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Toward Sustainable Mining: Repurposing Benguerir's Phosphate Mine Waste Rock for Road Subgrade Construction.

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Abstract. Natural aggregates are widely consumed worldwide by the road construction industry. Particularly in the phosphate sector, reducing industrial waste and conserving non-renewable natural resources can be achieved by utilizing unusual industrial wastes and by-products in road construction procedures. Road construction may find use for Phosphate Mine Waste Rocks (PMWR) as an alternate secondary raw material source. However, there are currently limitations on the use and valuation of these materials due to the Moroccan Guide for Road Earthworks (GMTR), which classifies them as waste products and so unsuitable for use in road building. Phosphate waste rocks are naturally existing sedimentary rocks that have mainly been mechanically fragmented, despite their designation. The purpose of this study is to assess PMWR's essential characteristics for application in road construction. At the Moroccan phosphate mine location of Benguerir, samples have been collected from screening stockpiles. Then, using international testing standards, environmental and health behaviours, chemical, mineralogical, physical, and geotechnical behaviours, these samples were analysed. The materials' suitability for use in subgrade layer was validated by laboratory and field experiments, hence allowing for their reclassification as conventional materials.

1 Introduction

Millions of tons of phosphate mining waste rocks (PMWR) are produced by phosphate mines in the Kingdom of Morocco. These PMWR rocks are placed on the surface in waste rock piles that span thousands of hectares [1]. These waste rocks mostly consist of the cover layer (topsoil, clays, and marls) and intercalation layers (limestones, marls, and flintstone) that are found in the phosphate sequence [2–4]. Intercalation layers and the cover layer are blasted and removed in the process of extracting phosphate ore. The PMWR are geochemically inert due to the high concentration of calcite and dolomite [5–8].

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Despite having characteristics similar to natural aggregates used in construction, PMWR are classified under the organic soils and industrial by-products category by the Moroccan Guide for Road Earthworks [9], specifically within the phosphate waste sub-class F3. As a result, they are not permitted for use in road construction.

Minimizing and recycling waste presents a key opportunity for advancing a sustainable and resource-efficient mining. This can be achieved by reducing waste production at the source or managing existing waste stored in dumps, waste rock piles, and tailings ponds [10].

The potential application of alternative aggregates, notably in the road construction industry, has received more attention recently [11]. Many examples have been studied the PMWR valorization in literature. Segui and al. [12] reviewed the use of mine waste, including PMWR, as geomaterials in road construction. It highlights their potential as sustainable alternatives to new aggregates, emphasizing the need for eco-friendly mining practices and effective waste management. Chlahbi and al. [4] demonstrated that the phosphate waste rock from the Benguerir mine exhibits diverse lithological, mineralogical, and physical-mechanical properties, making it suitable for various applications (especially for road construction materials). Ahmed and al. [13] explored the application of phosphate waste rocks in road construction through geotechnical characterization. Their findings indicated that these wastes have significant potential as road aggregates, comparable to natural ones. Substituting conventional aggregates with phosphate mine waste rocks (PMWR) could be a promising and eco-friendly alternative for road infrastructure projects. Amrani and al. [14] characterized Benguerir's PMWR and finds them chemically inert with suitable geotechnical properties for road construction. Optimal compaction conditions were identified, allowing PMWR to be used safely for embankments up to 15 meters high. Amrani and al. [15] demonstrated that phosphate mine waste rocks (PMWR) can be effectively used as an alternative material for constructing dry compacted embankments. Through a series of field and laboratory tests, a construction protocol has been developed for utilizing PMWR at their natural water content, ensuring the required stability and performance of the embankments. Amrani and al. [16] confirmed that 0–100 mm aggregates from screening waste rock are a viable, cost-effective, and environmentally stable option for capping layers in road construction. Utilizing PMWR could help reduce waste and preserve conventional aggregates. Finally, Chlahbi and al. [3] evaluate the feasibility of using phosphate waste rock (PWR), specifically marly clay and marly limestone, in road embankment construction. Chemically, they are rich in CaO, SiO_2, and MgO, and environmentally classified as non-hazardous. Stability analysis showed that embankments up to 10m high can be built with these materials, with marly limestone requiring additional reinforcement. Economically, using PWR within a 28km radius of the Benguerir mine offers cost savings over conventional materials.

