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TECHNICAL NOTE

Effects of Ceramic Waste, Marble Dust, and Cement in Pavement Sub-base Layer

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Abstract In this work, the effects of ceramic waste (CW), marble dust (MD), and cement on the performance of road sub-base layer characteristics were investigated. Industries routinely produce CW and MD, and the disposal of these types of waste is a major environmental problem in Algeria and worldwide. Thus, the recycling of these waste materials requires the development of long-term solutions. The goal of the current work is to estimate the effects of CW, MD, and ordinary Portland cement (OPC) on the soil of the sub-base layer improving its engineering properties, such as dry density and bearing capacity as measured by the California Bearing Ration (CBR). We planned different admixtures of soil containing 5, 10, and 15% CW, and 2, 3, 4, and 5% MD, and 1.5, and 2% OPC by dry weight. The attainment of sub-base materials was investigated with soil–CW only, soil–MD only, soil–OPC only and soil–CW–OPC. The results showed that the CBR values of sub-base materials increase with the addition of recycled wastes and OPC. The CBR values of mixtures with OPC only and OPC with CW were greater than that of CW and MD only. This work offers the possibility of improving the sub-base layer by the addition of CW, MD, and OPC to obtain greater economic and environmental sustainability through better resource utilization.

Keywords Sub-base layer · Ceramic waste · Marble dust · Cement–ceramic waste · Road construction

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1 Introduction

The Algerian government built around 4.5 million houses in the last two decades, which used a million tons of ceramic and marble per annum. Approximately 15–30% of the total quantities produced by ceramic industries were waste materials (Vagadia and Batti 2016), which, equate approximately 75,000–100,000 tonnes of waste per annum. Moreover, approximately 20% waste was generated during the overall production of marble (Satish et al. 2002). Currently, the CW is not recycled, and the existing method of disposal is by regular landfill (Pacheco-Torgal and Jalali 2010).

Using recycled wastes as alternative product materials is the main solution to the disposal of these wastes. Such a solution would save disposal costs and minimize environmental problems (Ahmed and Abouzeid 2009). Several research studies have

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reported that using CW as aggregate in concrete is cost effective and found a significant improvement characteristic (Amitkumar et al. 2013; Cabalar et al. 2016; Pacheco-Torgal and Jalali 2010; Medina et al. 2012; Topçu and Canbaz 2007). However, others have used CW as a fine aggregate in concrete, flexible pavement, rigid pavement and, hot mix asphalt (Vagadia and Batti 2016; Electricwala et al. 2013; Kofteci and Kokal 2014; Lopez et al. 2007; Pacheco-Torgal and Jalali 2010). Cabalar et al. (2016) tested replacing 0, 5, 10, 15, 20, and 30% fractions of the aggregate with CW, and they determined the dry densities and CBR values of road pavement sub-grade. They discovered that increasing CW increased the CBR and dry density values. Electricwala et al. (2013) studied the addition of ceramic dust in the rigid pavement, in which 10, 20, and 30% of the aggregate were replaced by ceramic dust. Their results showed that replacement by ceramic dust was not significant in terms of flexural strength nor decreased the strength of the mixtures. Chen and Idusuyi (2015) carried out experiments on the CBR, unconfined compressive strength (UCS), and free swell of 0–30% fractions of CW in increments of 5% to stabilize the sub-grade of flexible pavement. They concluded that the CBR and UCS increased while the free swell decreased with increasing CW. They also reported that the maximum dry density (MDD) increased and optimum moisture content (OMC) decreased. Satish et al. (2002) reported that the addition of MD in road construction provides higher compressive strength to bituminous concrete. The use of MD in road construction on poor soils reduced costs and contributes to resource conservation (Altuğ 2015).

The poor state of most roads and highways in Algeria reflects the poor characteristics of the underlying soils, which constitute the base or sub-grade material for the entire road structure. Some common soils in Algeria and around the world are mostly distinguished by their poor quality, weak shear strength, elevated compressibility, and low bearing capacity (Opeyemi et al. 2018). The requirement to ameliorate soil parameters for road and highway constructions can be achieved by using different stabilizers (Amu et al. 2011). On the other hand, the soil condition is an important factor in road and highway construction design. Currently, the advantageous use of additives to ameliorate soil, particularly for the sub-base layer, has increased in many countries and this tendency is predicted to increase in the coming years (Sazzad et al. 2010). Soils can become compressible or swell on contact with water, and this behavior of soils, can cause damage to various road projects constructed on these soils (Sabat 2012).

