sustainability

MDPI

Article

Field and Economic Studies on Mine Waste: Sustainable Reuse as Aggregates for Low Traffic Pavement Structure

Mustapha Amrani [1,2,*], Yassine Taha [3], Azzouz Kchikach [2], Mostafa Benzaazoua [3] and Rachid Hakkou [1,3]

1 IMED Laboratories, Faculté des Sciences et Techniques, Cadi Ayyad University, BP 549, Marrakech 40000, Morocco
2 L3G Laboratory, Faculté des Sciences et Techniques, Cadi Ayyad University, BP 549, Marrakech 40000, Morocco
3 Mining Environment and Circular Economy Program (EMEC), Mohammed VI Polytechnic University, Lot 660, Hay Moulay Rachid, Ben Guerir 43150, Morocco
* Correspondence: mustapha.amrani@ced.uca.ma

Abstract: The phosphate extraction and processing has followed a traditional linear consumption model, where wastes are continuously produced and surface land is filled in rock piles. Thus, to promote a circular economy in a mining context, more eco-friendly and sustainable solutions at the regional level are needed. This paper deals with the potential utilization of phosphate screening waste rock 0–100 mm (SWR) as alternative aggregates for pavement applications. Detailed in situ and laboratory tests have been made for SWR characterization, and the practical modalities of implementation have been defined. The findings proved that SWR (10–100 mm) materials can be successfully used without treatment in capping layer construction for low-volume traffic pavement projects. Due to its high apatite content, the remaining fraction (0–10 mm) can be exploited to recover the residual phosphate using the processing method that is currently followed by the mining company. Furthermore, the environmental investigations showed that SWR does not present any potential contamination risk to the surrounding environment. The economic feasibility analysis confirmed the workability of SWR reuse in a radius of 100 km around their dumps due to its lower cost compared to conventional aggregates. This simple amendment may ensure a smooth transition from a current linear extractive approach to a circular economy.

Keywords: phosphate mine waste rock; waste management; circular economy; field and economic investigations; capping layer materials

check for updates

Citation: Amrani, M.; Taha, Y.; Kchikach, A.; Benzaazoua, M.; Hakkou, R. Field and Economic Studies on Mine Waste: Sustainable Reuse as Aggregates for Low Traffic Pavement Structure. *Sustainability* **2022**, *14*, 12540. https://doi.org/10.3390/su141912540

Academic Editors: Duong Duc La, Hoai Phuong Nguyen Thi and Dinh Duc Nguyen

Received: 2 September 2022
Accepted: 27 September 2022
Published: 1 October 2022

1. Introduction

Several research initiatives have been attempted to explore the feasibility of recycling various solid wastes in road pavement applications. A technical reference document on the best available procedure for the execution of tailings and waste rock in mining activities has been reported by the European commission [1]. Several projects that used mine tailings as road construction aggregates have been revealed and discussed. Within this framework, partial substitution of conventional aggregate can be made by bottom ash, which results in better mechanical properties than the traditional asphalt pavement [2]. Kuranchie, Shukla, and Habibi [3] reported useful applications of mine tailings, waste rocks, fly ashes, and slags in civil engineering. Mine tailings alone and mixed with fly ash were shown to be successful as road embankment materials, both cost effectively and sustainably. A previous study demonstrated that coal mine waste rocks can be successfully used alone as a sustainable alternative material for the road embankment [4,5]. Furthermore, the use of stabilizing agents, namely fly ash and hydraulic road binder, allows for the utilization of waste in road sub-base layers for high-traffic pavements. Due to their highly favorable mechanical characteristics, the steel slag is considerably adopted for road structures [6,7]. Moreover, this solid waste provides sufficient performance and is also economical for pavement construction [8]. Sinha et al. [9] explore the possibility of using Zinc tailing waste material in road construction and filling. As a result, the geotechnical characterization revealed that the cement stabilized tailing can be used in sub-base layer and can save about 170 mm thickness of the aggregate layer. According to Vilaça [10], the analyses performed on iron ore tailings showed interesting possibilities for alignments with circular economy practices, through industrial symbiosis, with the use of this aggregates as raw materials in the paving technology. Other releases were also studied. In that context, interesting opportunities are offered by the valorization of quarrying and stone residues [11].

Phosphate mine waste rock provides encouraging geotechnical characteristics which makes them an alternative secondary resource to traditional borrow pit materials. The valorization of these unusual materials can contribute to the conservation of non-renewable natural resources and to the reduction of the large volume of solid waste produced by the phosphate industry. Recently, Amrani et al., [12] investigated possibilities for using the phosphate waste rock in road techniques. The authors confirmed through a series of experiments at laboratory and filed scales that these materials can be assimilated to the category of conventional natural aggregates and they can be used in embankment up to 15 m in height without any significant physical instability risks. Furthermore, the effect of dry compaction protocol on the collapse deformation and the shear strength properties of phosphate waste rock as embankment material was deeply assessed [13]. The dry compaction method, with the promotion of the use of materials at their natural moisture content, can be a serious alternative that could save water resources, especially in arid regions. The results of this study demonstrated the ability of phosphate waste rock to be used as embankment material with dry moisture content under total overburden stress below 200 kPa. Recently, more attention has been given to the valorization of phosphate waste rock, phosphate sludge, and phosphogypsum as asphalt binder additives for road pavement [14]. The results showed that the phosphogypsum-based asphalt binder performed better than the phosphate sludge-based binder in terms of rheological behavior characteristics. It was also proven in other research that phosphogypsum can be successfully used alone in embankment and as pavement material when mixed with hydraulic road binder, calcareous material, and clayey soil [15]. Due to its high acidity, phosphogypsum stabilized with alkaline materials and low-cost cementitious binder is an innovative and sustainable solution that can provide new horizons for phosphogypsum recycling.

The research activities mentioned above offer a very promising pathway for the valorization of phosphate waste rocks as capping layer materials. However, two limitations still currently exist and preclude their wide application: (i) The practical modalities of the implementation of these products in road pavement construction have not been thoroughly assessed, as well as the long-term behavior in their road environment. (ii) It remains unclear at this stage what the various financial costs related to the use of these unusual materials in capping layers structures would be. To overcome these two limitations, this study aims to explore the possibility of partial replacement of the conventional material with the phosphate-screening waste rock in capping layer construction.

The capping layer is an essential element in the structural design of road pavements insofar as it provides sufficient short-term load-bearing capacity which allows for the circulation of various construction machines during the building phase; it contributes to the dissipation of traffic stresses on the subgrade and also optimizes the pavement structure due to its long-term strength [16]. For this reason, an alternative aggregate intended for the capping layer must exhibit mechanical properties independently of its humidity state, which allows it to be sufficiently resistant to fragmentation and attrition. Thus, the functional characteristics of road structure must be guaranteed.

Several researches during the last decades investigated the possible reuse of mining residues in the construction sector, but, to the best knowledge of the authors, no research has investigated yet the valorization of phosphate waste rocks in the sub-base layers of road structure while tanking a holistic and integrated approach in view of economic, field, and industrial perspectives. This study will lead to a better understanding of the determining factors that can influence the SWR behavior under real loading conditions. In addition, the official use of these aggregates outside the mine site would be of great importance for Morocco, both in economic terms and in reducing the ecological burden on the environment.

This work presents a multi-scale approach in the laboratory and on the pilot scale, which makes it possible to take a position concerning the possible acceptability of these phosphate mining wastes in the capping layer. To address the aforementioned strategy, this study has been typically organized along four axes of action and research: laboratory characterizations, filed investigations, economic evaluation, and opportunity for transitioning to the circular economy thinking.

2. Experimental Program Procedure

In particular, the influence of the fine and coarse aggregates on the mixture's compactability of the screening waste rock was studied. The purpose of the characterization of the 0–100 mm aggregates in their raw state is twofold:

- This involves defining the initial state of the material with which the changes observed on the experimental trial field will be compared;
- It is a question of justifying the action of clipping the size fraction that contains significant contents of apatite and remains more sensitive to moisture variations. Once validated, this sustainable mining solution can promote the development of circular economy at the regional level.

Figure 1 highlights a summary of the methodology used in this work.