The aim of this paper is to focus on PMWR and its use as subgrade layer for road construction (Figure 1). Laboratory tests were conducted to assess the environmental and health impacts of the PMWR, as well as its chemical, mineralogical, physical, and geotechnical properties. Additionally, in situ tests were carried out to evaluate the behavior of these materials, including an in-situ plate load test.

Fig. 1. Schematic diagram of a typical road construction cross-section [17].

2 Materials and methods

2.1 General methodology

Figure 2 illustrates the detailed methodology applied in this study. The process started with the sampling and preparation of raw materials, followed by an extensive laboratory testing program. The raw materials were assessed for their environmental and health behaviors, as well as their chemical, mineralogical, physical and geotechnical properties. A plate load test was conducted to carry out field verification.

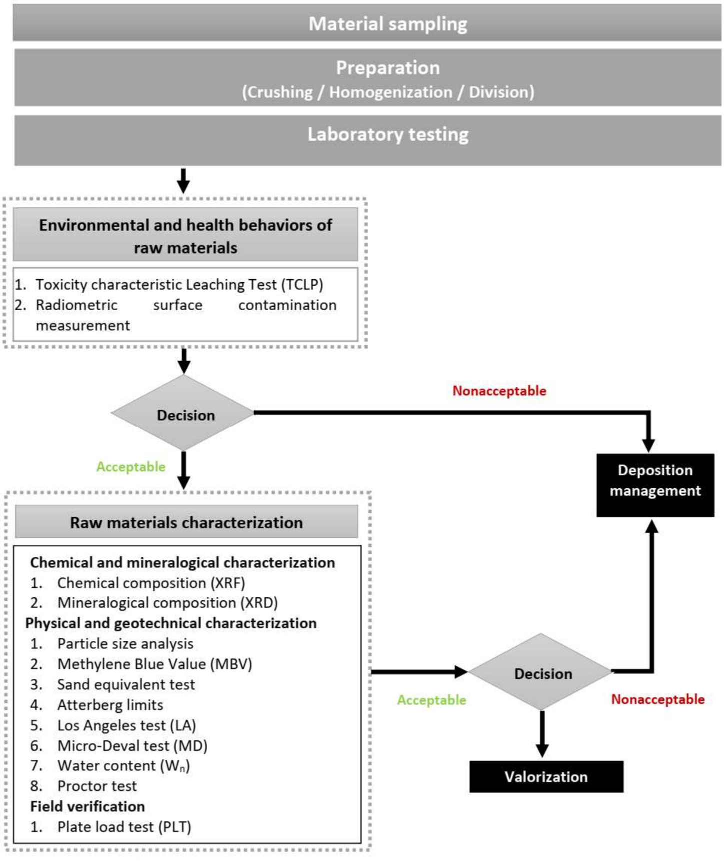

Fig. 2. General methodology followed for carrying out the study.

2.2 Raw material sampling and preparation

For laboratory testing, 2 tons of raw materials were sampled from phosphate mine waste rock (PMWR) piles [1,4] in Benguerir's Mine (Kingdom of Morocco) as shown on Figure 3. The PMWR were homogenized, divided and then crushed by a jaw crusher to reduce the particle size from 0/90mm to 0/31.5mm.

