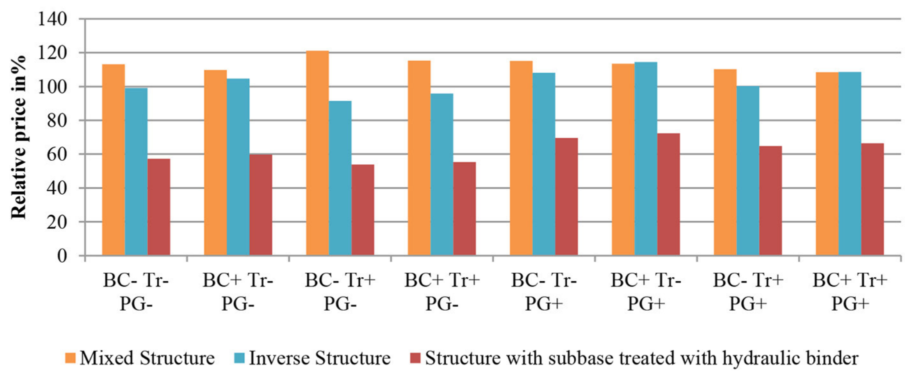

Figure 15. Relative price estimation of the mixed/inverse/treated pavement structure compared to a conventional structure (thick bituminous)

43% less expensive than reverse structure pavements. Mixed structures are the most expensive variant, which was expected given the cost of the bituminous layer which represents at least 40% of the thickness of the pavement.

Parametric study conclusion

Finally, the parametric study made it possible to conclude that whatever traffic, soil bearing capacity and the treated PG performances, pavements with subbase treated with hydraulic binder are very competitive compared to pavements with reverse and mixed structures.

CONCLUSIONS

In this article, the possibility of using materials consisting of Jorf Lasfar's PG is studied, mixed with a granular corrector (either sand or steel slag) and treated with cement, as a material for road construction (either as a subgrade or foundation layer).

The experimental study uses the DOE method, which optimizes the total number of trials while allowing obtaining reliable mathematical models for the studied responses.

This made it possible to determine models for the physical and mechanical responses used in the design of pavement materials. The models' quality is verified by testing a new mix not used in the DOE experimental points. Comparison between experimental values and predicted ones showed less than 8% relative deviation. Compositions' domains that meet the criteria appear to be large enough to allow further design.

Furthermore, the effects of traffic level, soil bearing capacity and mechanical performance of treated phosphogypsum mixtures are evaluated on pavement design for three different pavement structures (mixed, reverse and structure with treated sub-base) and determined that the best to adopt for maximizing PG valorization, and thus saving primary resources, is the pavement structure with subbase treated with hydraulic binder.

This work will continue using phosphate tailings as granular corrector and RHB instead of cement as a binder. A complete environmental and health assessment will be carried out on the different mixtures in order to validate their environmental harmlessness and the safety of their use.

Then with the construction of new pilots at different locations the work continues, having different soil bearing capacities, on classified national road network, using the three types of pavement structures evaluated in this paper.

Acknowledgements

Special thanks to Colas-GTR laboratory for their cooperation and kind support throughout my research period 2019. This work is funded by OCP group as part of pilot projects for phosphogypsum valorization in road construction. It has also benefited from a technical support from the Roads Department, in particular the National Center for Road Studies CNER, which we warmly thank, and a grant from the national scientific and technical research center CNRST. We do also want to warmly thank the GTR, partner in the project, for help and guidance from its laboratory LCC for the first experimental campaign.

REFERENCES

1. Amrani, M., Taha, Y., Kchikach, A., Benzaazoua, M., & Hakkou, R. (2020). Phosphogypsum recycling: New horizons for a more sustainable road material application. *Journal of Building Engineering*, *30*, 101267. https://doi.org/10.1016/j.jobe.2020.101267
2. Diouri C., K. Lahlou, A. Alaoui and K. El Omari,. (2022). *Valorisation du phosphogypse dans la construction routière au Maroc*. 11ème Congrès National de la Route, Dakhla, Maroc.
3. Diouri, C. A., Khoutayri, K. E., Lahlou, K., Omari, K. E., Alaoui, A., Safir, B., & Bendrihem, A. (2021). Valorisation de sous-produits industriels marocains en technique routière. *Academic Journal of Civil Engineering*, *39*(1), Article 1. https://doi.org/10.26168/ajce.39.1.24
4. Diouri, C., Echehbani, I., Lahlou, K., Omari, K. E., & Alaoui, A. (2022). Valorization of Moroccan phosphogypsum in road engineering: Parametric study. *Materials Today: Proceedings*, *58*, 1054–1058. https://doi.org/10.1016/j.matpr.2022.01.084
5. Felfoul, H., Ben Ouezdou, M., & Clastres, P. (2004). *Etude du phosphogypse de Sfax en vue d'une valorisation en technique routière*.
6. Havanagi, V., Sinha, A., & S., P. (2018). *Characterization of Phosphogypsum waste for Road construction*.
7. *Alize-LCPC – The Professional Software for Design of Pavement Structures*. Retrieved July 3, 2024, from http://www.alize-lcpc.com/fr/alize-applications.php

