Geotechnical Characterization of Phosphate Mining Waste Materials for Use in Pavement Construction

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ABSTRACT

Waste rock materials are becoming widely used in road pavement and building constructions in many countries. In this work, experimental laboratory tests were carried out on the waste rock produced from the extraction of the phosphate in the Kef-Essenoun mine, to study the performance of road pavement foundations built with these types of material. Two types of waste, namely phosphatic limestone (type 1) and limestone (type 2), were initially tested to determine the most suitable one to be used in pavement structures. The characterization tests showed that the presence of carbonate-fluorapatite and carbonate-fluorapatite, and calcite, dolomite, and quartz are predominant in phosphatic limestone and limestone, respectively. The Los Angeles Abrasion (LA) and Micro-Deval (MD) values range from 59.9% to 90.4% and 42.05% to 86.31% for phosphatic limestone and from 43.64% to 95.88% and 38.25% to 75% for limestone. The CBR values of type 1 and type 2 waste were found to be 10.5% and 18.7% respectively. The results show that these materials, classified as $B_{42}t_s$ and B_{42s} respectively, could be used cautiously in capping layers and pavement backfilling materials. Furthermore, they must be treated with a hydraulic binder such as cement in order to improve their physical and mechanical properties.

Keywords-characterization; mine waste; phosphatic limestone; limestone; road construction; Kef-Essenoun

I. INTRODUCTION

Road infrastructure projects require large quantities of materials. The growing demand for aggregates in the civil construction sector has become more pronounced in recent years as cities grow more and more. The use of unusual industrial mining products in road construction can contribute to the conservation of non-renewable natural resources and minimize the waste quantities produced by mining industries [1]. Such large amounts of waste, resulting from mining operations, have led to the awareness regarding their impact on environment, ecology, and geotechnical side. The release of toxic components from heavy metals and acid mine drainage are examples of such effects. Underground water contamination, large amounts of space of exploitable natural land, instability of the waste storage zone, and dust cloud generation are some examples of such effects. There are numerous economic and ecological gains in the exploitation of alternative materials for the road construction sector. When waste materials with adequate properties are used, it is possible to reduce energy consumption, transport distances, and extraction costs [2]. For several decades the reuse of waste materials as construction materials has been studied in depth, e.g. mine tailings [1-3], recycled construction and demolition wastes used in road construction, embankments and concrete [4-7], coal mining waste [8-9], plastic and rubber waste in flexible and rigid pavements, ferrocement mortar [10-12], steel slag and glass as secondary aggregates in asphalt mixtures [13-15], tungsten mining waste [16], marine sediments [17], bottom ash and fly ash in geotechnical engineering [18], iron and gold mining waste [19], and red mud and lime [20]. In addition, pozzolanic materials such as cement, lime, fly ash, cement kiln dust, and ordinary Portland cement have been used to stabilize some tailings materials for construction purposes [21-23].

Algeria has a large reserve of phosphate [24]. About 41ha of land are currently under exploitation in Kef-Essenoun. The current removal mining rate is 2.8 million tons of ore with a stripping ratio of approximately 2.2 which produces annually 10 million tons of waste that must be removed and disposed of. The accumulation for several decades of waste rock from open-pit phosphate mines and upgrading processes poses serious environmental, ecological, and health problems in the surrounding areas [25]. These types of waste are unsafe to humans, animals, and vegetation. They pollute the air, the surrounding soil, and contaminate the groundwater.

The main objective of this research consists in suggesting a reusing solution in order to reduce the negative impact of rock waste on the environment. Reusing consists of finding a new use for available waste materials with adequate acceptable properties in their current form in order to ovoid disposal on landfills. As reported in [26-31], those materials (phosphate tailings) could be widely used in building and road construction. The proposed reusing approach should be integrated in the Algerian road guide. It is worth noting that studies on phosphate mining waste in Algeria are rare, thus, chemical, mineralogical, physical, and geotechnical characterizations of mining waste from Kef-Essenoun phosphate mine were investigated in this study.