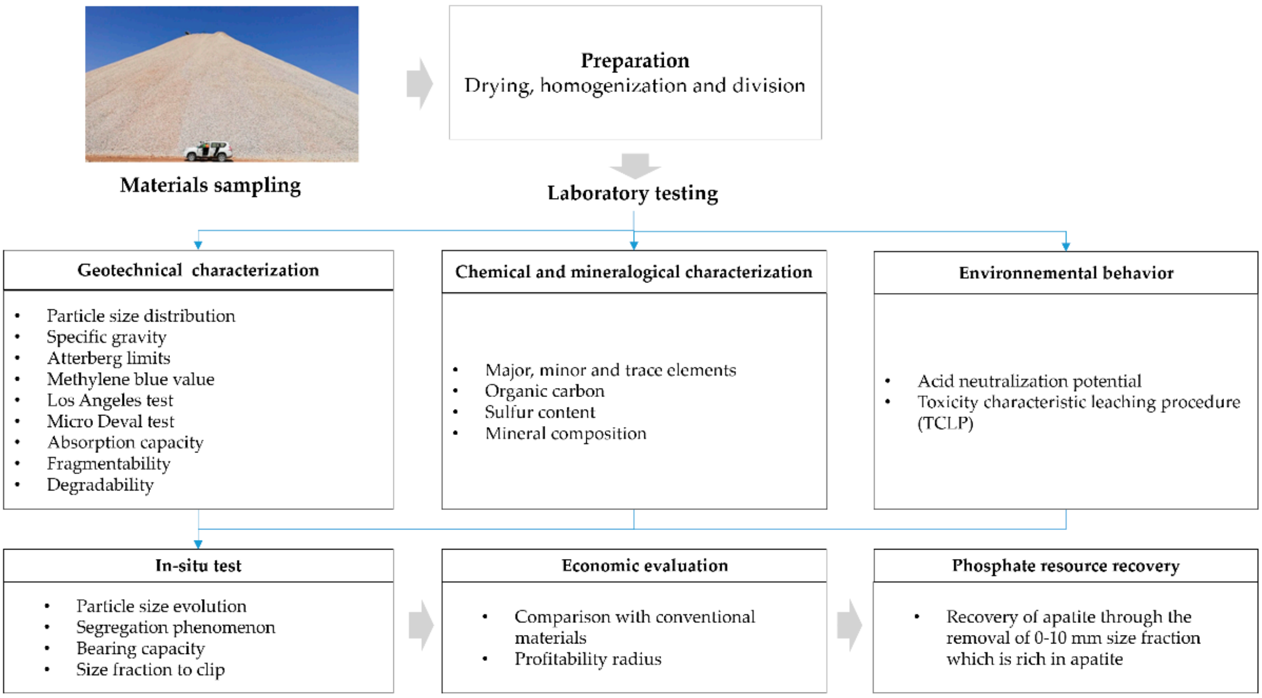

Figure 1. Summary of the methodology followed in this study.

2.1. Studied Materials

The product that results from the phosphate extraction undergoes a series of treatments aimed at reducing the quantity of waste rock and ensuring the required quality. The product is then transported across a conveyor belt to a screening station equipped with 10 × 10 mm mesh screens. The 10 mm screening residues are then evacuated by a series of conveyor belts towards the so-called screening waste rock piles (Figure 2). Those wastes are surface landfilled near the mining site to avoid high transport costs where alternatives are being developed.

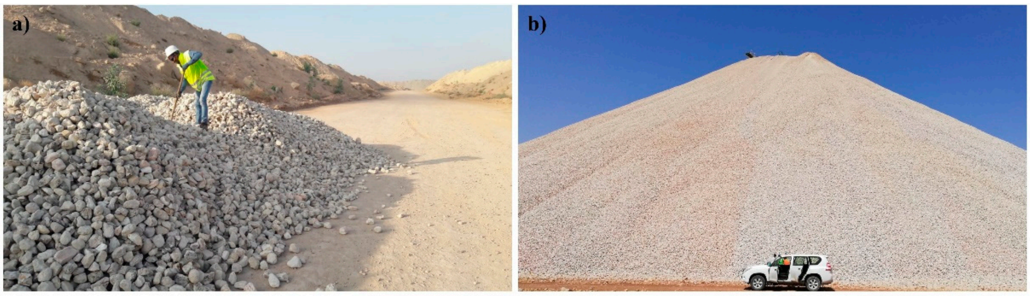

Figure 2. (**a**) Close up photo of SWR materials; (**b**) Screening waste rock piles (0–100 mm) of the phosphate mine site of Benguerir (Morocco).

Visibly, SWR products appear as a mixture of flint, limestone, indurated phosphate nodules, and siliceous clays. In the Benguerir phosphate mining exploitation area, approximately 2 million tons of screening waste rock are produced annually and stored in waste rock dumps. In order to be declared as waste of available resources, OCDE [17] recommends a minimum annual volume of 50,000 tons of waste. SWR aggregates should clearly be considered as solid waste of accessible resources.

In addition, from a regulation standpoint, the valorization of these waste rocks as aggregates in civil engineering is currently limited according to the GMTR [18] requirements. The guide has indeed classified these materials as mine wastes, which consequently cannot be used in road construction.

Representative samples were taken at a depth of 2 m from the top surface, middle, and bottom of the piles located in the Moroccan phosphate mine site of Benguerir, 70 km away from the city of Marrakech to the north. The field-collected samples were then homogenized and riffle-split into smaller sub-samples for further laboratory analysis. Both GTR [16] and GMTR [18] soil specifications are used for SWR product classification.

2.2. Laboratory Test Methods

In this paper, a series of mechanical tests are designed to identify the potential of this unusual product to evolve after its implementation. The quantification of the granulometric evolution has considerable importance for understanding the materials' behavior under diverse stresses. The fragmentation of the particles leads to a new gradation configuration and to a new redistribution of the constraints within it. Moreover, the main geotechnical properties of the SWR materials have also been investigated. The grading distribution curves were achieved through a dry sieving technique for elements with a diameter greater than 80 μm, and a granulometric test using a sedimentation approach was carried out for grain fraction less than 80 μm following the NF-EN-ISO-17892–4 [19] standard. The liquid limit (W_L) was determined using the Casagrande cup [20] when the plastic limit (W_P) was obtained by the rolled thread method [21]. In order to simulate the sensitivity of SWR materials to fragmentation under different in situ stress conditions and wetting–drying cycles, the fragmentability (FR) and degradability (DG) coefficients have been made on the 50–80 mm aggregate fractions according to the standard methods set by [22] and [23], respectively. The choice of the 50–80 mm size fraction has been motivated by its weight representativeness in the tested sample.

In this study, the resistance of SWR aggregates to wear and degradation by abrasion has been evaluated on 10–14 mm fractions using Micro-Deval (MD) and Los Angeles (LA) tests in accordance with the standards set by [24] and [25], respectively. The measurements of methylene blue absorption capacity (MBV) have been carried out following the requirements of the standard test set by [26]. The specific densities of rock elements have been measured by the hydrostatic weighing method following the specifications of [27].

The absorption capacity test makes it possible to determine the quantity of water that can be absorbed within the micro-cavities of the particles of the materials after immersion of a sample for 24 h according to the standard set by [28]. This test provides an idea of the resistance of the tested aggregates to freeze–thaw cycles. The test consists of immersing the aggregates (fraction 4–31.5 mm) in a pycnometer filled with water and compensating for the drop-in level during the test. At the end of the test, the aggregates are then dried before calculating the absorption coefficient.

The content of major and trace elements presented in the studied samples have been obtained using X-ray fluorescence (Bruker, Tiger Model, Bruker, Billerica, MA, USA) and inductively coupled plasma with atomic emission spectroscopy (ICP-AES) (Perkin Elmer Optima 3100 RL, Waltham, MA, USA). The X-ray diffraction measurements have been carried out to characterize the crystalline phases of SWR powdered samples. The Diffrac Plus EVA and TOPAS software programs were used to identify and quantify mineral species and abundances, respectively. The total sulfur (S) and total inorganic carbon © contents have been obtained by induction furnace analysis (ELTRA CS-2000, ELTRA, Haan, Germany).