The stabilization of soils for use in road and highway constructions with fine additives, develop, the engineering properties of the soils. This stabilization positively modifies the characteristics of many types of soils intended for use in road embankments by reducing compressibility and increasing bearing capacity (Ojuri and Oluwatuyi 2014).

Today, the increasing demand for construction materials as road pavement sub-base and the associated adverse impact on the environment necessitates the search for substitute materials from industries, including waste materials. Because the common sub-base materials are normally problematic in Algeria, they result in damage within a short time after construction and become more expensive to reconstruct each time. The reuse of CW and MD to stabilize sub-base road construction has the potential to render these waste practical substitute materials for road pavement sub-base. Therefore, the current work aims to assess the performance of CW, MD, and OPC added to soils intended for use as sub-base material. We examined the possibility of using CW, MD, and a small amount of OPC mixed with soil in road projects as a way of reusing CW and MD, and for reducing the rates of waste disposal by landfill. The specific goal of this work was to determine the best combination of CW, MD, and OPC mixed with soil to achieve the highest CBR and MDD of mixtures for use as sub-base material.

2 Materials and Methods

2.1 Materials

2.1.1 Soil

The soil investigated in this research was sampled from a new road construction site at Tixtar, Bordj Bou Arreridj, in the eastern province of Algeria. The initial investigation of the soil was conducted via experimental tests, such as the analysis of granulometry, CBR, and compaction to describe the soils. The particle size distribution of the natural soil is presented in Fig. 1. Table 1 presents the principal properties of the natural soil. The results show that the liquid limit (L.L) and plastic limit (P.L) are 30.37 and 24.05%, respectively. Furthermore, the plasticity index was 6.32%. The data in Table 1 also show that the MDD of the natural soil reaches 19.4 kN/m^3, which appears suitable for the sub-base layer; however, this type of soil becomes very soft when in contact with water.

2.1.2 Ceramic Waste (CW)

Depending on the procedures employed during production and transportation, a significant fraction of the ceramic products experience breakage and generates CW. Furthermore, the renovation of old buildings creates thousands of tonnes of CW each year. The CW can be used in the sub-base material to improve its strength and in this research, it was used as a coarse aggregate. Figure 1 presents the grain size distribution of CW.

2.1.3 Marble Dust (MD)

The growth in the construction of public and private buildings in Algeria, which use marble as a construction material for flooring and façade decoration, creates considerable quantities of MD every year.

2.1.4 Ordinary Portland Cement (OPC)

In this research, the OPC used was Matine Type II (42.5 MPa) from Lafarge. Through a process of densification, the OPC binds between natural soils particles. The interaction of the OPC with water converts the material to a hard, dense mass, the strength of which increases with time. The physical and chemical properties of OPC are presented in Table 2.

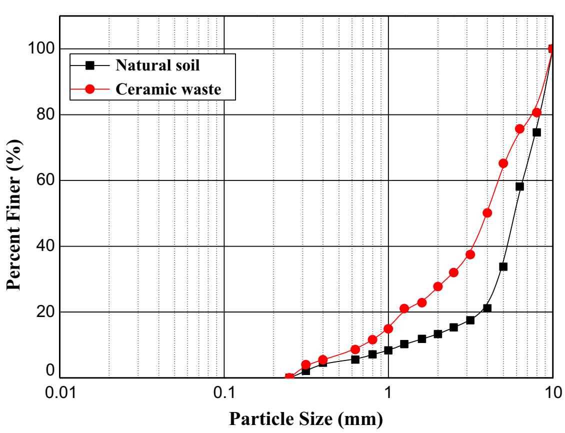

Fig. 1 Particle size distribution of soil and CW

Table 1 Basic properties of natural soils

Properties	Values
L.L (%)	30.37
P.L (%)	24.05
Ip (%)	6.32
γ_d (Kg/m^3)	19.4
Cu (%)	13.07
Cc (%)	1.44
e_o	0.095