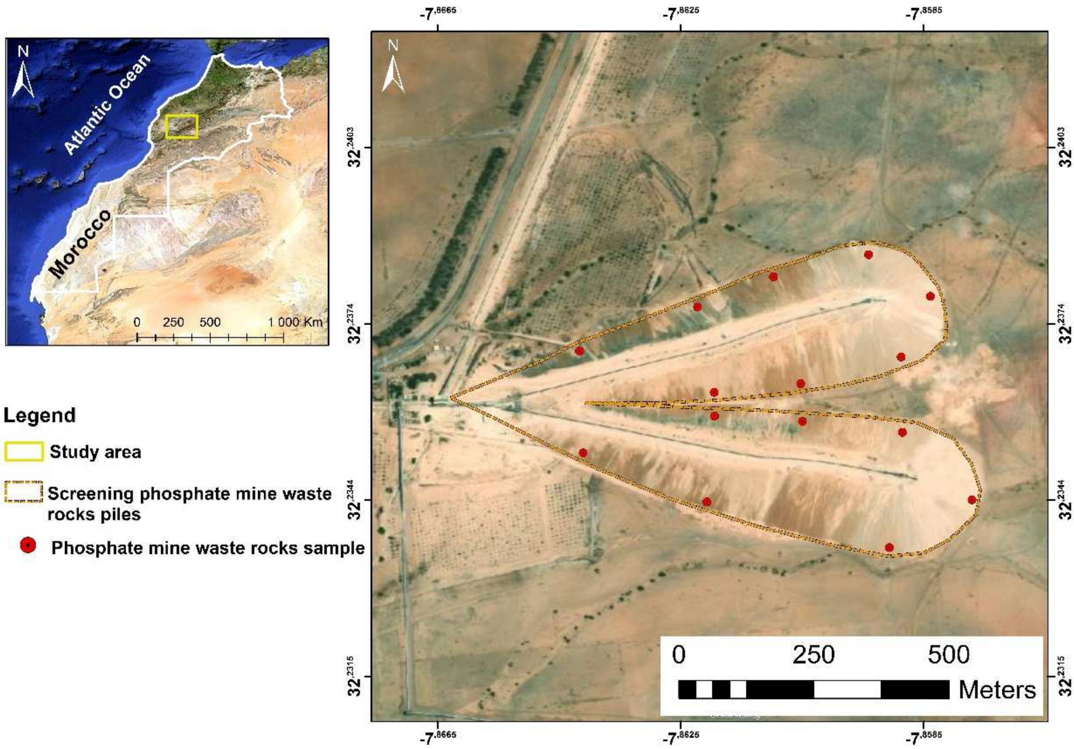

Fig. 3. Site plan of PMWR sampled locations.

2.3 Environmental and health behaviours

The Toxicity Characteristic Leaching Procedure (TCLP) test assesses the environmental risk of waste materials by measuring the concentration of hazardous substances that could leach out under controlled conditions. After filtration, the collected leachate is acidified and analyzed using ICP-OES. The results are then compared to regulatory limits set by the United States Environmental Protection Agency [18].

Surface contamination was measured using the RDS-80 Surface Contamination Meter, commercialized by Mirion Technologies. This device detects radiation including alpha particles with energies above 2 MeV, beta particles over 100 keV, and gamma and X-rays between 5 keV and 1.3 MeV. Ten samples were randomly taken from the sampled and prepared materials.

2.4 Chemical and mineralogical characterization

Several investigations were carried out at the Geo-Analytical Lab at GSMI to identify the bulk chemical composition of the PMWR. A RIGAKU (ZSX Primus IV) X-ray fluorescence (XRF) spectrometer was used to conduct a complete chemical characterization of the major elements (CaO, SiO_2, Al_2O_3, Fe_2O_3, MgO, K_2O, Na_2O, P_2O_5, and MnO). Because carbonate rocks are present, the carbonate content of milled samples was determined by calcination at 950°.

The PMWR were subjected to mineralogical characterization using a RIGAKU X-ray diffraction instrument (MiniFlex 600).

