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Case Report

Geological and Geomechanical Characterization of Phosphate Mine Waste Rock in View of Their Potential Civil Applications: A Case Study of the Benguerir Mine Site, Morocco

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Abstract: Sedimentary phosphate extraction in open-pit operations generates large volumes of waste rock (*WR*), which are mainly overburdens and interburdens. Traditionally, the WR is mixed and stored on the surface in waste rock piles (*WRP*s). This paper presents a case study of the Benguerir mine site in Morocco. It investigates the potential valorization of each *WR* lithology based on the geological and geomechanical properties to reduce their environmental footprint and create added value to "waste." The *WR* samples (soils and rocks) were collected from drill cores and mining trenches in the Benguerir mine. The geological characterization results using petrographic descriptions indicate the presence of nine phosphate layers and, in addition to the overburdens, eight interburdens. Four types of *WR* are identified: carbonate, siliceous, marly clay, and phosphate. The geomechanical characterization of soil-like samples showed an average plasticity index (*PI*) of 50% according to the methylene blue value (*MBV*) of 7.1, classifying them in the A3–A4 categories as plastic and clayey marl soils. The hard rock samples have excellent mechanical properties in terms of their uniaxial compressive strength (*UCS*), Los Angeles abrasion value (*LA*), and micro-Deval value (*MD*). The average compressive strength is 104 MPa for the flint, 35 MPa for the phosphate flint, 32 MPa for the silexite, 26 MPa for the limestone, 11 MPa for the indurated phosphate, and 8 MPa for the marly limestone. Based on the obtained results, these *WR*s can be considered as an excellent alternative secondary raw material for use in civil engineering applications, ceramics, and cement industries.

Keywords: phosphate waste rock; valorization pathways; geological characterization; geomechanical properties

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1. Introduction

Mining operations throughout the world generate large amounts of mining waste (e.g., waste rock, tailings, and sludge), most of which is stored in surface stockpiles, such as waste rock piles or tailings storage facilities (*TSF*s) for tailings or sludges [1]. Mining, minerals, and sustainable development (*MMSD*) assesses around 3500 active mining waste sites all around the globe, including *TSF*s and *WRP*s [2]. Mining operations generate approximately 100 billion tons of solid waste annually [3]. This mining waste may create major environmental hazards if not properly managed, and can significantly contribute to environmental pollution through air pathways and water leaching [2,4,5]. Mine waste management activities contribute to removing or minimizing environmental issues. During the last decade, several strategies emerged to provide a framework for sustainable mining development. With this initiative in mind, the mining industry must find ways to reuse or valorize waste to mitigate the environmental impact of its mining operations.

In the context of mining in Morocco, the exploitation of immense phosphate deposits presents the approaches in a favorable geological context, thus guaranteeing the diversity and abundance of mineral resources. Thus, the mining industry occupies an important place in the development of the national economy. Phosphate ore in Morocco is extracted by open-pit mining method. The extraction is performed through the strip-mining method. This method involves cutting the deposits into a group of panels and dividing the panels into 40 m-large trenches. This method includes a set of mining operations: the drilling, blasting, stripping, loading, and transportation of phosphate. The stripping ratio represents the amount of waste (overburden) that must be removed to extract a given amount of ore. A strip ratio of 3:1 means that 3 tons of waste rock are produced to extract 1 ton of phosphate rock. For 4.2 million tons (*Mt*) of phosphate rock annually extracted in 2020, the estimated mass of waste rock stored in piles was 12.3 Mt (*OCP* Group Benguerir Mine, Benguerir, Morocco). Indeed, this extraction method generates large volumes of waste (~3.8 million m^3) composed mainly of carbonates, clays, marls, and flints, which correspond to overburdens and interburdens. Preliminary studies showed that this waste may present properties similar to many raw materials used in the civil engineering sector [6]. The extracted phosphate waste is pushed by D11 bulldozers or moved by dragline into the previous trench already exploited ($n - 1$) to form piles, or is transported to a storage area. This waste is a source of landscape nuisance due to the accumulation of by-products in large areas, which are rehabilitated with difficulty.

The deposition of *WR* in piles generates the segregation of fine and coarse materials [1]. The waste rock is considered as a heterogeneous material in terms of its physical, chemical, mineralogical, and geomechanical properties [7,8]. This heterogeneity is the main challenge in *WR* piling [9]. For instance, the main factors influencing the piles' physical (geotechnical) instability are the geometric configuration, the properties of the materials, the topography of the site, the construction method, and the climatic and hydrological conditions [9–11]. The stability analysis of WRPs must consider all these factors for the optimal design selection and determination of the probable risks [10]. In terms of the chemical stability, the risk of surface and groundwater pollution due to phosphate mining operations is generally low because of the high carbonate content in waste rocks [12].

The valorization or reuse of mining waste is challenging for the global mining industry because of economic reasons and the climate emergency [3,13]. This can alleviate the growing demand for construction materials or civil engineering works by preserving the natural resources in materials and can reduce land use. Indeed, the potential reuse of mining by-products has been studied in the last decade to reduce or minimize the intense generation of mining waste and improve environmental management [2,6]. In general mining industry practice, waste rock is reused on the surface for road construction and reclamation purposes [6,12,14] and underground as cemented or uncemented rock fill [15–17]. However, outside of mining sites, the reuse of waste rock still needs to be improved [9]. Indeed, several studies have evaluated the technical potential of the valorization and reuse of mining waste as secondary or alternative raw materials to supply other industries, such as civil engineering, ceramic industries, cement, and geopolymers manufacturing.

Amrani and Taha [18] and Hakkou et al. [6] suggest that phosphate waste rock presents promising geotechnical properties and can be reused as materials for road construction. In addition, mining waste can be used as an alternative material to produce aggregates [19,20], fired bricks [21–23], ceramic materials [24–29], and cement [30]; they can also be used for the restoration of mining sites [12,14]. The valorization or reuse of phosphate waste rock as a secondary raw material might allow the conservation of natural resources and the reduction in the environmental footprint [21]. The reuse of mine waste rock in any valorization pathway depends on its basic chemical, mineralogical, and geotechnical properties.

This paper focuses on the lithology of phosphate extraction waste from the Benguerir mine in Morocco. The novelty of this paper lies in the fact that it deals with the problem of managing natural materials (which, at present, have the status of waste) upstream of the mining chain. Most papers deal with the problem downstream, i.e., after the ore is recovered and everything else is mixed and deposited. This approach is crucial because it allows for a more comprehensive understanding of the entire process, from extraction to disposal, and identifies opportunities for improvement at every stage. For this purpose, the main objective of this study is to describe the different lithologies of the interburdens and to evaluate their geomechanical proprieties in view of their potential applications. The specific objectives of this paper are: i) the detailed geological and geomechanical characterizations of waste rock found in the interburdens, and ii) the proposition of valorization scenarios for the studied waste rocks based on their characteristics.