2.2 Methods

2.2.1 Sample Elaboration and Laboratory Program

After the placement of the basic characteristics of the natural soil, it was passed through 5 mm sieve and air dried at approximately 105 °C. The soil was then blended with the coarse aggregate of CW, MD and soil–OPC–CW. The proportions of CW selected were 5, 10, and 15% by weight; the proportions of MD selected were 2, 3, 4, and 5% by weight, while the proportions of OPC selected were 1.5 and 2% by the weight of soil. To achieve identical apportionment required careful preparation and sufficient time. The modified proctor compaction test was performed to determine the MDD of the blends according to BS 1377-Part 4 (1990). For mixing purposes, the natural soil–CW, natural soil–MD and natural soil–OPC–CW were mixed carefully till a uniform color was obtained. According to NZTA (2017), the stabilization of the unbound aggregate using the binder typically requires $\leq$ 2% by dry weight. Furthermore, several researchers (Cabalar et al. 2016; Kapil and Ameta 2016) added 0–12% CW to stabilize embankments and 0–30% to stabilize road pavement sub-grade.

Compaction was then performed after mixing the combination. The addition of water as needed for the compaction process. In this work, the CBR test was carried out on the mixtures in soaked and unsoaked conditions. The performance of the sub-base material compressing CW, MD,and OPC mixed with the soil, as well as CW and OPC mixed with soil, was

Table 2 Physical properties-chemical composition of OPC (Mohamed and Abdelkrim 2014)

Designation	CEM-II/B 42.5 N NA 442 MATINE	
Physical properties	Normal consistency of the cement paste	25–28.5
	Blaine fineness	4160–5270 μm/m
	Initial setting	135–190 min
	End setting	190–285 min
	Shrink at 28 days	< 1000 μm/m
	Expansion	0.25–2.55 mm
	Compressive strength at 28 days	≥ 42.5 MPa
Chemical composition	Loss on ignition	7–12.5%
	Soluble residues	0.7–2%
	Sulfates	2–2.7%
	Magnesium oxide	1–2.2%
	Chlorides	0.01–0.05%
	Tricalcic silicates	55–62%
	Alkalis	0.5–0.75%

investigated. The specimens with OPC were kept in plastic bags for 24 h to avoid the evaporation of water, and were then cured 7, 14, and 28 days in water tanks for the soaked condition, and they were kept in the plastic bags for the unsoaked condition until the completion of the cementation process. The specimens without OPC were soaked for 96 h and kept for 24 h in plastic bags for the unsoaked condition. The MDD and OMC of the samples conformed to the guidelines specified in ASTM D1883 (2016). The various mixtures used in this work are presented in Table 3.

The resilient modulus is a mechanical property that indicates the stress–strain responses of flexible pavement sub-base layers under continual loading conditions, according to the standard method of AASHTO T 307-99 (2012). Relationship between M_R and CBR have been suggested by several authors for example, $M_R = 21\ (CBR)^{0.65}$ (Ayres 1997), and $M_R = 17.58\ (CBR)^{0.64}$ (Powell et al. 1984).

2.2.2 *Mechanism of Improvement*

Various techniques of soil improvement using cement, lime, fly ash or fibers, have been well studied by Ali et al. (2017) and Habiba (2017). In our work CW, MD, and CW-OPC were added to the soil, and the composition of the CW consisting of clay and GF sand, helped to fill most of the voids in the soil. The best results were obtained when the addition of CW was between 5 and 10%, above which the improvement became negative, possibly because the quantity of clay had passed the optimum. The addition of CW to the soil ameliorated the MDD and bearing capacity of the mixtures, owing to the effectiveness of optimum clay particles to the grain size of mixtures and soil surface area. Besides, MD has a high CaO content, which can generate the possible improvement in the soil characteristics. The combination of CW and a small amount of OPC as chemical stabilizers can