II. GENERAL SETTING

The Kef-Essenoun phosphate mine (34.726784 E, 7.895978 N) is located on the southern flank of Djebel Onk cretaceous anticline in the Eastern Saharan Atlas [32]. It is situated 7km southeast of Bir El Ater City (Tebessa, northeast Algeria) and about 21km to the Algerian-Tunisian border [33]. The study site extends approximately to 250ha and belongs to the Djebel Onk mining basin which represents the occidental part of Gafsa-Metaloui-Onk basin containing many phosphorite layers deposited from late Cretaceous to early Eocene [32-34]. Although this lateral continuity, the Kef- Essenoun deposit displays substantial differences to the Gafsa Metlaoui basin, especially with regard to the lithology and the succession particularly in the phosphorite formation [35-36]. In the Kef-Essenoun deposit, the sedimentary lithologies consist of ~ 500m thick succession of upper Cretaceous (Maastrichtian) to middle Eocene (Lutetian) age where upper thanetian phosphorite layer is mined for phosphate raw material [32-37].

Mine waste rock from Kef-Essenoun mine (Figure 1) consists of soil and rock excavated during the mining operations after the commercially recoverable part has been recovered. These waste rocks are unloaded and accumulated in huge quantities. Between 2006 and 2017, the estimated quantity of waste rock produced is approximately 5.5 to 18.5Mt/yr. This quantity will increase to more than 18Mt/yr in the future (Figure 2).

Fig. 1. Phosphate mine waste hips nearby the mining site.

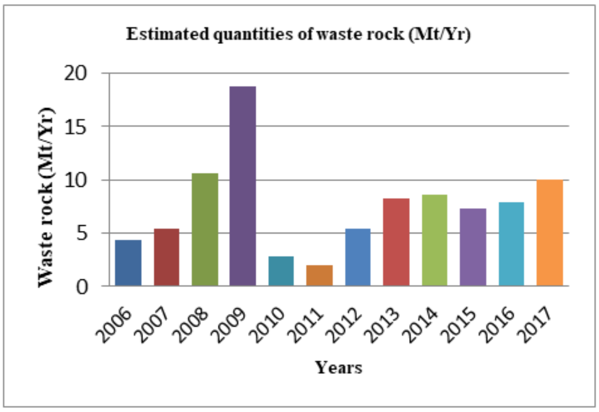

Fig. 2. Estimated quantities of waste rock from Kef-Essenoun [38].

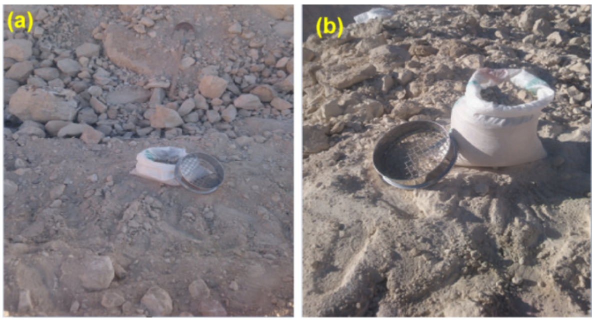

Fig. 3. Tailings of Kef Essenoun mine: (a) phosphatic limestone, (b) limestone.

Those amounts of waste can be utilized in the field of pavement construction. The reuse of mine tailings for subgrade and foundation layers is a relatively new approach in Algeria. The lack of fundamental knowledge about their behavior limits their reuse. Therefore, and in order to examine the various aspects concerning the possibility of using this mining waste in road engineering, complete characterization is necessary. The objective of this experimental study is to make a geotechnical characterization of the two recycled mining materials of Kef-Essenoun. In this research, the studied materials are phosphatic limestone (type 1) and limestone (type 2) (Figure 3).

III. EXPERIMENTAL PROGRAM AND TEST PROCEDURES

A. Initial Testing and Study Material Selection

The mining waste samples used in this research were collected from different locations of stacked tailings located in the surroundings of the Kef-Essenoun mine. The waste consists mainly of phosphatic limestone and limestone. These materials were brined to the laboratory in order to describe their mineralogical, chemical, physical, and mechanical properties.

B. Chemical and Mineralogical Characteristics

The analysis of the major elements was conducted by the Algerian phosphate company SOMIPHOS using colorimetric, gravimetric, volumetric, ionometric, and spectrophotometric by Atomic Absorption Spectrometry (AAS) analytical methods. The phosphate ore tailings of crystalline phases were performed by X-Ray Diffraction, (XRD). Diffraction patterns were made with a PANalytical X'Pert Pro diffractometer equipped with a conventional X-ray (Cu Kα radiation, running at 40kV and 30mA) with detection in the 2θ range of 10-90°.