2. Materials and Methods

2.1. Mine Site and Drill Core Locations

The study area is one of the parcels of the Gantour basin, "Benguerir mine," located 70 km north of Marrakech and 17 km east of Benguerir city. The Benguerir deposit is located in Western Meseta. Two well-individualized Paleozoic massifs are bound it: the Rehamna massif to the north (metamorphic and crystalline rocks) and the Jbilet massif (schists) to the south. The Benguerir deposit is a sedimentary type [31,32]. The phosphate series extends from Maastrichtian to Lutetian and is presented as phosphate layers and waste interburdens [33]. This deposit is an extended east–west plateau, with altitudes ranging between 396 and 596 m (Figure 1).

Six vertical drill cores (non-destructive technique) of varying depths between 60 and 95.5 m were created to understand the structure and composition of the Benguerir phosphate series (Figure 1). The core drillings were labeled as SC02, SC03, SC04, SC05, SC06, and SC07. Core drillings were conducted by the *PTSL* (Public Testing and Studies Laboratory), according to the XP P94-202 standard [34]. The cut rock cylinder was progressively placed in the inner tube of the core, which was 1.5 m long and 116 mm in diameter.

The coring technique used an injection of water mixed with additives (bentonite and polymer) to facilitate drilling, improve the lubrication of the rod, cool the crown, and control any possible influx or loss of fluids by stabilizing the borehole walls.

The location of the drill holes was chosen so that the entire mine was covered while targeting future mining trenches. The non-destructive technique made it possible to recover a continuous and intact sample cylinder (core) from the existing lithologies and to preserve the geological structures (faults, joints) as well as the textures of the rocks. For the characterization tests, some core samples were wrapped in paraffin films to preserve their natural moisture levels.

2.2. Sampling Strategy and Methodology

The sampling strategy for this study was performed by combining random and targeted methods. Two criteria were used: the facies and the availability of the quantities needed for the analysis. The random method was used to collect samples from the mining trenches (Tr1, Tr2, Tr3, Tr4, Tr5, Tr6, Tr7, Tr8, Tr9, Tr10, Tr11, Tr12, Tr13, Tr14, Tr15, Tr16, and Tr17), depending on the availability and accessibility of the layers to be sampled. The targeted method was used to obtain samples from the drill cores (SC02, SC03, SC04, SC05, SC06, and SC07). To ensure a representative sample, attention was paid to the lithological and structural descriptions to identify the parameters likely to impact the geomechanical characterization. These sampling approaches enabled us to collect representative intact samples. The adopted methodology for this study is shown in Figure 2.

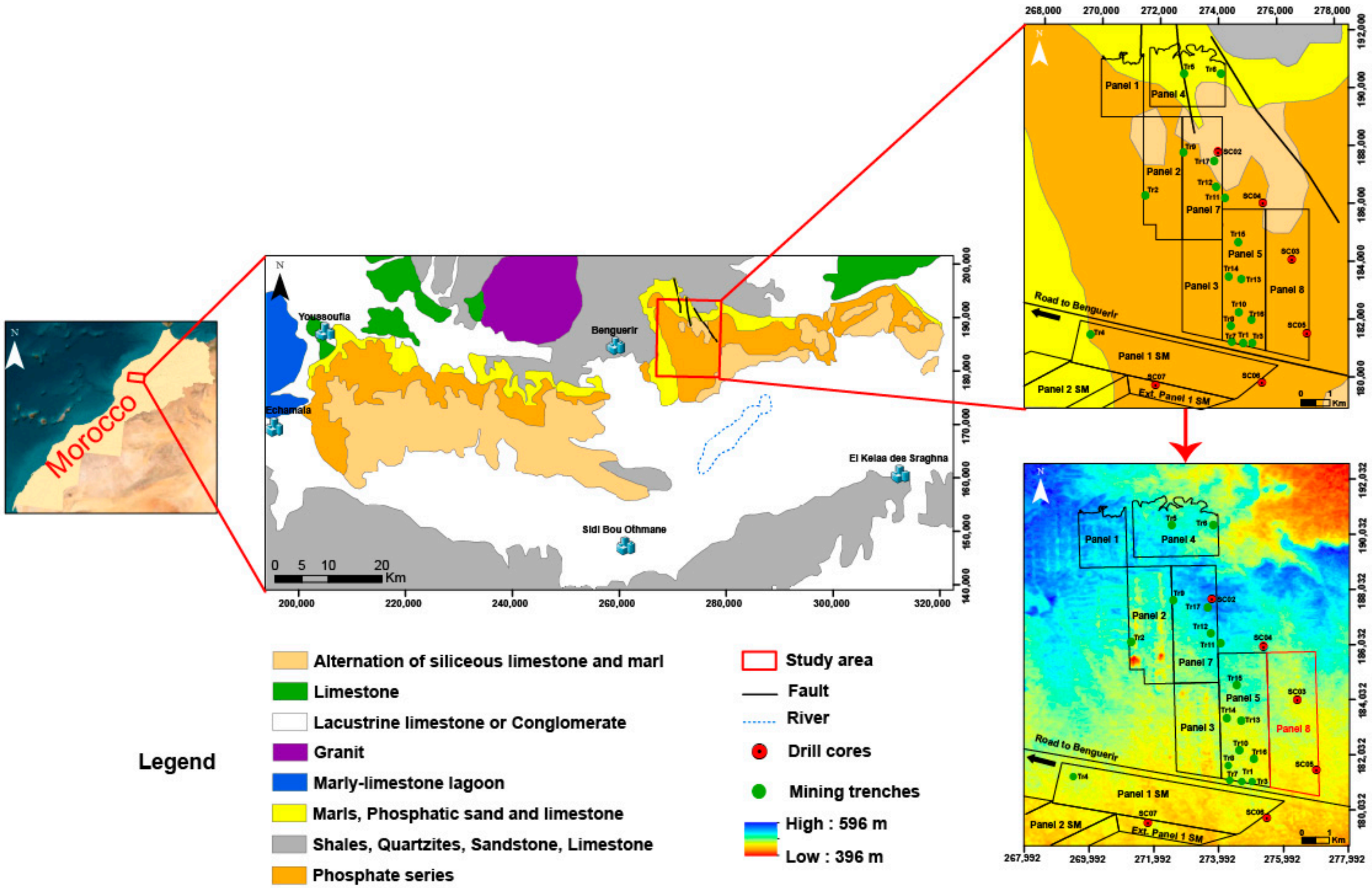

Figure 1. Schematic description of the Gantour basin's geology (based on the 1:1,000,000 geological map of Morocco).