Table 3 Mix design composition

Mix design	Mixture composition	Mix design	Mixture composition
S1	Natural soil	S9	Soil +10% CW
S2	Soil +5% CW + 1.5% C	S10	Soil +15% CW
S3	Soil + 10% CW +1.5% C	S11	Soil + 4% MD
S4	Soil + 15% CW + 1.5% C	S12	Soil + 5% MD
S5	Soil + 5% CW + 2% C	S13	Soil + 1.5% C
S6	Soil + 10% CW + 2% C	S14	Soil + 2% C
S7	Soil + 15% CW + 2% C	S15	Soil + 2% MD
S8	Soil + 5% CW	S16	Soil + 3% MD

CW ceramic waste, *C* cement, *MD* marble dust achieve high bearing capacity, the hydration of OPC occurs after the addition of water through the production of combinations of (C–S–H) and (C–A–H) and the production of surplus (CaOH). The results of the experimental tests were expected to indicate the optimum stabilizer type and quantities (Euro Soil Stab 2002).

3 Results and Discussion

3.1 Compactions Tests

3.1.1 Compaction of Natural Soil–CW

In this section, we analyzed the impact of CW content on the MDD-OMC relationship. The tendency is identical to that examined by Chen and Indusyi (2015) and Babita et al. (2014). The percentages of added CW were 5, 10, and 15% (Table 3). The results of the MDD and OMC for soil treated and untreated with CW are shown in Fig. 2.

A compatible increase in the MDD was identified when the addition of CW was in the range of 5–10%, above which the MDD decreased slightly, for example, when 15% CW was added to the soil, as displayed in Fig. 2.The MDD of natural soil is 19.4 kN/m^3, and it is 19.5 kN/m^3 and 19.9 kN/m^3 for 5 and 10% CW, respectively. However, when 15% CW was added to the natural soil, the MDD decreased from 19.9 kN/m^3 at 10% CW to19.5 kN/m^3 at 15% CW. Thus, the MDD decreased when the amount of CW passed 10%, possibly because the composition of the CW influenced that of the total mixture. It is well known that a high proportion of clay minerals composed ceramic, which could influence dry density if added in high quantities to the soil as a stabilizer. Similar results for stabilizing expansive soils using ceramic dust were found by Kapil and Ameta (2016) and Sabat (2012).

3.1.2 Compaction of Soil–MD

In this section, we examined soil treated with 2, 3, 4, and 5% MD. The outcomes are presented as water content plotted against density, in Fig. 3.

Figure 3 reveals that the MDD of soil treated with MD increases, in that the MDD of natural soil is 19.4 kN/m^3, while those of soil with 2, 3, 4, and 5% MD are 19.6, 19.6, 19.7, and 19.9 kN/m^3, respectively.

The MD is derived from the rock marble, which when used in this research work, is a very fine material that fills the void spaces between soil particles, and increases the MDD. Such a phenomenon was also reported previously by Neeladharan et al. (2018).Furthermore, Fig. 3 illustrates that as the MD dosage increases in the soil the OMC decreases. Thus, it is apparent that the OMC values are 12.96, 12.02, 11.72, 11.87, and 10.78% for soils treated with 0, 2, 3, 4, and 5% MD, respectively. The decrease in moisture content can be attributed to the fact that MD is the very fine material derived from rock, which absorbs a considerable amount of water in stabilized soil mixtures.