C. Physical and Mechanical Parameters of Waste Materials

The main physical and mechanical characteristics of the studied waste samples are shown in Table I. Using oven drying at 105°C (+/- 5°C), the measured initial water content was about 4.62% and 8.54% for phosphatic limestone and limestone, respectively (NF P94-050). The following parameters were measured:

- Specific gravity was measured with a NF P94-054 Pycnometer.
- Clay fraction activity was measured by methylene blue test (NF P 94-068).
- Liquid and plastic limits (NF P94-051).
- Particle size distribution was measured according to NF P 94-056.
- Modified proctor (NF-P 94-093).
- California bearing capacity (NF-P94-078).
- Los Angeles, micro-deval, and friability (P 18-573, P 18-572, P18-576).
- Unconfined compressive strength procedure NF P98-230-3.

The test particle size consists of a representative sample of soil passing through superposed sieves with openings from 50mm to 0.08mm. Figure 4 shows the particle size distribution curves of the samples. The samples were classified according to the modified LPC classification system. According to the particle size curve, the percentages of cobbles, gravel, sand, silt, and clay in phosphatic limestone and limestone were 51%, 29%, 17.28%, and 2.72%, and 27.5%,29%, 40.23%, and 3.27%, respectively. The coefficients of uniformity (Cu) and curvature (Cc) obtained for phosphatic limestone and limestone were 69.44, 17.85, and 0.36, 4.11, respectively. Based on the unified soil classification system, both sample types were classified as well-graded gravel (Gm). The particle size distribution and gradation characteristics of the tested samples are shown in Table I.

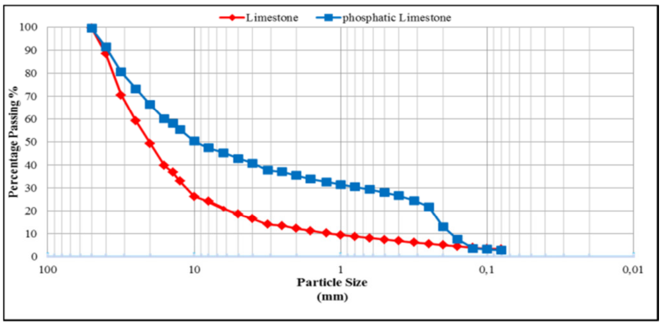

Fig. 4. Particle size distribution curves of phosphatic limestone and limestone waste.

D. Soil Classification

Based on the technical guidelines of embankment and capping layer construction (GTR), the tailing materials belong to the B Class of sand and gravel soils with fines. Depending on the nature of these materials, their class is B4. They have a passing percentage less than 12% and less than 70% from the of 80μm and 2mm sieves, respectively. There is no grain-size over 50mm. The methyl blue absorption value is more than 0.2. MD coefficient and LA coefficient are greater than 45. These types of materials are sensitive to water due to the existence of plastic fines and contain a large proportion of coarse particles, so they are generally pervious. The waste materials are classified as: B42ts (very dry) for type 1 and B42s (dry) for type 2 as can be shown in Figure 5.

TABLE I. PHYSICO-MECHNICAL PARAMETERS OF WASTE MATERIALS

Properties of mine railing	**Unit**	**Type1**	**Type2**
Moisture content	%	4.62	8.54
PH		6.8	7.8
Geotechnical properties—Natural parameters			
Grain - size distribution			
Color		Grayish	Beige
Shape		Angular	Angular
Particle size distribution			
Silt and clay	%	2.78	3.27
Sand		17.28	40.23
Gravel		29.00	29.00
Cobbles		51.00	27.50
Coefficient of uniformity (CU = D60/D10)		69.44	17.85
Coefficient of gradation		0.36	4.11
Cc = (D30)2/(D10 × D60) Group symbol LPC		Gm	Gm
Optimum Moisture content (Wopt)		12.30	14.15
Maximum dry density d_{max}	kN/m^3	1.85	2.00
Unsoaked CBR	%	24.724	36.675
Soaked CBR		10.548	18.293
Free swelling		0.303	0.308
Liquid limit (LL)		30.88	33.41
Plastic limit (PL)		Not measured	23.805
Plasticity index (PI)		-	9.6
Methylene blue value (MBV)	g/100g	0.83	1
Carbonate content	%	54	88
Organic matter		< 1	< 1
Sand Equivalent (SE)		22.22	12.82
Specific gravity	kN/m^3	2.737	2.631
Apparent specific gravity		1.434	1.328
Los Angeles abrasion test			
4/6.3 6.3/10 10/14	%	82.9 75.5 72.2	95.88 59.36 43.64
10/25 16/31 25/50	%	68.8 59.9 90.4	43.74 88.3 84.4
Micro Deval and deval test			
4/6.3 6.3/10 10/14	%	82.6 86.31 81.96	64 73 75
25/50		42.05	38.25
Sand friability coefficient		32	31
Material classification		B_{42} ts	B_{42} s
Unconfined Compressive Strength (UCS) after:			
24 hours	kN/m^2	182	520
14 days		683	2671
28 days		715	2807