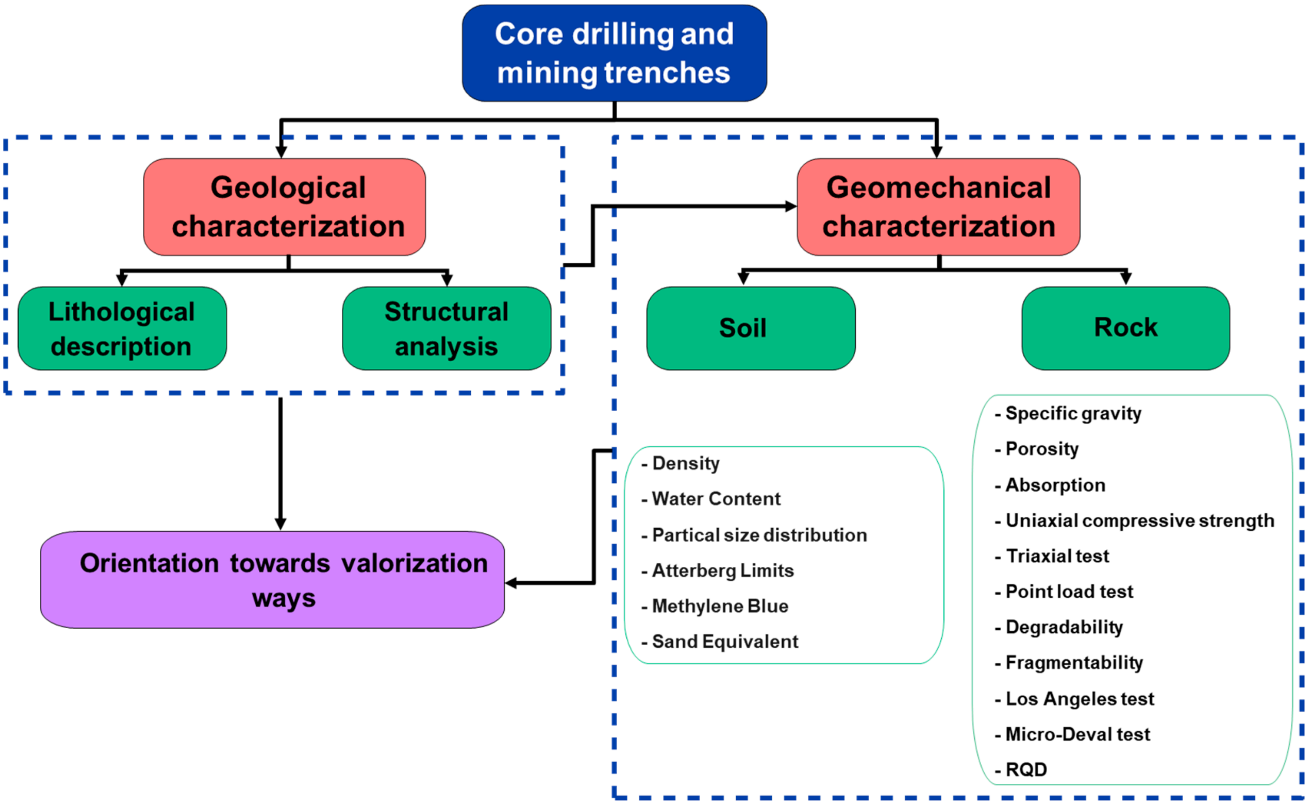

Figure 2. Schematic view of the methodological approach used.

Seven soil samples were collected from the C2/C3 interburdens of the Benguerir mine (see Figure 3), which was a thick interburden and remarkable for its yellow color. Three samples (A, B, and C) were taken from boreholes (SC02, SC04, and SC06), and four samples (Tr1, Tr2, Tr3, and Tr4) from mining trenches. The samples collected from the mining trenches involved using a hammer and hand shovel. The samples collected were placed in plastic bags, while the samples collected from the core were wrapped in paraffin film to keep their initial properties.

2.3. Structural Characterization

The structural characterization allowed us to obtain general information for the layers' nature, position, thickness, dip, etc. The techniques used in the structural characterization included core logging and a structural analysis using the rock quality designation (*RQD*). The cores were deposited in a natural order. The geological and structural descriptions were created to establish the lithological log. Drill core logging was performed as follows:

- Wetting the core to reveal the contrasts;
- Using hydrochloric acid (*HCl*) to test the presence or absence of carbonate;
- Identifying the hardness of the samples using basic techniques (glass, finger, or steel scraping);
- Petrographic descriptions.

In the logging, the following parameters were described: the thickness of each lithology, the chronological succession of the geological layers, and the presence of allochemes.

The structural descriptions of the drill cores were created using the rock quality designation, which was a crude indicator of rock quality [35]. *RQD* is defined as the percentage of intact drill core pieces longer than 100 mm over the total drilling length [36], and it is calculated as illustrated in Equation (1):

$$RQD = \frac{\sum Length\ of\ core\ pieces > 100\ \text{mm}\ length}{Total\ length\ of\ core\ run} \times 100 \quad (1)$$