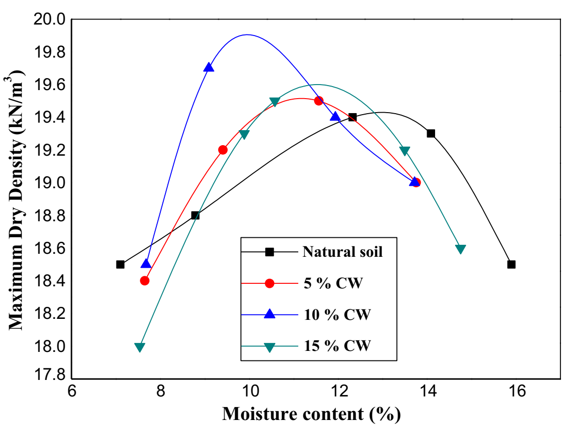

Fig. 2 Compaction curves of soils-CW

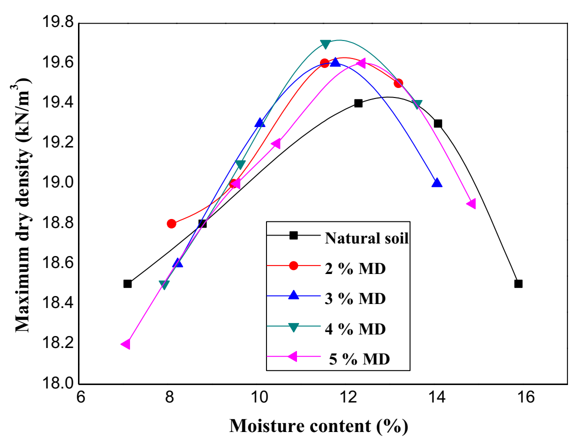

Fig. 3 Compaction curves of soils-MD

3.1.3 Compaction of Soil–OPC

In this section, we examined the dosage of OPC, which was 1.5 and 2% (Table 3), and the test results for MDD and OMC in treated and untreated soils are shown in Fig. 4. An increase in MDD was observed with increasing OPC content, as shown in Fig. 4. Comparable results were reported by Susana et al. (2017) and Melik et al. (2019).

The MDD of natural soil is 19.4 kN/m^3, and 19.6 kN/m^3 for soil treated with both 1.5, and 2% OPC, respectively. Thus, the MDD is almost constant when 1.5 and 2% OPC are added.

3.1.4 Compaction of Soil Treated with the CW + OPC

The MDD for the mixtures with 1.5, and 2% OPC and 5% CW; 1.5 and 2% OPC with 10% CW; and 1.5, and 2% OPC with 15% CW are presented in Figs. 5, 6, and 7 respectively.

Figure 5 reveals an increase in MDD with an increasing OPC from 1.5 to 2% with 5% CW, and similarly when 1.5 and 2% OPC are mixed with 10% CW, apparent in Fig. 6. On the other hand, Fig. 7 shows a decrease in MDD when OPC is added with 15% CW. We can conclude that, when the CW content is above 10%, the MDD decreases, possibly because of the influence of the high percentage of clay in the admixture. Similar behavior was observed by Chen and Indusyi (2015).

The OMC of the mixtures decreases as the MDD increases with an increasing percentage of each addition from 5 to 15% CW. However, the addition of OPC to the soil decreases the OMC. This decrease is