8. Jacques Goupy. (n.d.). *Les plans d'expériences*. Retrieved July 2, 2024, from https://www.eyrolles.com/Sciences/Livre/les-plans-d-experiences-9782100778027/
9. Meskini, S., Samdi, A., Ejjaouani, H., & Remmal, T. (2021). Valorization of phosphogypsum as a road material: Stabilizing effect of fly ash and lime additives on strength and durability. *Journal of Cleaner Production*, *323*, 129161. https://doi.org/10.1016/j.jclepro.2021.129161
10. Moutaouakil, A., Pineau, J. L., & Lahlou, K. (2015). La recherche d'un procédé viable de valorisation d'un phosphogypse provenant de l'industrie phosphatière marocaine. *Déchets, Sciences et Techniques*, *N°29-1er Trimestre 2003*. https://doi.org/10.4267/dechets-sciences-techniques.2231
11. Peng, B., Yang, Z., Yang, Z., & Peng, J. (2020). Effects of pH and fineness of phosphogypsum on mechanical performance of cement–phosphogypsum-stabilized soil and classification for road-used phosphogypsum. *Coatings*, *10*, 1021. https://doi.org/10.3390/coatings10111021
12. Phosphogypsum: Sustainable Management and Use. (n.d.). *Fertilizer*. Retrieved July 5, 2024, from https://www.fertilizer.org/resource/phosphogypsum-sustainable-management-and-use/
13. Projet de Norme Marocaine PNM 13.1.219 (2019)-Dimensionnement Structurel Des Chaussées Routières : Application Aux Chaussées Neuves.
14. Rutherford, P. M., Dudas, M. J., & Samek, R. A. (1994). Environmental impacts of phosphogypsum. *Science of The Total Environment*, *149*(1–2), 1–38. https://doi.org/10.1016/0048-9697(94)90002-7
15. Schaeffner (M.), Autoroutes, S. D. T. D. R. E., & Chaussees, L. C. D. P. E. (2000). *Traitement des sols à la chaux et/ou aux liants hydrauliques. Application à la réalisation des remblais et des couches de forme—Guide technique*. LCPC. Paris. https://side.developpement-durable.gouv.fr/ACCIDR/doc/SYRACUSE/228745/traitement-des-sols-a-la-chaux-et-ou-aux-liants-hydrauliques-application-a-la-realisation-des-rembla
16. SETRA Service d'Etudes Techniques des Routes et Autoroutes, & LCPC Laboratoire Central des Ponts et Chaussées. (1992). *Réalisation des remblais et des couches de forme (GTR) - Fascicule 1 - principes généraux: Guide technique* (Hors collection). Cerema. https://doc.cerema.fr/Default/doc/SYRACUSE/14456/realisation-des-remblais-et-des-couches-de-forme-gtr-fascicule-1-principes-generaux-guide-technique
17. Silva, L., Oliveira, M., Crissien, T., Santosh, M., Bolivar, J., Shao, L., Dotto, G., Gasparotto, J., & Schindler, M. (2022). A review on the environmental impact of phosphogypsum and potential health impacts through the release of nanoparticles. *Chemosphere*, 131513. https://doi.org/10.1016/j.chemosphere.2021.131513
18. Tayibi, H., Choura, M., López, F. A., Alguacil, F. J., & López-Delgado, A. (2009). Environmental impact and management of phosphogypsum. *Journal of Environmental Management*, *90*(8), 2377–2386. https://doi.org/10.1016/j.jenvman.2009.03.007
19. *Traitement des sols à la chaux et/ou aux liants hydrauliques | Publications du Cerema*. (2007, August 1). http://www.cerema.fr/fr/centre-ressources/boutique/traitement-sols-chaux-etou-aux-liants-hydrauliques
20. Vick, S. G. (1984). Discussion to "*Analyses of Flow Failures of Mine Tailings Dams*" and "*Investigation of Flow Failures of Tailings Dams*" by Jey K. Jeyapalan, by J. Michael Duncan, and H. Bolton Seed (February, 1983). *Journal of Geotechnical Engineering*, *110*(3), 454–456. https://doi.org/10.1061/(ASCE)0733-9410(1984)110:3(454)
21. Weiksnar, K., Laux, S., Clavier, K., & Townsend, T. (2023). Influence of trace chemical constituents in phosphogypsum for road base applications: A review. *Resources Conservation and Recycling*, *199*. https://doi.org/10.1016/j.resconrec.2023.107237