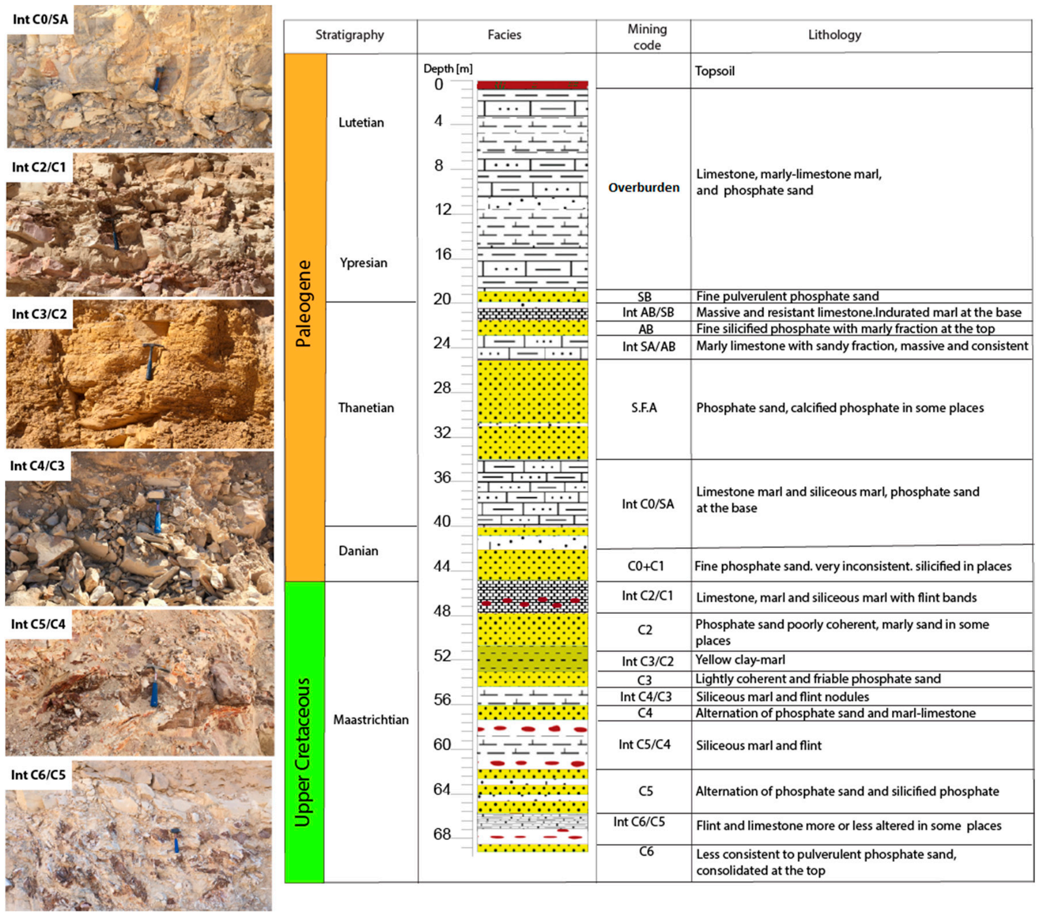

Figure 3. Synthetic litho-stratigraphic section of the Benguerir mine.

2.4. Geomechanical Characterization

The geomechanical characterization presented in this paper involves rocks and soil-like samples taken from different lithologies and depths. The geomechanical characterization was performed for each core drilling, and some samples were taken from the mining trenches. Laboratory tests were conducted to determine the mechanical and physical properties.

The gravimetric water content of the samples was measured using the oven-drying method (NM13.1.152) [37], while the bulk density was measured using the water-immersion method (NM13.1.119) [38]. The particle size distribution was determined using two techniques: dry sieving after washing for more than 80 µm of coarse particles and sedimentation with deflocculant for fine particles (NM00.8.083 and NM13.1.008 standards) [39,40]. The Atterberg limit test was performed on the 0/400 µm fraction to determine the liquid limit (*LL*), plastic limit (*PL*), and plasticity index (*PI*) according to the NF-P94-052-1 and NF-P94-051 standards [41,42]. The methylene blue value (*MBV*), which measured the adsorption capacity of soil material, was determined on a fraction < 5 mm, according to the NM00.8.095 standard [43]. The sand equivalent (*SE*) was measured on the 0/2 mm fraction in fine aggregates according to the NF EN 933-8+A1 standard [44]. This test aimed to rapidly evaluate the relative portion of clay in the sand.

The characterization of hard rock samples was evaluated for the various rock units within the interburdens. Six lithological facies (limestone, marly limestone, flint, phosphate flint, silexite, and indurated phosphate) were studied. The tests on the hard rock samples allowed us to determine the physical and mechanical properties, the uniaxial compressive strength (*UCS* or σ_c), and the resistance to fragmentation and wear by mutual friction of the elements of an aggregate. Specific gravity, porosity, and absorption are the primary physical properties of rocks. These properties were measured in accordance with NF P94-410-1, NF P94-410-2, and NF P94-410-3 standards [45–47]. These physical properties were widely used to evaluate and compare different correlations between the samples and lithologies. The *UCS* should be determined from uniaxial compression tests. However, in this study, the *UCS* values were indirectly derived from other tests, such as point load and triaxial tests, using empirical equations in order to obtain more compressive strength data. The *UCS* test was performed in accordance with the NF P94-420 standard [48] on core samples (cylindrical specimens with a circular cross-section). The triaxial tests were performed under consolidated-drained (*CD*) conditions in accordance with the NF P94-074 standard [49]. This test involved shearing at least three specimens from the same sample. The intrinsic parameters obtained from this test were cohesion (c) and friction angle (φ). These parameters were used to calculate the uniaxial compressive strength. The PLT is an alternative method to obtain the *UCS* indirectly and can be performed on rock samples without using special preparation techniques. The rock samples were compressed between two conical steel plates until failure occurred, in accordance with the XP P 94-429 standard [50].

In order to measure the sensitivity of these materials to fragmentation and degradability under the effect of mechanical stresses and climatic cycles, several geomechanical characterization tests were performed to evaluate the materials' resistance regarding fragmentation and wear under the effect of mechanical solicitations. The fraction of +10/−14 mm was chosen for the determination of the Los Angeles abrasion and micro-Deval values in accordance with the NF EN 1097-1 and NM.10.1.138 standards [51,52]. The resistance to the fragmentation and degradability coefficients of the samples were measured on the 40/80 mm fraction in accordance with the NF P94-066 and NF P94-067 standards [53,54], respectively.

3. Results and Discussion

3.1. Geological Characterization

Lithological Description and Rock Quality by *RQD*

A significant variety of lithological formations characterized the phosphate series of the Benguerir mine. This series comprised nine phosphate and eight waste layers (interburdens) (Figure 3). In addition to the interburdens, other layers were called "phosphate Slabs" with carbonate or siliceous matrices. They were generally found at the wall or between the phosphate layers, and their numbers differed from one area to another. Four types of waste rock were identified: carbonate (limestone and marly limestone), siliceous (flint and silexite), marly clay, and phosphate (phosphate flint and indurated phosphate). The nine interburdens were left in place in piles. From top to bottom, the following interburdens (Int) were identified:

- Int AB/SB: composed of massive and competent limestones, topped by a phosphate limestone/ phosphate flint with coprolites. Indurated marl at the base.
- Int SA/AB: composed of marly limestone with a sandy fraction. It is large and consistent.
- Int C0/SA: this interburden has a thickness that exceeds 8 m and is composed of limestone and whitish siliceous marl mottled with iron and manganese oxides. Phosphate sand at the base.
- Int C2/C1: composed of an alternation in grayish limestone, whitish siliceous marl, and compact beige marl with flint bands at the base.
- Int C3/C2: composed of yellow clay marl. At the top, there is calcified sandy marl.
- Int C4/C3: composed of siliceous marl and brown flint nodules.
- Int C5/C4: composed of an alternation in whitish siliceous marl with brown flint. Passage of phosphate marly sand in the middle.
- Int C6/C5: composed of an alternation in limestone and brown flint.