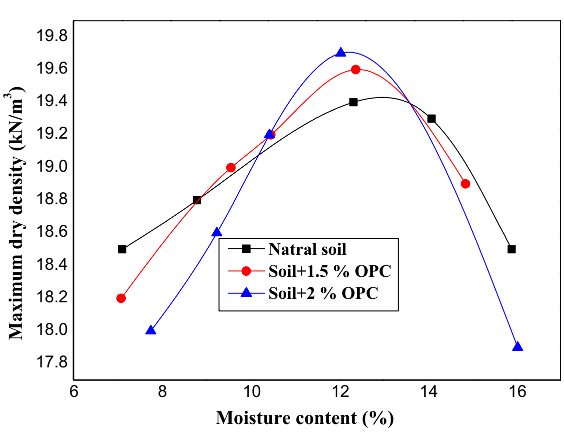

Fig. 4 Compaction curves of soils-OPC

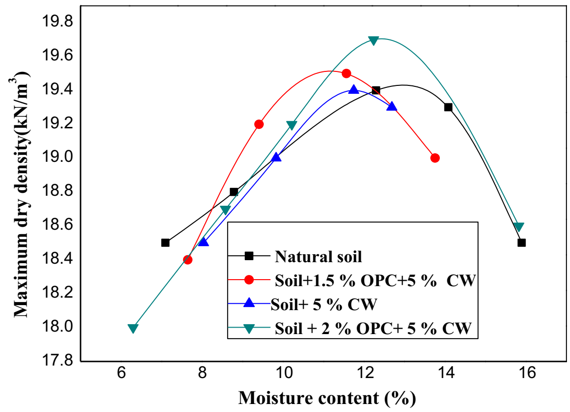

Fig. 5 Compaction curves of soils-cement- 5% CW

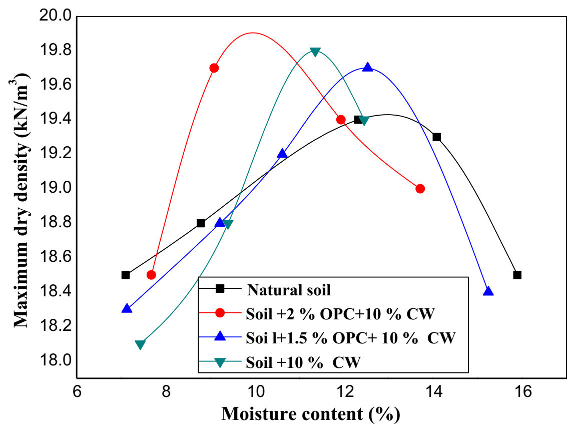

Fig. 6 Compaction curves of soils-OPC- 10% CW

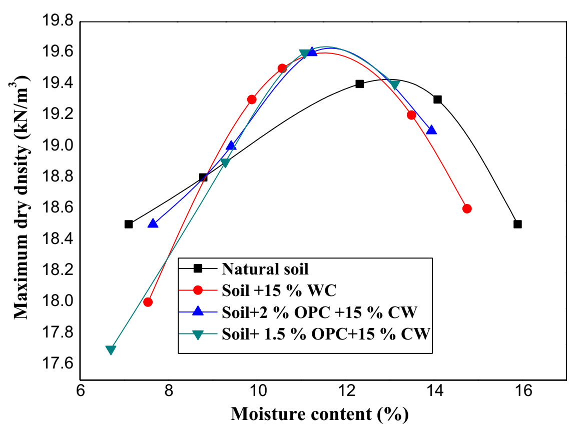

Fig. 7 Compaction curves of soils-cement- 15% CW

caused by the fines in the additives to the soil, which absorb more water.

3.2 CBR Tests

3.2.1 CBR Test for Natural Soil–OPC

The influence of OPC and curing time on the sub-base material is shown in Fig. 8, in which the CBR values increase with the increase in OPC dosage. Furthermore, the CBR values increase with curing time. We are convinced that the hydrated cement binds between the soil particles reduce void spaces. Moreover, it reduces the compressibility and increases the strength of the soil. The blend of 1.5 and 2% OPC–soil enhances the results for unsoaked and soaked CBR from 88 to 99% at 28 days and from 68% to 129% at 28 days. Such behavior was observed with cement-soil mixtures by Al-Homidy et al. (2016).

3.2.2 CBR for Soil–CW, Soil–MD, and Soil–OPC–CW

Figure 9 shows that the CBR values for the mixtures of soil treated with 5, 10, and 15% CW and 4, and 5% MD. The CBR values were 51.64, 75.26, 94.05, 73.24, 81.57, and 91.55% for 0, 5, 10, and 15% CW, and 4 and 5% MD, respectively, in the unsoaked condition. Further, it is apparent that the addition of CW above 10% decreases the CBR values owing to the high content of clay minerals in the CW. The blend of CW and, MD with soil provides higher CBR values in the unsoaked condition, however, very low values in the soaked condition, although typically the CBR values used for sub-base material are in the soaked condition.

To examine the influence of the percentages of CW on the CBR values of the soil in the soaked and unsoaked conditions, we examined the effects of the addition of 1.5 and 2% OPC, to soil treated with 0, 5, 10, and 15% CW by air dried weight of soil, under both conditions. It is apparent from Fig. 9 that the CBR values increase with increasing percentages of CW in the soaked and unsoaked mixtures. The addition of 1.5% OPC and 0, 5, 10 and 15% of CW gave a range of CBR values in the soaked condition from 5.82, 112.5, 116.31, and 106.4%, respectively. Moreover, the addition of 2% OPC and 0, 5, 10, and 15% of CW