Note: D10, D30 and D60 represent the percentage of soil particles that are smaller than 10, 30, and 60%, respectively

TABLE II. CHEMICAL COMPOSITION OF THE PHOSPHATIC LIMESTONE (TYPE 1) AND LIMESTONE (TYPE 2) WASTE

Major elements (wt %)															**Trace elements (ppm)**		
P_2O_5		**SO_3**	**CO_2**	**CaO**	**Al_2O_3**	**MgO**	**Fe_2O_3**	**SiO_2**	**Na_2O**	**K_2O**	**LOI**	**F**	**H_2O**	**COrg**	**Pb**	**Zn**	**Cu**
Type1	0.40	0.72	0.02	37.84	0.70	4.66	0.35	10.40	0.42	0.04	18.80	2.05	1.54	0.22	30	60	2.50
Type2	0.89	0.03	39.06	49.77	0.25	5.24	0.26	2.30	0.09	0.01	40.70	0.40	0.72	0.02	30	32.5	3.00

IV. RESULTS AND DISCUSSION

A. Chemical and Mineralogical

1) X-Ray Diffraction (XRD)

The XRD pattern of the two samples is illustrated in Figure 6. It shows the presence of the apatite mineral class with variable substitution rates of CO_3^{-2}, F^- and OH^-, including carbonate-fluorapatite [$Ca_{10}(PO_4)_5CO_3F_{1.5}(OH)_{0.5}$], fluorapatite [$Ca_5(PO_4)_3F$], carbonate-apatite [$Ca_{10}(PO_4)_6$], carbonate-hydroxyapatite [$Ca_{10}(PO_4)_3(CO_3)_3(OH)_2$], hydroxyapatite [$Ca_5(PO_4)_3(OH)$], and hydrated phosphate, but the gangue elements are basically represented by calcite [$CaCO_3$], quartz [SiO_2], dolomite [$CaMg(CO_3)_2$], and gypsum [CaSO4] [39-40]. Carbonate-fluorapatite is the dominant phase indexed in a hexagonal symmetry (SG: P63/m) according to the ASTM XRD data reference 98-003-4653 [41]. However, limestone is richer than phosphatic limestone in calcite, quartz, and dolomite.

2) Chemical Analysis

The chemical analysis results of the two phosphate waste types is presented in Table II. The results show a high percentage of major elements CaO, SiO_2, and MgO for Type 1 and CaO, MgO, and SiO_2 for Type 2. However, Type 1 has higher concentrations of P_2O_5. The chemical composition confirms that the mineral composition of phosphatic limestone and limestone contains four main minerals: carbonate-fluorapatite, calcite, dolomite, and quartz. The results are in agreement with the findings of [25, 34-43].

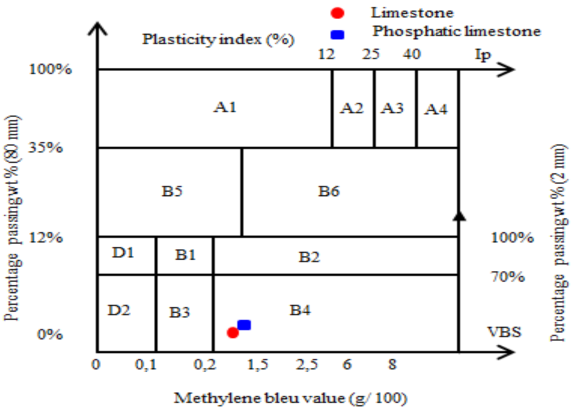

Fig. 5. Classification of studied waste samples: A: fine soil, B: sandy and gravely soil with fine particles, and D: soil insensitive to water.