2.5 Physical and geotechnical characterization

A series of tests were conducted at the Geomaterials LAB of University Mohamed VI Polytechnic (UM6P) to assess the physical and geotechnical properties of PMWR. The characterization began with particle size distribution analysis according to NF EN ISO 17892-4 (2018). The methylene blue value (MBV) was determined on the 0/5 mm fraction to assess the material's adsorption capacity, following the NF-P94-068 standard. The Equivalent Sand Value (ESV) was assessed in accordance with the EN N933-8+A1 (2015) to quantify the presence of fine dust or clay-like particles in granular fractions, indicating the cleanliness of the sand. The Atterberg limits, including liquid limit (LL) and plastic limit (PL), were determined in line with NF EN ISO 17892-12 (2018). The Los Angeles abrasion value (LA) and Micro Deval value (MD) were measured using the 10/14 mm fraction, following NF EN1097-2 (2020) and NF EN 1097-1 (2011) standards, respectively. Water content of PMWR was determined according to NF EN 1097-5 (2008) by drying the material. Lastly, the compaction characteristics, including optimum moisture content (w_{opn}) and maximum dry density (γ_d max), were determined using the Proctor test in accordance with NF P94-093 (2014).

2.6 Field verification

A careful approach is necessary when conducting a test board with a plate load test as stated in the NF P94-117-1 standard (2000). After placement, the material needs to be properly compacted. When the surface is ready, a rigid plate is placed on the prepared soil and a progressive load is applied using a hydraulic or pneumatic system to start the plate load test (Figure 4).

Fig. 4. Plate Load Test execution.

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Using displacement sensors, the soil's deformation under the plate is measured at different load levels.

The plate load test was carried out on a plot of land measuring 10 meters in length and 10 meters in width, with a material thickness of 30 cm. Compaction was performed using a V5 compactor, operating at speeds of 1.5 to 3 km/h. This testing enabled the measurement of EV1 (MPa), the initial modulus of elasticity, which gauges the material's stiffness before loading. After applying the load, EV2 (MPa) was measured to assess the material's stiffness post-loading. The ratio K (EV2/EV1) was then calculated to determine the degree of stiffness change, providing insight into the extent of material compaction.

3 Results and discussion

3.1 Environmental and health behaviours

The findings from the ICP-OES analysis of PMWR, conducted according to the TCLP protocol, are shown in Table 1. The concentrations of contaminants (like As, Pb, and Cr) were measured and compared to the regulatory limits established by the US Environmental Protection Agency (EPA). The analysis indicates that the levels of these pollutants in PMWR comply with the EPA's regulatory standards, suggesting that the materials are safe.

Table 1. Results of the Toxicity Characteristic Leaching Procedure (TCLP) of PWS and PWR samples.

Sample	Trace elements (mg/L)						
	As	Ba	Cd	Cr	Pb	Ag	Zn
PMWR	< 0.1	0.55	0.15	< 0.1	< 0.1	< 0.1	0.25
US EPA Standards	5	100	1	5	5	5	2

Furthermore, values for surface contamination based on the document SSR-6 (Rev.1) of the international atomic energy agency (IAEA) transport regulations [19] were taken into consideration. The observed values (which are 4 Bq/Cm^2 for beta and gamma emitters and 0.4 Bq/Cm^2 for all other alpha emitters and low toxicity alpha emitters) are below the upper limit overall, as shown at Figure 5.

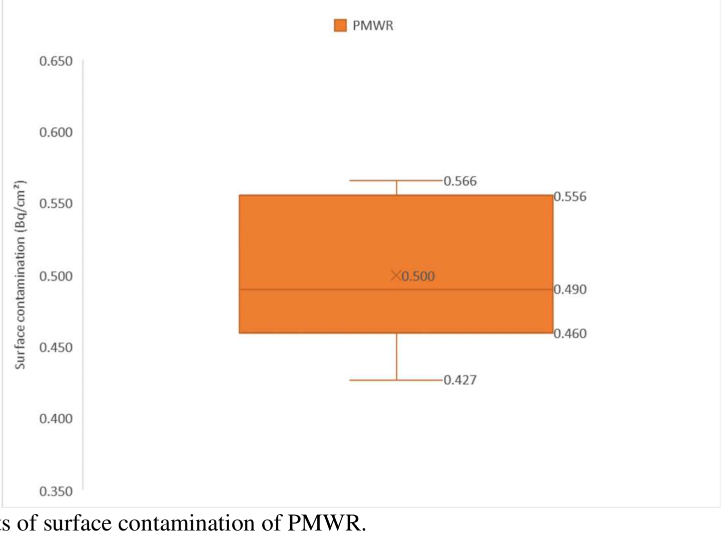

Fig. 5. Results of surface contamination of PMWR.