Moreover, the leaching properties of the screening waste rock was evaluated using the Toxicity Characteristic Leaching Procedure (TCLP) [29]. The samples were prepared by crushed SWR to pass through a 9.5 mm sieve. The leaching solution used has a pH of 4.93 ± 0.05. The obtained results are then compared with US-EPA thresholds [30]. This test is used to verify the potential release of impurities and contaminants.

2.3. Field Testing Campaigns

Field-testing on a trial pavement foundation was carried out in order to assess the hydro-mechanical behavior of the SWR materials during compaction and to determine the practical modalities of implementation, which will be applied for the capping layer applications.

According to the GMTR [18] specifications, the compaction of the capping layers should make it possible to obtain a minimum bearing capacity of 50 MPa and satisfy the densification requirements referred to as "q3 level", which is consequently reflected by the following two conditions:

- The average dry density over the entire thickness of the compacted layer, $\gamma d_{EL} \geq 98.5\%\ \gamma d_{ref}$;
- The dry density on the bottom of the compacted layer, $\gamma d_{BL} \geq 96\%\ \gamma d_{ref}$.

In order to achieve theses technical specifications, the parameters defined below have been monitored during the performance of these trial sections:

- The bearing capacity characteristics were evaluated according to the plat-loading test [31];
- The evolutionary behavior highlighted by the determination of grading curves and methylene blue adsorption capacity values before and after applying the in situ optimal compaction energy;
- The degree of compaction disclosed by the dry densities' measurements.

In addition, the mechanical behavior parameters (LA and MD) are taken into account to assess the technical feasibility of using these materials in capping layer structures.

Two full-scale experiment sections were carried out on a runway inside the Benguerir phosphate mine. They were each constructed on 30 m length, 7 m width, and around 1 m height on a compacted embankment presenting an average bearing capacity EV2 of 58 MPa. In addition, three superimposed layers of 0.30 m thickness were compacted at their optimum moisture content using a calibrated vibratory roller compactor classified V4 according to the standard set by [32]. Moreover, two different series of compaction energy levels have been studied: 5, 7, 9 and 7, 9, 11 passes of the roller compactor. Whereas the translation speed of the compactor machine was fixed at 2.5 km/h for the first series and 3.5 km/h for the second, the first series of compaction energies concerns the 10–100 mm size fraction while the second is planned for 25–100 mm materials. The choice of these compaction energies was sourced from the implementation method of similar geotechnical materials presented in the French guide tables [16]. The in situ dry densities on the bottom and over the entire thickness of the three compacted layers were measured using a membrane densitometer device following [33].

3. Results and Discussion

3.1. Environmental Characteristics

The results of the toxicity characteristic leaching procedure (TCLP) test of the 0–100 mm size fraction of the SWR product are summarized in Table 1. The results show that all concentrations of harmful pollutants were well below the upper limits set by US-EPA regulations for hazardous elements. It can also be stated that:

- The limited release of metals is due to the low initial content of heavy metals contained in these materials, the high stability of the inert minerals present (silica and aluminosilicates), and minerals with high neutralizing capacity such as dolomite and calcite;
- The screening waste rock studied shall not, under any circumstances, be classified as hazardous waste; moreover, it is essential to recognize these materials in the same terms as conventional aggregates.

Table 1. Leaching properties of SWR sample.

	Zn	Se	Pb	Cu	Cr	Cd	As	V
Concentration (mg/L)	0.71	<0.10	<0.60	<0.50	<0.20	<0.10	<1	<1
Limits (US-EPA)	2	1	5	-	5	1	5	-

3.2. Laboratory Characterization of 0–100 mm Aggregates Gradation of SWR

The typical particle size distribution curve of the screening waste rock (SWR) is presented in Figure 3. It reveals a gravelly soil texture and has a D_{max} of 100 mm, which passes through the sieve at 80 µm of 10.1% and 76.3% by weight of particles that have a diameter less than 50 mm. The uniformity coefficient, Cu > 2, and curvature coefficient, 1 < Cc <3, reveals the grain size spread of the SWR materials.

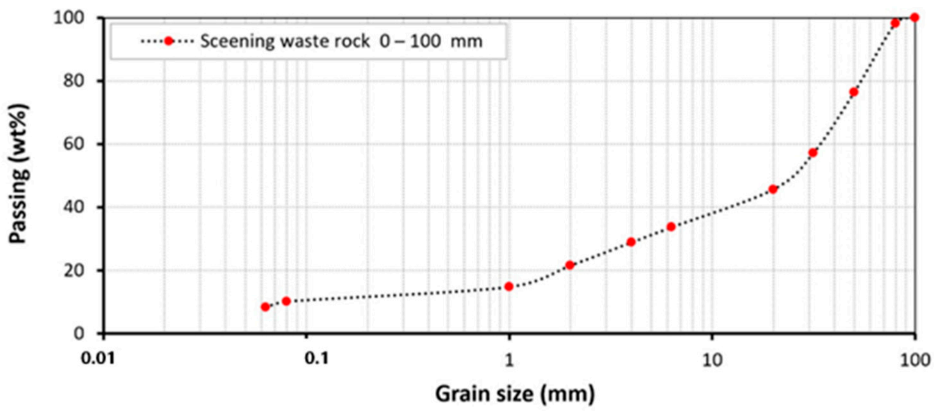

Figure 3. Particle size distribution curve of SWR materials.

From the point of view of plasticity, these materials show low plastic behavior. For the absorption capacity of their particles (degree of clay), it depends on the particle size grading that will be subjected to the test. In fact, it is observed that the methylene blue value (MBV) is revised upwards from 0.58 to 0.69 g/100 g by changing the particle gradation subjected to the test from 0–5 mm to 0–400 µm. This result was expected because the test on the 0–400 µm fraction takes elements that are rich in soluble minerals into account, in particular P_2O_5.

On the basis of the mechanical results, especially the density measurement, presented in Table 2, it is important to note that the obtained value of Gs corresponds to specific gravity measured on conventional aggregates. It can be also seen that the bulk density of these dry screening waste rocks is of the order of 1.47 g/cm^3.

Table 2. Geotechnical properties of the SWR materials (0–100 mm).

Properties	Value
Atterberg limits, (%)	
W_L	35
W_P	24
P_I	11
Absorption capacity	
Water absorption capacity, (%)	4.95
MBV, (g/100 g)	
MBV (0–5 mm)	0.58
MBV (0–400 µm)	0.69
Mechanical properties	
G_s	2.665
LA (25–50 mm), (%)	42
MD (25–50 mm), (%)	51
FR (50–80 mm)	6.35
DG (50–80 mm)	7.75
SWR classification following GMTR and GTR guides	C_1B_{42}

It can be also seen that these materials are moderately resistant to fragmentation (LA = 43%, FR = 6.35%). By contrast, the resistance of their coarse aggregates to wear abrasion is relatively low because the values of the MD and DG tests are respectively equal to 51% and 7.15. As a result, the SWR are therefore moderately degradable and not very fragmentable aggregates. Furthermore, if we take the future target area of use (Benguerir region, which is characterized by an arid climate) into consideration, the action of stresses developed by the freezing of water on particles breaking is considered negligible. Consequently, the influence of freeze–thaw cycles (a weathering process that frequently occurs in cold climates) on the mechanical properties of SWR aggregates has not been taken into account in this study. However, the value of the water absorption coefficient mentioned in Table 2 is provided for information.

On the basis of these findings, the SWR aggregates can be classified in the category of gravel materials with little clay content (C_1B4_2) of both Moroccan and GTR guides [16,18]. In this raw state, the specifications of the GMTR guide do not allow the direct use of these materials in capping layer construction without treatment when the clay parameters exceed the required thresholds, namely MBV < 0.5 g/100 g and P_I < 10%. The results of the main geotechnical properties of these materials are summarized in Table 2.

The Physico-chemical and mineralogical analysis of the studied materials are highlighted in Table 3. The findings revealed several oxides in the composition of SWR. The SiO_2 and CaO are 27.4% and 36.3%, respectively. P_2O_5 is present in a considerable amount of SWR aggregates, whereas the contents of Al_2O_3, MgO, and NaO_2 are present in smaller proportions. X-ray diffraction studies showed that the SWR sample is mainly composed of fluorapatite (37.5%) and quartz (26.4%). Much smaller amounts of dolomite, clays, and calcite are also detected.