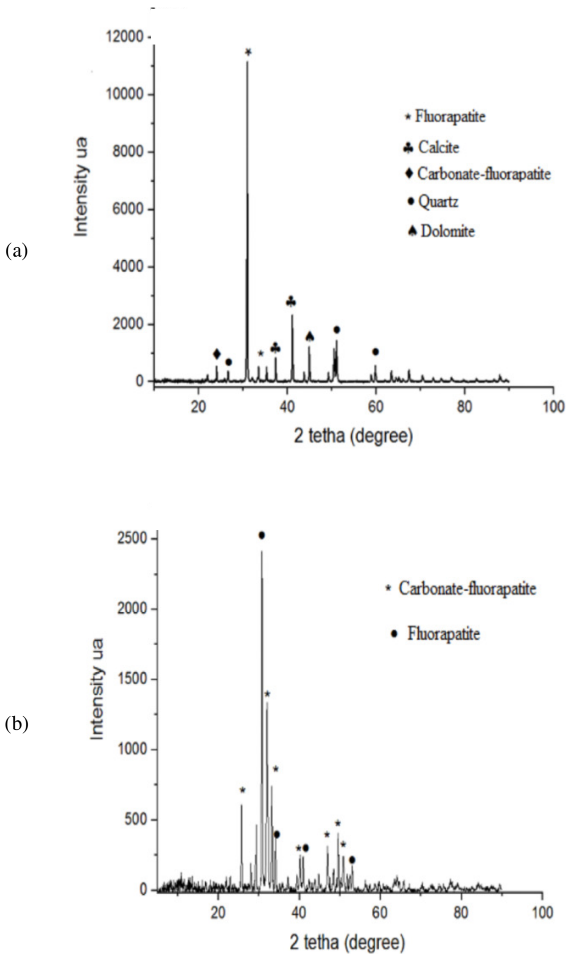

Fig. 6. XRD analysis of Kef-Essenoun mine waste: (a) phosphatic limestone, (b) limestone.

B. Basic Characteristics

The waste materials used in this study were grayish and beige in color for type 1 and type 2 respectively, with dry moisture content due to the arid climate of the region. The pH values of the tailings are 6.8 and 7.8, indicating basic pH. The specific gravity of limestone is lower than that of phosphatic limestone due to the presence of P_2O_5 in the latter. The phosphatic limestone sample is non-plastic, and thus, the measurement of the plastic limit and index was avoided. However, the limestone sample has a Plasticity Index (PI) of 9.6% which was validated by the methylene blue test.

C. Mechanical Behavior of the Materials

1) Compaction Characteristics

The results of compaction tests of the waste materials, in terms of dry density and measured water contents, are given in Figure 7.

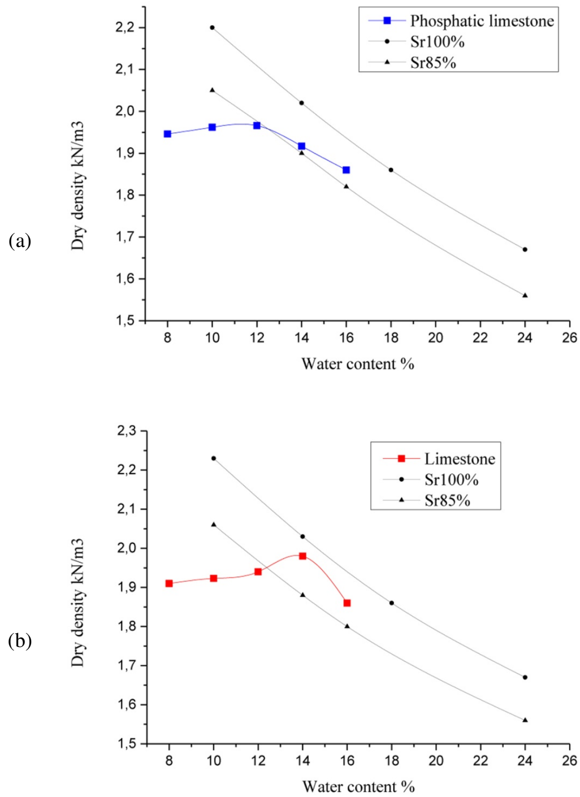

Fig. 7. Corresponding modified proctor compaction curves for mine wastes of (a) phosphatic limestone, (b) limestone.