3.2 Chemical and mineralogical characterization

Table 2 presents the chemical composition of PMWR. The pre-dominant oxides are CaO and SiO2, in presence of Al2O3 and MgO, along with 14.21% P2O5 and traces of K2O and Na2O.

Table 2. Chemical compositions of PMWR (%).

CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	Na_2O	P_2O_5	LOI	CaF_2	SO_3	CO_2	Total (%)
34.27	23.77	0.75	0.59	3.19	0.13	0.50	14.21	15.65	2.98	0.84	2.22	99.11

The mineralogical composition of PMWR is highlighted in figure 6, showing that the primary phases identified include dolomite, calcite, quartz, calcium fluoride, and montmorillonite. The findings from the mineralogical analyses are supported by the results of the chemical analyses performed and the findings of Safhi & al. [2]. In fact, the manual-sorting of 25 tons of Benguerir PMWR screening piles showed that they are mainly composed of indured phosphate (30%), flintstone (14%), phos-flint (14%), silicious marls (20%), dolomitic limestone (14%), silexite (5%), tender marls (2%), and some clays.

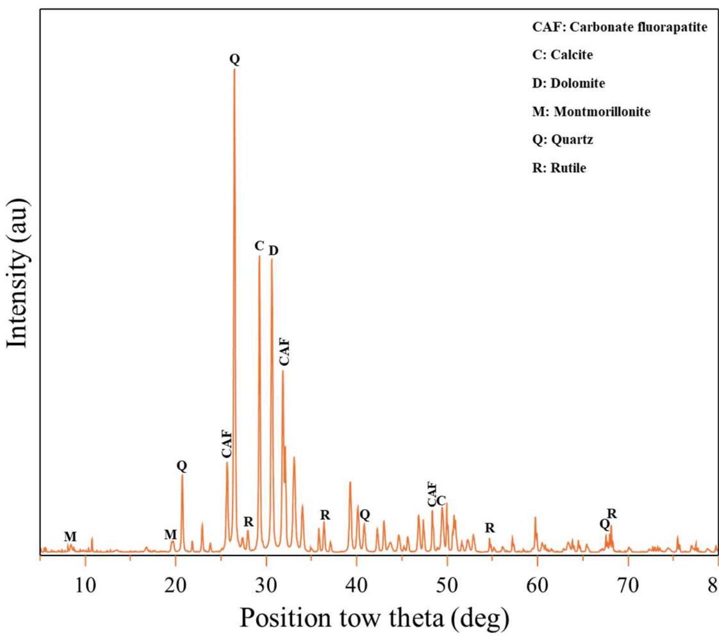

Fig. 6. XRD diffractograms of PMWR.

3.3 Physical and geotechnical characterization

The results of the physical and geotechnical identification tests are summarized in Table 3. The material shows promising characteristics for use as subgrade layer for road construction. It features a maximum particle size of 31.5 mm and a median particle size of 8 mm, suggesting a well-graded distribution that supports effective compaction. The Methylene Blue Test values of 6.24 to 6.52 indicate a moderate clay content, which is within acceptable limits. The Sand Equivalent Test results, ranging from 26% to 28%, highlight a relatively high proportion of fines. With a Liquid Limit of 28% and Plastic Limit values between 16% and 17%, the material demonstrates moderate plasticity. The Plasticity Index of 24% reflects significant plasticity, which could influence compaction behavior. These results align with the material's nature, which is a blend of various facies, including rich deposits as well as clays and marls [2].