The findings above are helpful for an easier interpretation of the geotechnical results. To overcome the risk of fragmentation during implementation, the plasticity requirements [18] for possible use of SWR as capping layer aggregates are added and a specific action on the granularity level has to be taken. Specifically, the moisture-sensitive fine fraction 0-d mm by prior screening technique is eliminated before the compaction process.

Furthermore, as shown in Table 4, the significant content of the P_2O_5 and clays minerals found in the chemical composition of 0–100 mm raw aggregates can lead to the further analysis of the proportions of this precious element in smaller size particles. The purpose of this initiative is to have clear and complete data to precisely determine the fraction that must be capped for a profitable exploitation of phosphate ore.

Table 3. Chemical and mineralogical properties of 0–100 mm size fraction of SWR material.

Major Elements	SWR 0–100 mm (%)
SiO_2	27.4
Al_2O_3	1.9
Fe_2O_3	0.4
CaO	36.3
MgO	2.9
K_2O	0.3
NaO_2	1.8
P_2O_5	17.4
TiO_2	0.1
MnO	0
C_{org}	0.17
S	0.22
LOI	10.91
Mineralogical composition	
Quartz (SiO_2)	26.4
Dolomite ((Ca,Mg)($CO_3)_2$)	13.3
Fluorapatite (Ca5($PO_4)_3$F)	37.5
Calcite ($CaCO_3$)	7.7
Total clays	13.4

Table 4. Chemical and mineralogical characteristics per size fraction.

Major Elements (%)	SWR 0–25 mm	SWR 0–10 mm	SWR 10–100 mm	SWR 25–100 mm
SiO_2	21.3	15.4	34.6	36.5
Al_2O_3	2.1	2.8	0.58	0.4
Fe_2O_3	0.17	1.2	0.21	0.2
CaO	42.3	44.1	33.7	32.1
MgO	2.3	1.9	3.2	3.1
K_2O	0.2	0.3	0.1	0.3
NaO_2	2	2.3	1.6	1.2
P_2O_5	18.8	22.3	14	13.2
TiO_2	0.1	0.1	0.05	0.1
MnO	0	0	0.06	0
C_{org}	0.2	0.19	0.21	0.19
S	0.21	0.21	0.19	0.22
LOI	9.6	9.4	11.8	12.3
Mineralogical composition (%)				
Quartz (SiO_2)	24.8	15.8	34.1	37.6
Dolomite ((Ca,Mg)($CO_3)_2$)	10.5	8.9	14.6	14.2
Fluorapatite (Ca5($PO_4)_3$F)	40.9	48.6	30.5	28.7
Calcite ($CaCO_3$)	9.5	9.9	16.4	15.3
Total clays	14.8	16.9	4.2	3.3

The chemical and mineralogical characteristics of the various gradations of SWR materials summarized in Table 4 revealed that the P_2O_5 and clay minerals are particularly significant because the size grading is smaller. In addition, compared to 0–10 mm, the 0–25 mm fraction is more interesting in terms of geotechnical properties and it has a higher proportion of quartz and dolomite with less content of clay particles. However, the risk level of segregation is becoming increasingly serious. For its part, clipping the 0–100 mm size fraction is more profitable in terms of exploitation of phosphate ore and safer from the point of view of stability and bearing capacity after implementation.

It is important to highlight that the gradation aggregates 0–10 mm and 0–25 mm represent 35.5% and 47.2%, respectively, of the total weight of the SWR samples. The presence of indurated phosphate nodules can explain the considerable amount of P_2O_5

found on the SWR aggregates even after clipping the 0–10 mm particle size fraction. This is a result of the fact that the size fraction to be capped can only be based on a clear analysis of both the laboratory and filed trial results.

3.3. Laboratory of Both 10–100 and 25–100 mm Aggregate Gradations

The particle size curves depicted in Figure 4 show that the 10–100 mm and 25–100 mm samples have fine particles of 1.05% and 0.8%, a D_{50} of 37 and 49 mm, and their percentages of passing through a 50 mm mesh sieve were 78.15 and 48.3%, respectively. Therefore, it concerns gravelly materials with low contents of fine particles that contain large elements (D_{max} > 50 mm). In addition, with a proportion of particles greater than 20 mm, which greatly exceeds the threshold of 30%, the screening waste rock cannot be proctored within the meaning of the Proctor standard. However, the Proctor test was performed on the 0–20 mm fraction but its interpretation is limited to the assessment of its moisture content W_{OPN}.

The grading analyses of both 10–100 mm and 25–100 mm aggregate size fractions of the screening waste rock are shown in Table 5. It can be seen that the two samples have a granularity with strong gravelly dominance, are less spread out because the Cu is very close to 2, and are well graduated because the Cc is between 1 and 3. The spread of their initial particle size distributions will certainly undergo an evolution after compaction conditions.

Table 5. The main geotechnical properties of the studied SWR materials.

Parameter	SWR (10–100 mm)	(SWR 25–100 mm)
D_{max} (mm)	100	100
D_{50} (mm)	37	49
Cu	2.22	2
Cc	1.09	0.89
Particle-size analysis, (%)		
<63 µm	0.31	0.12
<80 µm	1.05	0.80
<2 mm	2.13	1.01
<20 mm	14.2	2.61
<50 mm	78.15	48.3
P_I (%)	<6	<6
MBV (g/100 g)	0.21	0.15
Standard Proctor test		
W_{OPN} (%)	9.16	9.12
GTR and GMTR classification	C_1B_4	C_2B_4

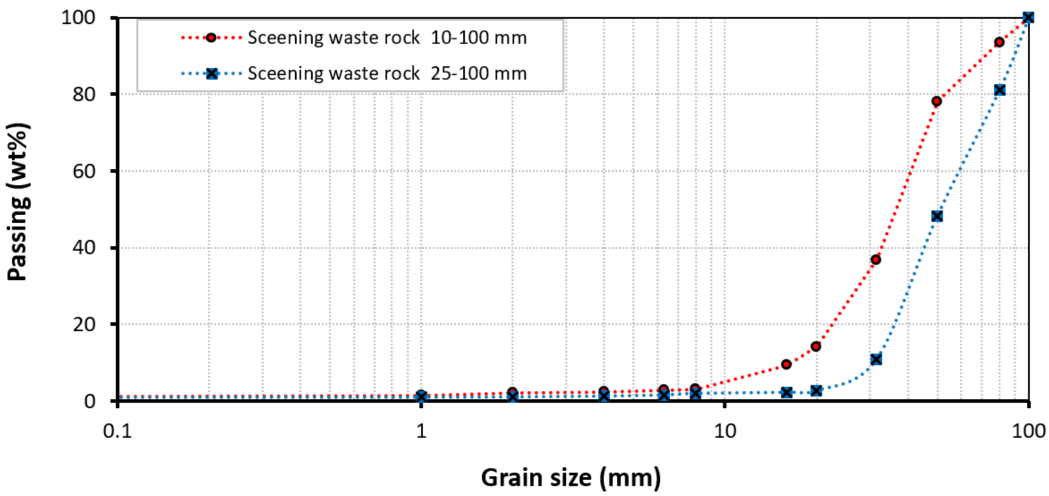

Figure 4. Particle size distribution of both 10–100 mm and 25–100 mm aggregate gradations.

These findings are useful in noting that the obtained gradations 10–100 mm and 25–100 mm could be considered as materials that are insensitive to water before compaction; however, the phenomenon of instability, change in particle size distribution (evolutionary behavior), and particle segregation after implementation are assessed through the performance of full-scale tests.

3.4. Field Trial Experiments

In this section, the results obtained from the field investigations are analyzed and the behaviors of the tested SWR materials under real working conditions are also assessed. Both construction phases and engineering machines carried out for the construction of the two full-scale field tests have been described in Figure 5.

Figure 5. Various stages of the two full-scale field tests of the capping layers sections: (**a**) topographic layout and plate load test on existing embankment; (**b**) levelling with a grader; (**c**) watering the material up to WOPN; (**d**) compacting operation.