The phosphate rock series of the Benguerir mine is affected by silicification and dolomitization. Due to the circulation of groundwater rich in silica or magnesium in the existing veins and fractures, the silica is deposited, and depending on the degree of silicification, nodules of quartz or flint are formed. However, in the case of dolomitization, the magnesium ions replace the calcium ions present in the carbonate rocks; therefore, the limestone rocks are transformed into dolomites.

According to the litho-stratigraphic correlation presented in Figure 4, the study area constitutes a non-horizontal litho-stratigraphic series (folded series) with quasi-variable thicknesses. This deformation can be justified by the presence of faults to the north of the series and by being adjacent to the Paleozoic basement of Rehamna. The average thickness of each unit can be seen in Figure 3. The sequence of units appears to be relatively stable in space but with quasi-variable thicknesses and sometimes interrupted units (i.e., no thickness in some drill holes, the case of AB interburdens).

The total *RQD* of the study area was calculated by averaging the *RQD* values of each borehole (Figure 4). The effect of the difference in run lengths could be eliminated by weighting this average by the length of each run for each drill hole (geometric average). The total *RQD* was 23 %; therefore, according to Deere's classification in 1968, the rock mass quality of the studied area could be qualified as very poor (fractured rock mass).

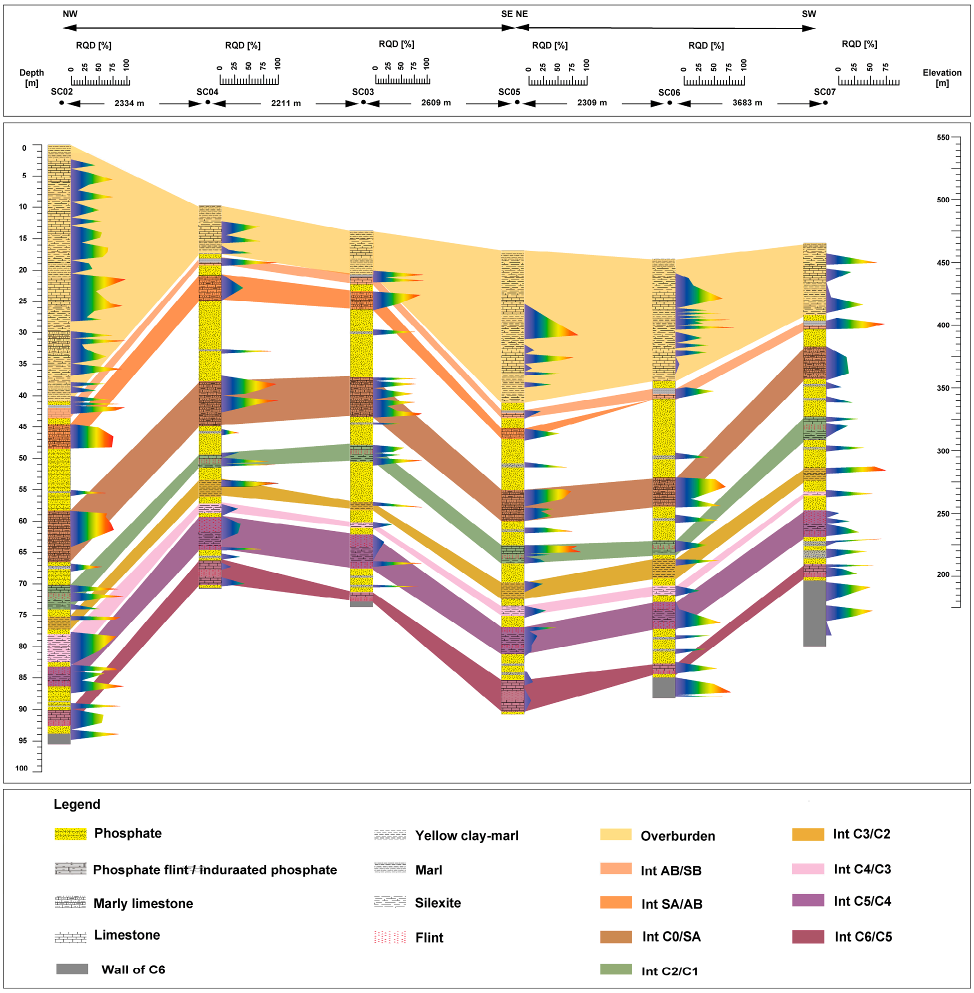

Figure 4. NW–SE and NE SW cross-sections and the variations in *RQD*s in the Benguerir mine.

3.2. Geomechanical Characterization

3.2.1. Soil-Like Samples

Table 1 presents the results of the physical and geomechanical characterizations of the soil-like samples. The studied soil-like samples, located in the C3/C2 interburdens, were characterized by a thickness exceeding 3 m, and the mustard yellow color was remarkable in the phosphate series. The C3/C2-level soils had relatively low natural water contents that varies between 4.5% and 7.5%, with an average of 5.9%. These variations in the natural water content could be related to the quantity of fine or clayey elements in the analyzed samples. The bulk density varied between 1824 and 1917 kg/m^3 with an average of 1886 kg/m^3. The sand equivalent test result shows the presence of a fine material. The results of the methylene blue values obtained vary between 6 and 10, which indicates the presence of clayey soil. Indeed, the soil-like samples were composed of particles sized d < 80 µm (or P80 µm) to at least 91%, except for sample (C) where P80 µm = 64%. Particles smaller than 2 µm (clay size) were present in more than 38%. The Atterberg limits showed that these soils were plastic to very plastic. Figure 5A shows the plasticity chart; most of the samples are located above the "A Line", which means that they are clays with high plasticity, except for sample 'Tr4', which is located below this line and corresponds either to inorganic silts of variable compressibility or to elastic silts or organic clays.

Table 1. Physical and geotechnical properties of soil-like samples.

		Samples C3/C2							Deviation
Variables	**Units**	**A**	**B**	**C**	**Tr1**	**Tr2**	**Tr3**	**Tr4**	
w	[%]	-	-	-	4.5	7.5	5.1	6.5	1
ρ	[kg/m^3]	-	-	-	1892	1917	1824	1912	31
P max	mm	0.1	10	25	0.3	1	0.3	0.1	7
P 80 µm	[%]	100	91	64	98	97	98	100	8.6
P 2 µm	[%]	74	70	52	38	41	38	45	12
MBV	-	9.2	10	6	6.13	6.22	6.07	6.32	1.4
SE	[%]	-	-	-	FS	FS	FS	FS	-
LL	[%]	106	109	95	75	83	65	60	16
PL	[%]	37	39	35	32	38	27	35	3
PI	[%]	69	70	60	43	45	38	25	14

w: water content; *ρ*: bulk density; *P*: particle size; *MBV*: methylene blue value; *SE*: sand equivalent; *LL*: liquid limit; *PL*: plastic limit; *IP*: plasticity index; *FS*: fine sand.