The 85% and 100% saturation curves are also shown. The results indicate that the limestone waste provides the highest MDD of 2.00g/cm^{3}and OMC of 14.15%. Generally, the compaction characteristics depend on both the grain size distribution and the specific gravity of the materials. In this case, the presence of cenospheres (hollow particles of large size) is the main cause for the lower density of the phosphatic limestone samples.

2) California Bearing Ratio (CBR)

Figure 8 shows the values of both unsoaked CBR and soaked CBR after 4 days of curing in water related to the MDD. It can be observed that the CBR values of the two types of samples increase as the MDD increases. It is also noticed that the phosphatic limestone waste gives a value of soaked CBR of 10.5%, indicating medium bearing capacity material, while the obtained value of soaked CBR of 18.7% of limestone indicates that it can be used as an appropriate material for the foundation layers of pavements. The FSI of samples obtained for type 1 and type 2 samples are 0.303% and 0.308%, respectively. These results show that these waste materials are not expansive (IS 2720 (Part XL)).

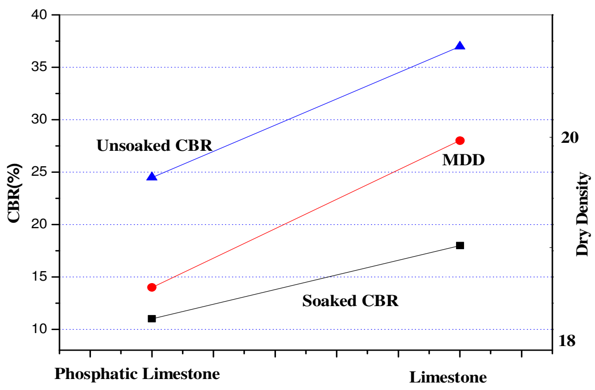

Fig. 8. CBR values related to MDD.

3) Los Angeles and Micro-Deval

The variation of LA and MD values is shown in Table I. The LA values range from 59.9% to 90.4% for phosphatic limestone and from 43.64% to 95.88% for limestone for all the considered granular classes. The results indicate that limestone waste gives more suitable values, but these waste materials are unsuitable for pavement constructions. The values of LA and MD tests of materials have to be less than 45%. Sand Friability (FS) coefficient is an indicator to assess the resistance of untreated sandy materials used for pavement subgrade to traffic loading. The FS values of the samples are 32% and 31% for type 1 and 2 materials, respectively. The recommended limit for this use is FS ≤ 60.

4) Unconfined Compressive Strength (UCS)

The UCS of the mining waste samples was tested after 1, 14, and 28 days of curing as shown in Figure 9. It is well known that the materials gain in strength overtime and the magnitude of compressive strength increased with increasing MDD of the compacted granular material. It was also shown that the compressive strength of limestone at 28 days is 3.9 times larger than that of the phosphatic limestone. On the other hand, the mechanical characteristics do not deteriorate with time. The limestone closes the interior ports by cementing the grains (lime reacts strongly with water and compaction energy), favored by the plasticity of the compacted material. In this case, limestone and rock behave similarly and the compressive resistance increases over time. Furthermore, the phosphatic limestone does not cement during compaction due to the absence of plasticity and the presence of a large content of friable phosphate, which explains its lower mechanical resistance.

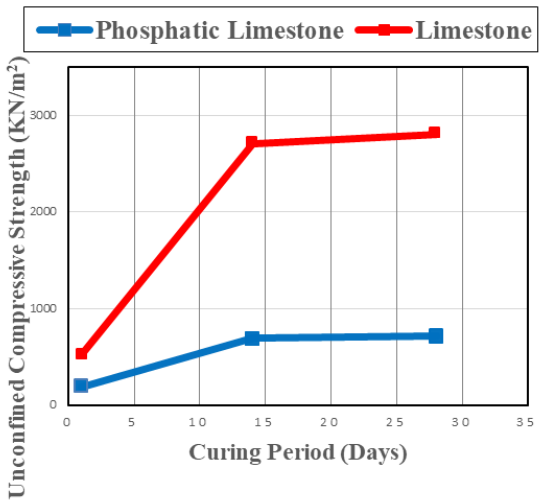

Fig. 9. UCS of samples cured for 1, 14, and 28 days.