The field experiment on the 25–100 mm aggregates shows the great difficulty of compaction and the tendency of the separation of the grain boundary due to the phenomenon of generalized segregation, which concerned practically all of the surface of the layer (Figure 6). This poor granular arrangement observed can be explained primarily by the lack of fine aggregates, and one can add the difference in size and density of the particles to this. This phenomenon of segregation is detrimental to the mechanical properties of the used materials and can cause short- and long-term bearing defects. As a result, the proposal to use the 25–100 mm fraction of screening waste rock in the capping layers was rejected. Furthermore, the presence of fine elements developed after compaction significantly reduced the extent of the segregation phenomenon on the 10–100 mm aggregate size grading trial section. However, it is highly advisable, for the future realizations of the capping layer, to operate the mixing of these materials using a crawler bulldozer, which was not programmed during this field test. This can lead us to eliminate the coarse aggregates of 50–100 mm which prevent the correct spreading of the platform.

Figure 6. The appearance of the surface layer of the 25–100 mm aggregate size grading of SWR. (**a**) Poor granular arrangement observed during compaction; (**b**) dominant surface appearance at the end of the compaction, which reveals a high segregation phenomenon.

3.4.1. Evolutionary Behaviour of SWR Materials: Field Measurements

Figure 7 illustrates the grain size evolution of the SWR (10–100 mm) under the compaction energies developed by 5, 7, and 9 passes of the compactor. It is noteworthy that D_{50} has decreased from 37 mm to 35.34 mm and 33.8 mm under 5, 7, and 9 passes, respectively. It has been also seen that the 20–100 mm size grading remains the most affected by the granulometric evolution. The passes at 80 µm evolved from 1.05% before implementation to 2.79%, 4.61%, and 4.77% after 5, 7, and 9 passes of the roller compactor, respectively. Furthermore, a slight evolution in passing at 2 mm after compaction was also observed. With a Cu of 3.6 and a Cc of 1.88, the particle size curve of the SWR (10–100 mm) after 7 passes of the compactor is well spread out and well graduated. In this research, the fine activity of 10–100 mm size grading has been assessed using the methylene blue adsorption method. Based on this, the MBV value obtained on the 0–5 mm fraction of the sample taken after 7 passes was 0.22 g/100 g. Hence, an evolution of 4.8% after compaction process was observed. Based on the analysis of the gradation and MBV results above, the following points can be concluded:

- The 10–100 mm size fraction of the studied SWR can be considered as slightly evolving materials; nevertheless, a stable state was noticed after 7 passes.
- It retains its insensitivity to moisture variations even after the compaction process.

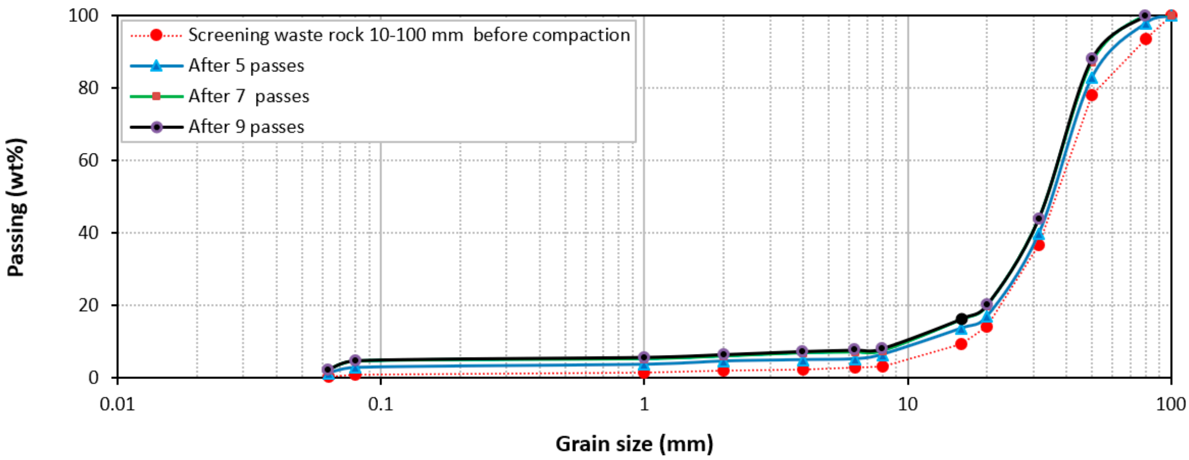

Figure 7. Evolution of grading curves of SWR (10–100 mm) according to the number of compactor passes.

3.4.2. Densification Measurements

The weight percentage of the 0–20 mm size fraction had not risen above the threshold of 70% of total SWR mass even after compaction, thus the maximum dry density of the standard Proctor test had not been taken as the reference to calculate the degrees of compaction. The dry density reference will be the one that corresponds to the maximum value of the six points of in situ dry densities recorded after the application of the various planned compaction energies. The results of the dry density according to the compacting energy on the bottom and over the entire thickness of the three compacted layers have been summarized in Table 6 below.

Table 6. Dry densities according to the compaction energies.

Layer	Compaction Energies	γd_{EL} (kN/m^3)	Degree of Compaction (%)	γd_{BL} (kN/m^3)	Degree of Compaction (%)	Thickness (m)
First layer	5 passes	19.2 ± 0.021	95.90	18.4 ± 0.023	91.90	0.32
	7 passes	19.8 ± 0.02	98.90	19.1 ± 0.025	95.40	0.30
	9 passes	19.7 ± 0.03	98.40	19 ± 0.027	94.90	0.31
Second layer	5 passes	19.4 ± 0.022	96.90	18.6 ± 0.026	92.90	0.31
	7 passes	20.02 ± 0.029	100.00	19.2 ± 0.021	95.90	0.32
	9 passes	19.9 ± 0.026	99.40	19 ± 0.028	94.90	0.29
Third layer	5 passes	18.9 ± 0.031	94.40	18.5 ± 0.029	92.40	0.32
	7 passes	19.9 ± 0.027	99.40	19.1 ± 0.024	95.40	0.29
	9 passes	19.9 ± 0.028	99.40	18.9 ± 0.03	94.40	0.30

These finding are helpful for an easier interpretation of the results. Clearly, the maximum dry density corresponding to 20.02 kN/m^3 was recorded under the compaction energy of 7 passes and the dry density reference, γd_{ref}, for calculating the degree of compaction is therefore taken as being equal to 20.02 kN/m^3. Furthermore, the energy produced by 5 compactor passes remained insufficient while 9 passes is not economically viable. In addition, it is important to note an asymptotic behavior at 7 compactor passes. Moreover, all of the γd_{EL} and γd_{BL} under 7 passes are greater than the 98.5%γd_{ref} and 95%γd_{ref}, respectively. Hence, the optimal compaction energy, which makes it possible to guarantee the densification condition, corresponds to 7 passes using a vibratory roller compactor class V4.

It is particularly important to state that the assimilation of the 10–100 mm size grading of SWR aggregates to the category of gravelly materials of class C_1B_{42}, is insufficient to reflect its particular geotechnical behavior. The compaction difficulty during the in situ tests was mainly related to the degree of heterogeneity of grading and density that was observed, which required an additional pass of the compactor machine to achieve the projected compaction quality objectives.

3.4.3. Bearing Capacity Evaluation

The bearing capacity measurements were made, for each compaction energy, after the completion of the third layer by calculating the deformability modulus under static loading when applied to a rigid plate following the standards set by [31]. In addition, six measurement points were carried out for each of the methods applied by the test protocol. In view of the results presented in Table 7, it was noted that there was asymptotic behavior at 7 passes with a slight drop in lift after 9 passes. The ratio k values highlighted the good quality of the compaction process obtained after 7 passes, which was contrary to the energy developed by 5 passes that remains insufficient (k > 2). Given the issue of cost effectiveness, the energy under 9 passes has been excluded. It should be mentioned that under 7 compactor passes, the obtained plate test modulus EV_2 is above the required threshold of 50 MPa.

Table 7. Results of the plate load test performed after compaction of the 3rd layer of SWR (10–100 mm).