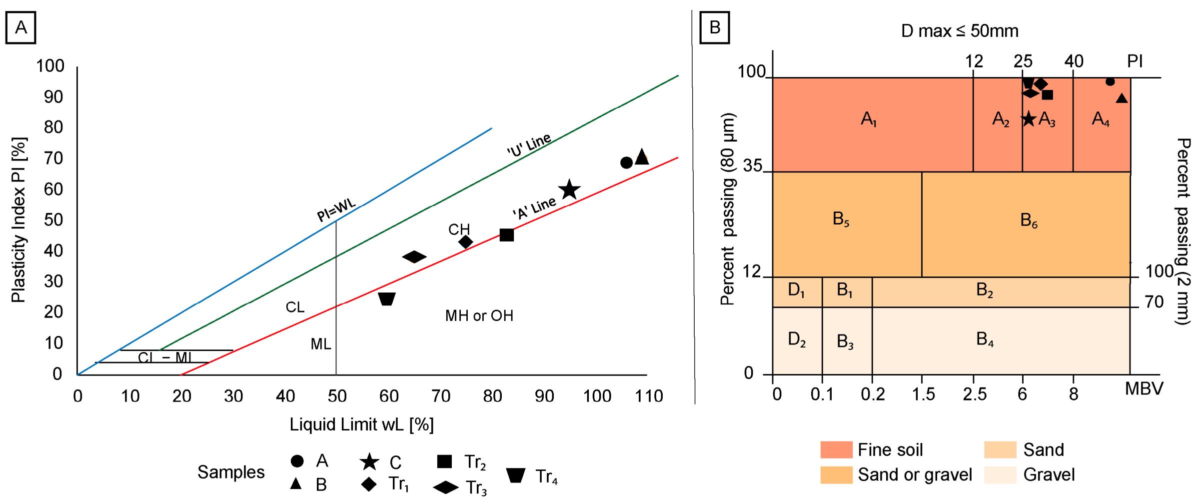

Figure 5. (**A**) Plasticity chart and (**B**) classification of studied soil-like samples based on soil classifications [55].

According to the results of the physical characterization and the road earthwork guide (*REG*) classification NF-P11-300 [55], the C3/C2 interburden soil can be classified in the A3–A4 category (fine soil); plastic to very plastic; and the category of clayey marl (Figure 5B). This soil was significantly cohesive with medium and low water contents, and was sticky or slippery when wet.

3.2.2. Hard Rock Samples

Figure 6 shows the variation in the *UCS* with the depth and rock unit for each borehole. The overall results show that the variation in the *UCS* does not depend on the depth, but rather on the facies encountered and on the quality of the terrain, i.e., the presence of micro-faults and faults that affect the geomechanical properties of the rock unit. Flint has the highest average *UCS* value of 104 MPa, followed by phosphate flint (35 MPa), silexite (32 MPa), limestone (26 MPa), indurated phosphate (11 MPa), and marly limestone (8 MPa) (Figure S1). Specific gravity, porosity, and absorption are shown in Figures S2 and S3. The specific gravity values vary in the range 1.4–2.5. Flint and phosphate flint have high specific gravity values and low porosity and absorption values. For the limestone, three categories can be distinguished: (i) porous limestone with more than 30% porosity, with a specific gravity in the 1.5–1.8 range; (ii) medium-porosity limestone (the most abundant type) with a porosity value between 10% and 30% and an average specific gravity value in the 1.7–2.3 range; and (iii) compact limestone with a porosity lower than 10% and a specific gravity value in the 2.3–2.5 range. Silexite has a medium specific gravity value (1.6) and low porosity and absorption values (<16%). Marly limestone and indurated phosphate present higher porosity and absorption values (44.5% and 31% for Marly limestone and 38% and 23% for indurated phosphate) and low specific gravity values (<2).