V. POSSIBILITY OF USING WASTE MATERIALS IN ROAD CONSTRUCTION

For the road material field the general rating of the mining wastes as sub-grade materials ranges from fair to poor. The phosphatic limestone waste is considered a water-sensitive material, found in a very dry hydrous state (ts) and is not normally reusable in the embankment construction or capping layer, but in certain cases, its humidification can be considered to bring it to the s (dry) or m (normal) state. The use of limestone waste material could be allowed in road construction with treatment by hydraulic binders. This treatment requires prior measurement of their mechanical strength. For compaction procedure, the very dry soil is considered as being impossible to compact properly by standard methods. In both dry (s) and very dry (ts) states, those soils are not easy to compact to form stable fill structures.

The catalog of the National Agency for Technical Control of Public Works Algerian for new pavement design [44], requires the use of well-graded (GW) materials with PI less than 10% and LA less than 40% in the base layer. The findings indicate that waste rock materials, which are categorized as B42ts and B42s, respectively, should be used with caution as backfill and capping materials for road paving. They need to be treated with a hydraulic binder, such as cement, to increase their mechanical and physical qualities, raising their classes as a result. Increasing the mechanical properties of the tailing materials to be used as pavement sub-base materials will be cost effective and ecologically friendly since it will result in thinner sub-base layers and will maybe reduce the thickness of the pavement layer. In this case, stabilization is the best choice. As the mine is expanded, the waste piles created by its exploitation will ultimately result in great environmental and ecological issues. From the economic and environmental perspectives, the reuses of such waste are beneficial.

VI. CONCLUSIONS

The management of tailings and waste from mines and quarries is an essential requirement to limit their environmental, ecological, and geotechnical impacts. In the current research work, a characterization of two tailings from the Kef-Essenoun mine (phosphatic limestone and limestone) was investigated in order to allow reusing these materials in pavement foundations. The main findings of this investigation can be summarized as follows:

- The waste materials contain mainly CaO, SiO_2, and MgO. The phosphatic limestone has a much higher concentration of P_2O_5 (22.66 wt%) than limestone (0.89 wt%). In terms of trace elements, very low concentrations of Pb, Zn, and Cu were detected. The mineralogical composition of the two phosphate wastes contains four main minerals: carbonate-fluorapatite, calcite, dolomite, and quartz.
- The materials are well-graded gravel containing all grain sizes from cobbles down to clay. The particles were of angular shape with very low plasticity index. They have no grains larger than 50mm, a passing proportion from of 80μm sieve less than 12%, and less than 70% for the 2mm sieve.
- The Los Angeles and Micro-Deval coefficients of the studied materials exceeded 45%, and they are classified as B42ts (phosphatic limestone) and B42s (limestone).
- From the points of mechanical behavior and applicability in road construction, the values of CBR and UCS, increase with MDD and the UCS increases with curing age.
- The mechanical performance of limestone waste is more appropriate than phosphatic limestone's, and is governed essentially by the phosphate content (P_2O_5 wt%). The mechanical proprieties are improved with higher phosphate content. The phosphatic limestone presents low plasticity and a larger proportion of friable phosphate which lead to less material compaction.
- In terms of environmental impact, the efficient reuse of mining waste in the road sector field helps reduce the production of waste, thereby minimizing the environmental damage and ensuring sustainable construction. Both waste materials considered in this study could be used in pavement structure construction provided that they are treated with hydraulic binders.

Based on this study, the presented methodology could constitute a starting point for the investigation of the reuse of the mining waste of Kef-Essenoun mine in the field of road construction.

VII. DECLARATIONS

A. Author Contributions

Rachida Malaoui conducted all the physical and geotechnical characterization tests, investigation, formal analysis, and the writing of the original draft. Abderraouf Soukeur interpreted the chemical and mineralogical characterizations. The geological part was conducted by Rabah Kechiched. The interpretation of the results and the writing of the paper were done by Rachida Malaoui, Adel Djellali, and Abderraouf Soukeur. El Haddi Harkati and Mohamed Redha Soltani were responsible for conceptualization, supervision, writing, reviewing, editing, and funding acquisition.

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LIST OF ABBREVIATIONS

CBR	California Bearing Ratio
Corg	Organic carbon content
FSI	Free Swelling Index
LA	Los Angeles abrasion value
LOI	Loss on Ignition
MBV	Methylene Blue Value
MDD	Maximum Dry Density
MD	Micro Deval value
Mt/yr	Million tons per year
OMC	Optimum Moisture Content
PI	Plasticity Index
UCS	Unconfined Compressive Strength
XRD	X-Ray Diffraction

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