Parameter	Unit	Compaction Energies		
		5 Passes	7 Passes	9 Passes
Standard deviation	%	3.05	2.52	2.44
EV_1	MPa	41.28	64.21	59.41
EV_2	MPa	88.75	106.6	99.21
k	-	2.15	1.66	1.67

3.4.4. Practical Compaction Protocol for the Capping Layer Application

Based on the results of the field trial, the practical modalities of implementation for the optimal use of the 10–100 mm aggregate gradation in capping layer construction are shown in Table 8. In view of the aforementioned findings, it can be concluded that according to the GMTR guide, the 10–100 mm size grading of SWR aggregates can be used without treatment in the capping layer structure for a low-volume traffic pavement project (less than or equal to T3). This corresponds to a daily number of heavy goods transport vehicles over 8 tons between 50 and 150. The use of an unusual material in road construction is further conditioned by its technical and environmental feasibility, and mostly by its economic feasibility. Within this framework, the economic evaluation of the alternative solution will represent an essential step before operational use.

Table 8. Practical modalities of implementation for using SWR (10–100 mm) in capping layer structure.

Hydric Conditions	Compactor Class	COMPACTOR Speed (km/h)	Compaction Energy	Thickness (m)
Average moisture status	V4	3.5	7 passes	0.30

4. Economic Analysis

The present preliminary economic analysis is performed using the same cost model given by Amrani, Taha, Kchikach, Benzaazoua, and Hakkou [4]. In this study, it aimed to determine the area of cost effectiveness of the phosphate mine of the Benguerir site, beyond which the SWR will be no longer be competitive given the average prices of capping layer structures made with conventional aggregates.

In this work, the calculation of the overall cost for SWR foundation layer utilization generally requires taking into account the costs of investment (COPEX) and maintenance (OPEX) during the service life. The evaluation consists of analyzing the main costs related to the scenario based on using the SWR in the capping layer construction and subsequently comparing them to those generated by the traditional materials. As maintenance and operating costs are often meant to be very similar, the approach will focus only on the construction costs life cycle (COPEX). The road capping layer application mainly includes extraction, loading, transportation, unloading, and implementation of materials. However, the most important parameter affecting the overall cost is that of transport from the distance from the supply resources to the destination. Using a 15 m^3 truck capacity in normal conditions, the calculation of the total cost of transport requires taking into consideration the variable and fixed costs. Table 9 lists the different costs for transporting road pavement materials and the fundamental assumptions that underlie the calculation of the cost effectiveness.

Table 9. The variable and fixed charges expected for transporting road pavement materials.

Variables Charges	Fixed Charges
Raw materials (fuel) Track maintenance (emptying, repair, washing ...) Tires wear	Driver (salary, travel expenses ...) Track charges (cost related to financing, depreciation, taxes, insurance, technical visits...) Operating costs (administrative costs, taxes...)

The determination of profitability radius draws mainly on the following survey-based data:

- Operating costs of a medium-sized company (road construction).
- Track maintenance every 10,000 km (on average).
- Changing the set of tires every 40,000 km (on average).
- Average consumption of a 15 m^3 load truck from a flat to hilly area, taken equal to 48 L/100 km.
- The calculation of the annual distance travelled of 74,880 km, which assumes an average daily of 240 km.
- The various financial costs mentioned below are chiefly based on a survey carried out between February 2019 and January 2020 on nearly a dozen companies specializing in road construction in the Benguerir region.

For the purpose in this work, the average prices per year of different services planned for transporting capping layer materials are illustrated in Table 10. This is the financial manifestation of the charges mentioned in Table 9.

Table 10. Annual costs related to the various services provided for transporting road pavement materials.

Designation	Costs (€)
Depreciation expense	2900
Expenses driving staff	7800
Insurance fees	1160
Dues and taxes	1015
Total fixed fees (€)	12,875
Fuel and lubricant	35,942
Pneumatic	2400
Maintenance and repair	2450
Total variables fees (€)	40,792
Operating costs	2500
Other	1000
Total structure fees (€)	3500
Total return price (€)	57,167
Cost price per kilometer rolled (€)	0.76
Cost price per m^3 kilometer (€)	0.05

Table 11 gives a financial comparison analysis between SWR and conventional aggregates supplied from a local quarry. This contrast is based on the details of the costs of the planned tasks for the realization of capping layers in accordance with the terms of the specification and the corresponding monitoring plan.

The profitability radius (R) can be determined according to the following Equation (1):

$$(((\mathrm{P} + \mathrm{R.T}).\mathrm{Coeff}(\exp)) + \Sigma(\text{the other } \cos\text{ts})).\mathrm{Pro} = \mathrm{Sp} \quad (1)$$

where P is purchase of materials, R is profitability radius, T is cost of transport, Coeff (exp) is the expansion coefficient, The other costs are the cost of implementation + purchase of materials + loading cost, Pro is profit margin, and Sp is sale price.

Table 11. Calculation details of profitability radius.

Average Costs Excluding Taxes	Unit	SWR Materials	Conventional Aggregates
Cost of transport	€·m^3/km	0.05	0.05
Expansion coefficient		1.25	1.25
Profit margin	%	15	15
Prior screening	€	3	3
Loading cost	€	0.5	0.5
Cost of implementation	€	2.6	2.5
Purchase of materials	€	0.2	1.5
Selling price of capping layer service	€	14.5	14.5
Profitability radius (R)	km	100	75

Based on the reported results in Table 11, the SWR materials can be used as capping layer materials in a radius of 100 km around the phosphate mining area of Benguerir, unlike conventional aggregates that lose their profitability beyond 75 km. This calculation was done assuming that conventional resources are available, otherwise this radius of profitability will have to correct downward.

It is also necessary to note that this profitability radius certainly becomes far wider if the positive economic spin-offs relevant to the exploitation of phosphate ore founded in the fine capped size grading are taken into consideration.

5. Circular Economy

The Moroccan phosphate mining industry has followed a classical linear production process in which wastes are continuously generated and stock-piled in dumps and tailing storage facilities [34]. These wastes are generally considered as a source of pollution and must be handled accordingly, which also comes with additional management costs. The transition from the current linear conception model to a circular economy approach requires integrating novel mining procedures for waste management such as material sorting and classification. The purpose is to close loops and to simultaneously safeguard natural resources. Novel sustainable and eco-friendly solutions are required to minimize waste generation and societal impacts, to optimize energy consumption, to decrease the possible environmental impacts on air and water, and to encourage the valorization of produced waste.

This section aims to highlight the opportunity related to the transformation of a specific type of mining rock waste into a useable product via reuse, and prepare a smooth transition to the circular supply chains. This is essential to partially decrease the demand for new natural resource quarries and, more importantly, to generate economic profits [35–38].

As mentioned previously, SWR cannot be directly used without treatment because capping layer aggregates, due to the existence of a fine fraction that is very sensitive to moisture variations, contain high contents of apatite. From a resource governance perspective, it is suggested to recover the fine fraction that is rich in apatite (48%) and send it to the current processing methods. The recovery of apatite using gravity and physical processes is possible from both economic and feasibility standpoints. The coarse fraction can efficiently be used as materials for capping layer applications (Figure 8). Finally, simple changes in the storage process can ensure a smooth transition from a traditional linear consumption model to a circular economy. The installation of a screening station equipped with 10 × 10 mm mesh screens upstream of the SWR storage makes it possible to recover the size fraction that is less than the 10 mm mesh sieve and rich in P_2O_5.