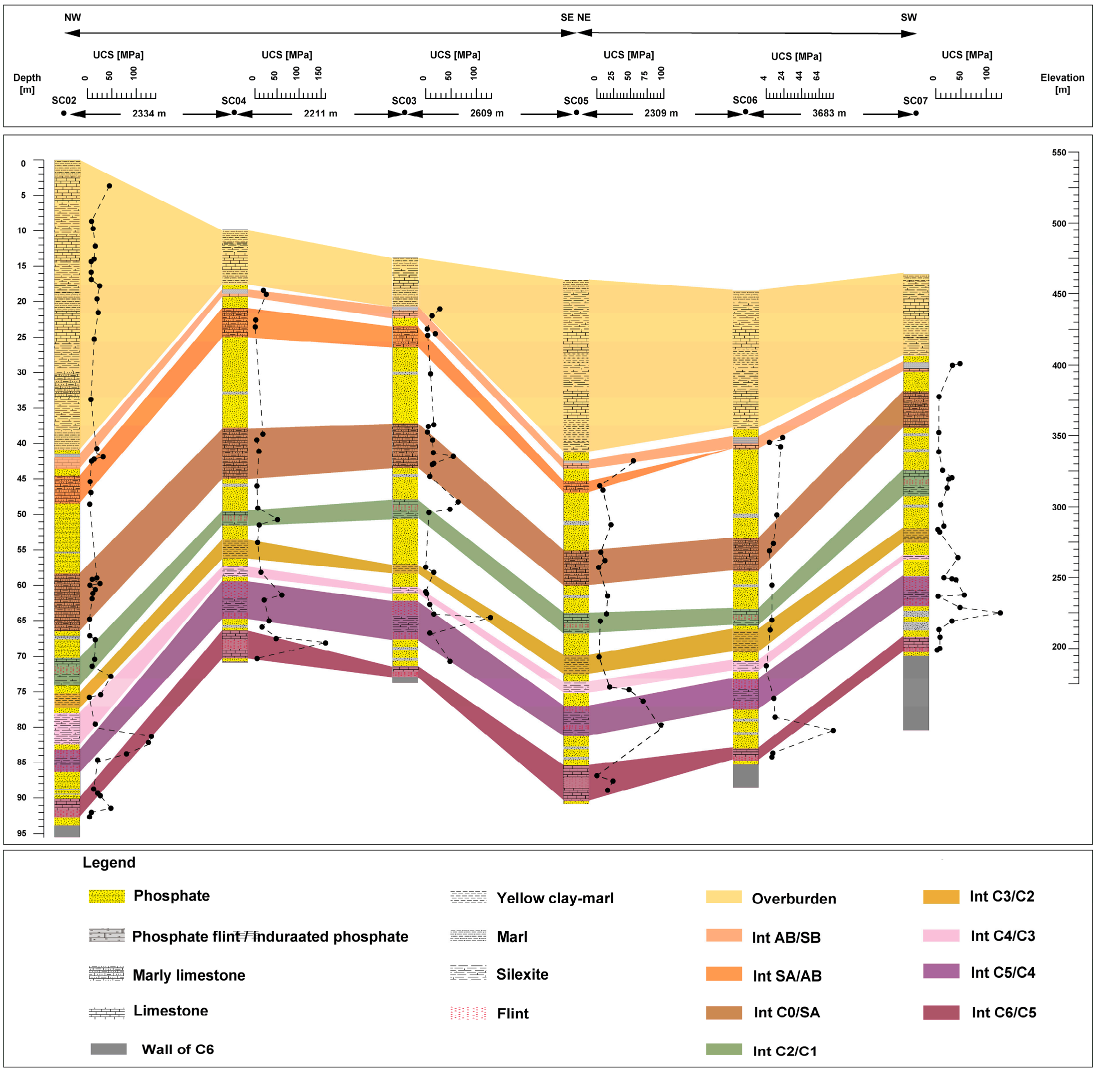

Figure 6. Variations in the UCS, with the depth and the rock unit for each borehole.

The results of the mechanical characterization tests are summarized in Table 2. The fragmentability and degradability indices are, respectively, lower than thresholds 7 and 5 of the earthwork's material classification NF-P11-300 standard [55], except for a few samples of indurated phosphate, phosphate flint, and limestone. The tested materials can be considered poorly to moderately fragmentable and degradable under hydric solicitations. For the Los Angeles test, the flint, phosphate flint, and a few samples of limestone and silexite have *LA* (%) values below the 50% threshold. These results mean that these samples have good fragmentation resistance and good hardness properties according to the ACI 211.1 and NF EN 12620 standards [56,57]. Thus, these waste rocks can be used as aggregate and support the various stresses associated with pavement foundation constructions [20,58]. The micro-Deval coefficient values show that flint and some phosphate flint samples have values lower than 35%; they are the most suitable for use as aggregates.

Table 2. Physical properties of the hard rock samples.

Tests	Los Angeles [%]	Micro-Deval [%]	Fragmentability	Degradability
Flint	22–39 (6)	9–48 (12)	1–2 (0.5)	1 (0)
Phosphate flint	29–33 (2)	28–40 (6)	2 (0)	1 (0)
Silexite	35–75 (13)	39–88 (15)	2–6 (1.5)	1–1.4 (0.2)
Limestone	24–77 (15)	37–98 (18)	1–6 (1.1)	1–12 (4.3)
Indurated phosphate	76–93 (4.5)	94–100 (2)	6–11 (2.3)	1–5 (2)
Marly limestone	86–99 (2)	96–100 (6)	6–9 (0)	1–5 (0)

Values in parenthesis refer to the deviations.

3.3. Implication Results/Discussion

The phosphate waste rock from the Benguerir mine presented a wide range of properties (lithological, mineralogical, and physical–mechanical), promoting their use in several applications. The geomechanical properties and potential ways of valorizing *PWR*s are summarized in Table 3. The results of the characterization of the hard rock samples show that the C5/C4 and Int C6/C5 interburden flints have good physical and mechanical properties in terms of *UCS* (up to 64 MPa), *LA* (lower than 40%), and *MD* (lower than 48%). The flint is a siliceous, cryptocrystalline, and extremely hard siliceous rock with an average *UCS* of about 600 MPa [59]. In a study performed by Safhi et al. (2022) [58], the flint from Benguerir mine revealed the presence of SiO_2 (93.6%), CaO (1.6%), P_2O_5 (1.9%), and 1.8% LOI, with a corresponding mineralogical composition of quartz (95%), calcite (1.8%), and apatite (1.2%). This flint can be used in the civil engineering sector. Flint lithology requires simple crushing to be used as an aggregate in the ballasts of railroads, embankments, layers forming road structures, or other advanced uses, such as an aggregate of high-performance concrete, etc. [20,58,60].

Table 3. The geomechanical properties and potential valorization methods.

			Lithology						
		Units	**Flint**	**Phosphate Flint**	**Silexite**	**Limestone**	**Indurated Phosphate**	**Marly Limestone**	**Clayey Marl**
Geomechanical proprieties	*UCS*	[MPa]	104	35	32	26	11	8	
	LA	[%]	33	31	50	62	88	95	
	MD	[%]	33	34	65	81	98	98	
	Fragmentability	-	2	2	3	4	9	7	
	Degradability	-	1	1	1	4	2	3	
	Specific gravity	-	2.5	2.2	1.6	1.9	1.9	1.7	
	porosity	[%]	3	19	12	25	28	33	
	Absorption	[%]	1	9	6	14	15	20	
	w	[%]							6
	ρ	[kg/m^3]							1886
	D max	mm							5
	<80 µm	[%]							93
	<2 µm	[%]							51
	MBV	-							7
	SE	[%]							Fine sand
	LL	[%]							85
	PL	[%]							35
Valorization methods	Aggregate		X	X	X	X			
	Lightweight aggregate				X				
	Concrete		X		X	X			
	Asphalt		X			X			
	Road construction		X	X		X			
	Embankment							X	X
	Brick manufacturing								X
	Cement				X	X		X	X
	Field ceramics								X
	Neutralization					X		X	
	Recovery of phosphate			X			X		

Silexite is generally located at Int C4/C3 and Int C5/C4. It is a siliceous marl with a purplish-pink color. The silexite mainly comprises 80% SiO_2, 4.5% of CaO, and 3.7% of MgO, with a corresponding mineralogical composition of quartz and dolomite [58,60]. Using silexite in civil engineering projects can provide a range of economic benefits. Its importance in civil engineering is due to its ability to provide an ideal material for construction purposes (aggregate), particularly in the form of crushed stone, sand, and gravel. This rock is also used in various forms as a lightweight aggregate due to its low density, which is used in the production of concrete and other building materials. Furthermore, due to its high strength and low cost, silexite can be used as an aggregate for construction projects, such as bridges, dams, and other structures. Additionally, silexite can be used as a natural filler in the production of concrete in order to reduce the cost of the material without compromising its strength and durability [58].