Geotechnically, the Los Angeles Abrasion values of 36% to 39% and Micro Deval results of 48% to 51% suggest moderate wear resistance, though some susceptibility to degradation. The low water content of 0.47% and optimum moisture content range of 14.6% to 15.5% indicate that careful moisture control is needed during compaction. The maximum dry density of 1.96 to 1.97 t/m³ confirms good compaction potential.

Table 3. Physical and geotechnical properties of PMWR.

Parameters	Unit	Value
Physical proprieties		
Maximum size (D_{max})	mm	31.5
Median particle size (D_{50})	mm	8
Methylene blue Value (MBV)	g/100g of 0-2mm fraction	0.624 to 0.652
Equivalent sans value (ESV)	%	26 to 28
Liquid limit (LL)	%	28
Plastic Limit (PL)	%	16 to 17
Plasticity Index (PI)	%	24
Geotechnical properties		
Los Angeles (LA)	%	36 to 39
Micro Deval (MD)	%	48 to 51
Water content (W_n)	%	0.47 to 0.53
Optimum Moisture content (w_{opn})	%	14.6 to 15.5
Maximum dry density (g_d max)	t/m³	1.96 to 1.97

Overall, while the material is suitable for subgrade applications, its plasticity and abrasion resistance should be closely evaluated to ensure optimal performance and durability. This evaluation was conducted by a field verification, to observe its performance under real conditions.

3.4 Field verification

Table 4 presents the results of the plate load tests conducted in the field.

Table 4. Plate load test results on PMWR materials.

Plate load test (min 3 measurements)	Units	8 passes	10 passes	12 passes
EV1	MPA	59.8 to 83.9	92.2 to 106	70.3 to 80.3
EV2	MPA	76.3 to 88.2	118.4 to 125	102.3 to 115.4
K (EV2/EV1)	-	1.1 to 1.3	1.2 to 1.3	1.3 to 1.5

The results of the plate load test demonstrate that, despite the material's stiffness increases with additional passes, it starts to decline after 12 passes. Even as the K ratio increases, initial stiffness (EV1) and post-loading stiffness (EV2) ascend to 10 passes, but EV2 starts to fall at 12 passes. This indicates that even while the material first compresses and becomes more rigid with more passes, with excessive loading, its stiffness may even decrease to a limit. More passes can result in an increase in the K ratio, which indicates material compaction and highlights the material's improved stability and load-bearing capacity. The results suggest optimal compaction and stiffness are achieved with 10 passes.

4 Conclusion and perspectives

This study, consisting of a health and environmental verification, chemical, mineralogical, physical and geotechnical characterization of phosphate mine waste rocks.

The main conclusions from the laboratory and in situ trial tests to assess the potential use of these materials for subgrade road construction are the following:

1- The environmental and health characterization results indicate that PMWR meets the limits set by international standards, suggesting that the material poses no significant risk;

2- Despite its higher plasticity and abrasion resistance, field test section has determined the optimal compaction conditions for using PMWR in subgrade layers. These conditions include applying compaction energy through 10 passes with a V5 vibratory roller compactor, ensuring a minimum compacted layer thickness of 30 cm;

3- Based on the results of a comprehensive characterization process, PMWR can be classified as conventional natural aggregates. Their use, particularly as a subgrade layer, will make a significant contribution to conserving natural resources.

Even with a significant degree of variation associated with multiple scales (including the extraction process, the storage technique, and the petrography of the original rocks), it has been proved one more time that PMWR can be used in civil engineering, especially as alternative subgrade aggregates for road construction.

Scaling up the valorization of PMWR as a subgrade layer necessitates large-scale pilot projects to evaluate its durability and economic feasibility. Proving successful scalability will establish its potential as a sustainable solution for construction.

Ultimately, PMWR should be categorized as natural aggregates by updating the Moroccan Guide for Road Earthworks (GMTR).

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