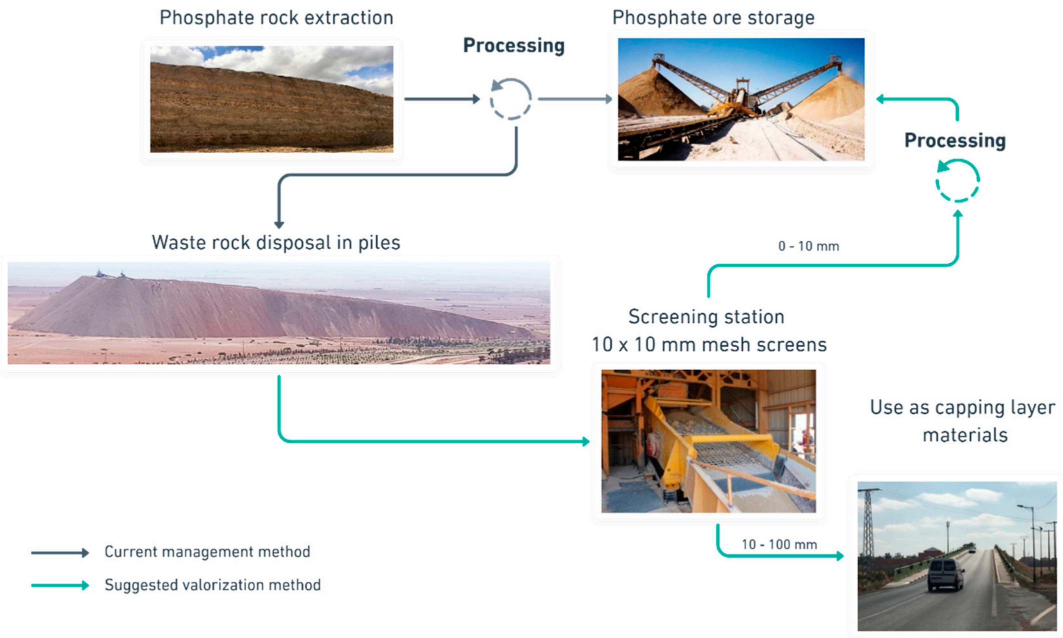

Figure 8. From a traditional linear consumption model to a circular phosphate economy: the case of screening waste rock for capping layer applications and lost phosphate recovery.

The technique of automatic phosphate ore sorting can be evaluated in depth before deciding on its application to recover the remaining amount of P_2O_5 in the SWR aggregates. In this study, a representative sample was used. However, it is necessary to evaluate the challenges related to geotechnical and mineralogical heterogeneity of the SWR materials from one phosphate mining site to another.

6. Conclusions

This paper presents a multi-scalar approach for both laboratory and field investigations that take positions concerning the possible acceptability of phosphate screening waste rock in capping layer construction. The exploitation of the experimental results can lead to the following various practical conclusions:

- The studied screening waste rock should not be classified as hazardous waste, as is the case at the moment for the GMTR guide. Moreover, it is essential to recognize these materials in the same terms as conventional aggregates;
- The specifications of the GMTR guide do not allow the direct use of raw 0–100 mm gradation of SWR as a capping layer aggregate without treatment as long as the clay parameters exceed the required thresholds;
- Clipping of the 0–10 mm sieve fraction rich in P_2O_5 remains a very useful technical and sustainable action. The findings of the full-scale investigations that were carried out on the 10–100 mm aggregates have confirmed the adaptability of these materials to a possible use, without treatment, for low-volume traffic pavement projects. There was also proven economic interest associated with the exploitation of the phosphate ore with a high apatite content that was found in this fine aggregate size. Moreover, such an approach can ensure a smooth transition from a traditional linear consumption model to a circular economy;
- The technique of automatic phosphate ore sorting can be evaluated in depth before deciding on its application to recover the remaining amount of P_2O_5 in the SWR aggregates;
- Segregation is a deleterious phenomenon of the homogeneity properties of gravel materials, which contributes to the reduction of the adhesive bond strength. Consequently, it can lead to short- and long-term bearing defects. As a result, the proposal to use the 25–100 mm fraction of SWR as capping layer materials was ruled out;

- The practical modalities of implementation for the optimal use of the 10–100 mm aggregate gradation in capping layer applications have been determined. Compared to conventional materials, compaction difficulties have been observed.

Regarding the economic issue, SWR materials with the same features as the conventional equivalent are economically and conceptually attractive for capping layer applications because they may be easier and quicker to prepare with a comparable overall selling price.

In conclusion, the technical validity coupled with economic profitability and environmental stability of 0–100 mm aggregates of SWR for capping layer structures have been confirmed. As the road sector in Morocco consumes heavy volumes of aggregates, the valorization of screening waste rock could therefore constitute a serious alternative that could make it possible to reduce the quantities of stored piles and preserve partially conventional aggregates by constituting a new source of raw materials. However, this vision faces certain obstacles, such as the absence of clear regulations and technical standards that are adapted to the use of these materials. In this context, all waste management alternatives for regional development should be updated for the technical references that are currently the case for the GMTR guide, which can consider these findings to overcome this ban.

7. Recommendations

In road design, permanent deformations of unbound granular material in sub-base layers represent the main causes of distress, which can lead to rutting of the pavement surface. For this reason, further tests are required to evaluate the resilient and permanent deformation behavior of SWR aggregates under cyclic loading.

Author Contributions: Conceptualization, M.A.; formal analysis, Y.T.; funding acquisition, R.H.; investigation, M.A. and M.B.; project administration, Y.T., M.B. and R.H.; resources, R.H.; supervision, Y.T., A.K., M.B. and R.H.; writing—original draft, M.A.; writing—review & editing, M.A., Y.T., M.B. and R.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by OCP Group (Morocco), grant number RE01.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors greatly acknowledge the OCP-SA collaborators for the great help concerning the sampling and full-scale trial test conducting. The authors are also grateful to the staff of Mohammed VI Polytechnic University for their valuable contributions to the solid samples' characterizations.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

Cc	Coefficient of curvature, Cc = d30/(d60·d10)
Cu	Uniformity coefficient, Cu = d60/d10
DG	Degradability coefficient
D_{max}	The largest diameter of grain, in mm
d10 and d60	The sizes for which the cumulative distribution are respectively 10% and 60%, in mm
D_{50}	Mean particle size, in mm
EV_1 and EV	Strain modulus, are respectively determined from first (0.2 MPa) and second (0.25 MPa) load cycles under a normalized rigid plate, in MPa
FR	Fragmentability coefficient
Gs	Specific gravity
k	Ratio, $k = EV_2/EV_1$
LA	Los Angeles abrasion value, in %
MD	Micro-Deval value, in %

MBV	Methylene blue adsorption value, in g/100 g
P_L	Plasticity index, in %
R	The radius of profitability, in km
SWR	Phosphate screening waste rock
TCLP	Toxicity characteristic leaching procedure
W_L	Liquid limit, in %
W_{OPN}	Optimum water content of standard Proctor test, in %
W_P	Plastic limit, in %
XRD	X-ray diffraction
γd_{ref}	Maximum in situ dry unit weight, in kN/m^3
γd_{BL}	In situ dry density on the bottom of the compacted layer, kN/m^3
γd_{EL}	In situ dry density over the entire thickness of the compacted layer, kN/m^3