Phosphate flint and indurated phosphate are generally located at Int AB/SB, A3/A2, C5M/C5S, and C5I/C5M. These two facies (phosphate flint and indurated phosphate) are grouped in the phosphate waste category. In a previous study by Safhi et al. (2022) [58], the mineralogical characterization of phosphate flint revealed the presence of phosphate grains as apatite (38.3%) and quartz (47.5%), which were the major minerals that cemented the phosphate grains. Indurated phosphate constitutes the phosphate grain as fluorapatite (48%), bioclasts, and coprolites; these elements are cemented by micrite dominated by carbonates. The geomechanical characterization of phosphate flint presents good mechanical properties (*UCS* = 35 MPa, *LA* = 31%, and *MD* = 34%), which means that it can be valorized as an aggregate and for road construction due to its high resistance to weathering, and its ability to provide a durable and cost-effective pavement material. While indurated phosphate presents weak properties (*UCS* = 11 MPa, *LA* = 84%, and *MD* = 97%) and it is not recommended to use or valorize it in the field of civil engineering, on the other hand, approaches to exploit it have been introduce in the studies (i.e., screening, sorting, and further processing methods [58,61]).

The carbonate category (limestone and marly limestone) is the most abundant in the phosphate series, almost occurring in all the interburdens. This category presents a variation in mechanical properties ranging from low to high values. They can be valorized as raw materials in civil engineering [58,62], ceramic application, and the cement industry [63]. Additionally, they can be used to control acid mine drainage, due to their high carbonate content [12,61], and as a stabilizing agent for acidic tailings [14,64].

The soil-like samples analyzed in this study were located at the Int C3/C2 interburden. It corresponded to clayey marl with high plasticity. These samples were materials with good geotechnical behavior, which could be used as raw materials, especially in embankment brick manufacturing, cement, and field ceramics [58,63,65–67].

The valorization of phosphate waste rock is an important step in overcoming the challenge of waste management and reducing the environmental impacts of phosphate mining. It can produce valuable waste products, supporting green production and recycling in the phosphate industry. Moreover, it can create economic and environmental benefits for local communities by providing additional resources that can be sold for profits. Furthermore, the technologies used in the valorization of phosphate waste rock can be applied in other industries to create sustainable solutions. It is clear that the valorization of phosphate waste rock can effectively address the problem of phosphate waste disposal and should be considered when implementing clean and efficient solutions in the phosphate industry.

The integration of the mining circular economy in the mining industry relies on the creation of a sustainable model that satisfies a three-facet equilibrium: economic, environmental, and social [61,68] (Figure 7). The valorization of phosphate mining waste rock is a major concern regarding their environmental footprint and the development of the mine. The phosphate industry can ensure the valorization of waste rock to preserve the natural resources and reduce land-use impacts.

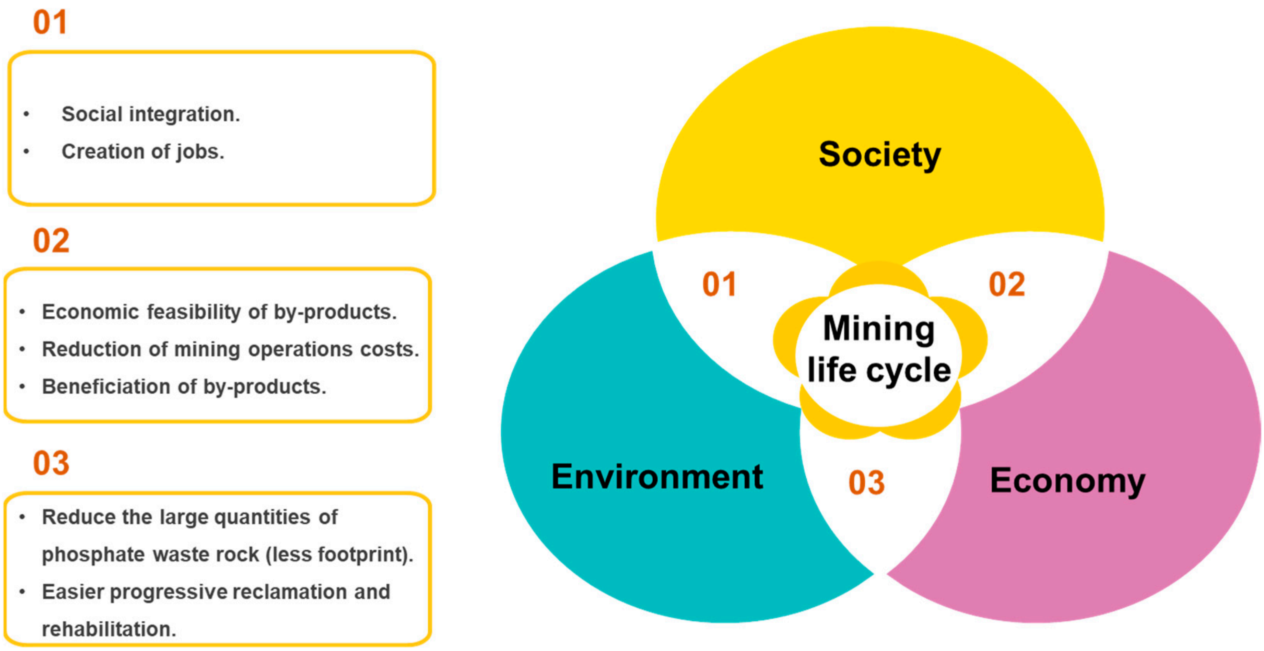

Figure 7. Sustainable mining practices.

4. Conclusions

The present study investigated the potential application of each phosphate waste rock lithology sample based on the geological and geomechanical properties. The experimental work on the soil-like and hard rock samples collected from the six drill cores and mining trenches at the Benguerir mine site in Morocco presented the following conclusions:

- The Benguerir phosphate series was composed, in addition to overburden, of nine phosphate and eight waste layers (interburdens). The existence of other levels called "phosphate slabs" with carbonate or siliceous matrix was present.
- Four types of waste rock were identified: carbonate (limestone and marly limestone), siliceous (flint), marl clay, and phosphate (phosphate flint and indurated phosphate).
- The unit sequences of the Benguerir deposit appeared to be relatively stable in space but with variable thicknesses and sometimes interrupted units.
- The soil-like samples were classified in the category A3–A4 (fine soil), plastic to very plastic, and the category of clayey marl. They could be used as raw materials, especially for brick manufacturing, cement, and field ceramics.
- The hard rock samples presented promising geomechanical properties and could be considered an excellent alternative secondary raw material for civil engineering, the cement industry, and phosphate recovery.

It is recommended to complete this study by other types of characterizations (chemical, mineralogical, and environmental) to evaluate all the properties.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/min13101291/s1, Figure S1: UCS intervals for the six facies.; Figure S2: variations in specific gravity values with porosity for the six facies; Figure S3: variations in porosity values with absorption for the five facies.

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