References

1. European-Commission. *Best Available Techniques for Management of Tailings and Waste-Rock in Mining Activities*; Publications Office of the European Union: Luxembourg, 2018; ISBN 978-92-79-77178-1. JRC109657. [CrossRef]
2. Becquart, F.; Bernard, F.; Abriak, N.E.; Zentar, R. Monotonic aspects of the mechanical behaviour of bottom ash from municipal solid waste incineration and its potential use for road construction. *Waste Manag.* **2009**, *29*, 1320–1329. [CrossRef] [PubMed]
3. Kuranchie, F.A.; Shukla, S.K.; Habibi, D. Mine wastes in Western Australia and their suitability for embankment construction. In Proceedings of the Geo-Congress 2013: Stability and Performance of Slopes and Embankments III, San Diego, CA, USA, 3–7 March 2013; pp. 1443–1452.
4. Amrani, M.; Taha, Y.; el Haloui, Y.; Benzaazoua, M.; Hakkou, R. Sustainable reuse of coal mine waste: Experimental and economic assessments for embankments and pavement layer applications in Morocco. *Minerals* **2020**, *10*, 851. [CrossRef]
5. Ormsby, W.C.; Fohs, D.G. Use of waste and by-products in highway construction. *Transp. Res. Rec.* **1990**, *1288*, 47–58.
6. Poulikakos, L.; Papadaskalopoulou, C.; Hofko, B.; Gschösser, F.; Falchetto, A.C.; Bueno, M.; Arraigada, M.; Sousa, J.; Ruiz, R.; Petit, C. Harvesting the unexplored potential of European waste materials for road construction. *Resour. Conserv. Recycl.* **2017**, *116*, 32–44. [CrossRef]
7. Pasetto, M.; Baldo, N. Experimental evaluation of high performance base course and road base asphalt concrete with electric arc furnace steel slags. *J. Hazard. Mater.* **2010**, *181*, 938–948. [CrossRef] [PubMed]
8. Zore, T.; Valunjkar, S. Utilization of fly ash and steel slag in road construction—A comparative study. *EJGE* **2010**, *IS BUND. Q*. Available online: https://www.researchgate.net/publication/268060587_Utilization_of_Fly_Ash_and_Steel_Slag_in_Road_Construction_-_A_Comparative_Study (accessed on 26 September 2022).
9. Sinha, A.K.; Havanagi, V.G.; Sreekantan, P.G.; Chandra, S. Geotechnical characterisation of zinc tailing waste material for road construction. *Geomech. Geoengin.* **2021**, 1–21. [CrossRef]
10. Vilaça, A.S.I.; Simão, L.; Montedo, O.R.K.; de Oliveira, A.N.; Raupp-Pereira, F. Waste valorization of iron ore tailings in Brazil: Assessment metrics from a circular economy perspective. *Resour. Policy* **2022**, *75*, 102477. [CrossRef]
11. Careddu, N.; Dino, G.A. Reuse of residual sludge from stone processing: Differences and similarities between sludge coming from carbonate and silicate stones—Italian experiences. *Environ. Earth Sci.* **2016**, *75*, 1–9. [CrossRef]
12. Amrani, M.; Taha, Y.; Kchikach, A.; Benzaazoua, M.; Hakkou, R. Valorization of phosphate mine waste rocks as materials for road construction. *Minerals* **2019**, *9*, 237. [CrossRef]
13. Amrani, M.; Taha, Y.; Elghali, A.; Benzaazoua, M.; Kchikach, A.; Hakkou, R. An experimental investigation on collapsible behavior of dry compacted phosphate mine waste rock in road embankment. *Transp. Geotech.* **2021**, *26*, 100439. [CrossRef]
14. Amrani, M.; el Haloui, Y.; Hajikarimi, P.; Sehaqui, H.; Hakkou, R.; Barbachi, M.; Taha, Y. Feasibility of using phosphate wastes for enhancing high-temperature rheological characteristics of asphalt binder. *J. Mater. Cycles Waste Manag.* **2020**, *22*, 1407–1417. [CrossRef]
15. Amrani, M.; Taha, Y.; Kchikach, A.; Benzaazoua, M.; Hakkou, R. Phosphogypsum recycling: New horizons for a more sustainable road material application. *J. Build. Eng.* **2020**, *30*, 101267. [CrossRef]
16. GTR. Réalisation des remblais et des couches de forme, guide technique. In *Fascicule I et II, édition LCPC, SETRA*; GTR: Paris, France, 2000.
17. OCDE. *Utilisation de Déchets et Sous-Produits en Technique Routière*; Organisation de Coopération et de Développement Economique: Paris, France, 1977.
18. GMTR. *Guide Marocain pour les Terrassements Routier. Direction des Routes et de la Circulation Routière. 2002. Fasci-cule 1*; Ministère de l'Equipement: Rabat, Royaume du Maroc, 2002; 106p.
19. *NF-EN-ISO-17892-4*; Geotechnical Investigation and Testing—Laboratory Testing of Soil—Part 4: Determination of Particle Size Distribution AFNOR Editions Online Store. AFNOR editions: La Plaine Saint-Denis, France, 1992.
20. *NF-P94-052-1*; Soil: Investigation and Testing. Atterberg Limit Determination. Part 1: Liquid Limit. Cone Penetrometer Method.—Sols: Reconnaissance et Essais. AFNOR editions: La Plaine Saint-Denis, France, 1995.

21. *NF-P94-051*; Soil: Inverstigation and Testing. Determination of Atterberg's Limits. Liquid Limit Test Using Cassagrande Apparatus. Plastic Limit Test on Rolled Thread.—Sols: Reconnaissance et Essais. AFNOR editions: La Plaine Saint-Denis, France, 1993.
22. *NF-P94-066*; Soils: Investigation and Tests. Fragmentability Coefficient of Rocky Material.—Sols: Reconnaissance et Essais. AFNOR editions: La Plaine Saint-Denis, France, 1992.
23. *NF-P94-067*; Soils: Investigation and Tests. Degradability Coefficient of Rocky Material.—Sols: Reconnaissance et Essais. AFNOR editions: La Plaine Saint-Denis, France, 1992.
24. *NF-EN-1097-1*; Tests for Mechanical and Physical Properties of Aggregates—Part 1: Determination of the Resistance to Wear (Micro-Deval). AFNOR editions: La Plaine Saint-Denis, France, 2011.
25. *NF-EN-1097-2*; Tests for Mechanical and Physical Properties of Aggregates—Part 2: Methods for the Determination of Resistance to Fragmentation. AFNOR editions: La Plaine Saint-Denis, France, 2010.
26. *NF-P94-068*; Soils: Investigation and Testing. Measuring of the Methylene Blue Adsorption Capacity of à Rocky Soil. Determination of the Methylene Blue of à Soil by Means of the Stain Test.—Sols: Reconnaissance et Essais. AFNOR editions: La Plaine Saint-Denis, France, 1998.
27. *NF-P94-064*; Reconnaissance et Essais- Masse Volumique Sèche d'un Elément de Roche-Méthode par Pesée Hydrostatique. AFNOR: Paris, France, 1993.
28. *EN-1097-6*; Essais pour Déterminer les Caractéristiques Mécaniques et Physiques des Granulats—Partie 6: Détermination de la Masse Volumique Réelle et du Coefficient D'absorption D'eau. AFNOR: Paris, France, 1993.
29. *EPA-1311*; SW-846 Test Method 1311: Toxicity Characteristic Leaching Procedure, Washington, DC. AFNOR editions: La Plaine Saint-Denis, France, 1992.
30. US-EPA. *Hazardous Waste Characteristics. A User-Friendly Reference Document*; AFNOR editions: La Plaine Saint-Denis, France, 2009.
31. *NF-P94-117-1*; Soils: Investigation and Testing—Formation Level Bearing Capacity—Part 1: Plate Test Static Deformation Module (EV2)—Sols: Reconnaissance et Essais. AFNOR editions: La Plaine Saint-Denis, France, 2000.
32. *NF-P98-736*; Road Construction and Maintenance Equipment. Compactors. Classification.—Matériel de Construction et D'entretien des Routes. AFNOR editions: La Plaine Saint-Denis, France, 1992.
33. *NF-P94-061-2*; Soils: Investigation and Testing. Determination of Density of Materials on Site. Part 2: Membrane Densitometer Method.—Sols: Reconnaissance et Essais. AFNOR editions: La Plaine Saint-Denis, France, 1996.
34. Taha, Y.; Elghali, A.; Hakkou, R.; Benzaazoua, M. Towards Zero Solid Waste in the Sedimentary Phosphate Industry: Challenges and Opportunities. *Minerals* **2021**, *11*, 1250. [CrossRef]
35. Zhao, Y.; Zang, L.; Li, Z.; Qin, J. Discussion on the model of mining circular economy. *Energy Procedia* **2012**, *16*, 438–443. [CrossRef]
36. Van Zyl, D.; Shields, D.; Agioutantis, Z.; Joyce, S. Waste not, want not-rethinking the tailings and mine waste issue. *AusIMM Bull.* **2016**. [CrossRef]
37. Kinnunen, P.H.M.; Kaksonen, A.H. Towards circular economy in mining: Opportunities and bottlenecks for tailings valorization. *J. Clean. Prod.* **2019**, *228*, 153–160. [CrossRef]
38. Bukhkalo, S.I.; Klemeš, J.J.; Tovazhnyanskyy, L.L.; Arsenyeva, O.P.; Kapustenko, P.O.; Perevertaylenko, O.Y. *Eco-Friendly Synergetic Processes of Municipal Solid Waste Polymer Utilization*; The Italian Association of Chemical Engineering: Florence, Italy, 2018.