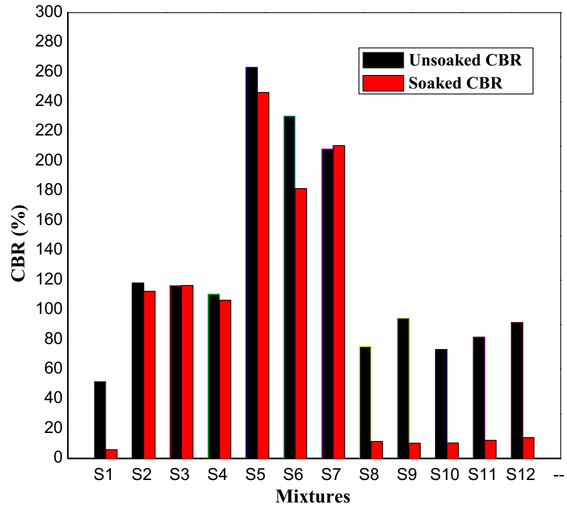

Fig. 9 Effect of CWC- MD and CW- OPC on CBR

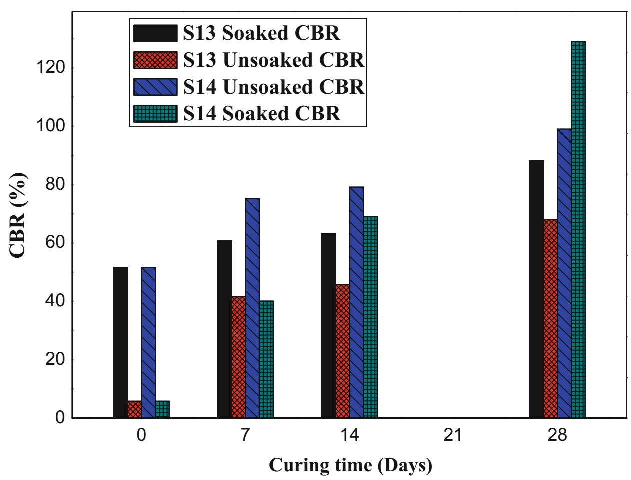

Fig. 8 CBR results with curing time

Table 4 Literature model for M_R prediction as a function of CBR

Reference	Model (MPa)	Mixtures													
		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14
Ayres (1997)	$M_R = 21\ (CBR)^{0.65}$	65	458	462	436	752	616	679	102	95	96	107	116	326	494
Powell et al. (1984)	$M_R = 17.58\ (CBR)^{0.64}$	54	361	368	348	596	489	539	83	77	79	87	95	261	394

Table 5 Cost analysed for the (%) replacement

Replacement (%)	(%) Reduction in cost (approx)
S2	7.5
S3	11
S4	15
S5	7
S6	10
S7	13
S8	10
S9	13
S10	18

provided CBR values in the soaked condition from 5.82, 246.31, 181.45, and 210.48%, respectively.

The addition of 1.5% OPC and 0, 5, 10, and 15% of CW gave a range of CBR values in the unsoaked condition from 51.64, 117.94, 116.14, and 110.5%, respectively. It is also apparent that the addition of 2% OPC and 0, 5, 10, and 15% CW gave CBR values in the unsoaked condition of 51.64, 263.10, 230.46, and 208.14%, respectively. The higher values of CBR were obtained from mixtures with 2% OPC and 5 and 10% CW as shown in Fig. 9.

These results confirmed those of the compaction test. However, the CBR results for soil in the soaked condition are much higher than the minimum required CBR of 25% and 60–80% for sub-grade and sub-base materials layers, respectively (NZTA 2016; Ramzi et al. 2012).

3.3 Resilient Modulus

In this section, we calculated the M_R from equations proposed in the literature. Table 4 presents the results of the M_R calculations for different mixtures. The untreated soil gives an M_R of less than 65 MPa, where as soil mixed with CW and MD only gives an M_R of around 100 MPa. The blend of soil with CW and OPC, and the blend of soil with OPC only give higher M_R values of around 400–750 MPa, where increases in the amount of OPC, result in increases in the M_R.

The minimum M_R required for pavements by DPTI (2011) is 300 MPa, which is a value that the mixtures of soil with wastes and OPC meet. Further, these results conform to those of Aust Stab (2015) and Mousa et al. (2017).

4 Cost Analysis

It was considered important in the present work to estimate the cost of 1 m^3 of the sub-base material. The costs were calculated according to the market rates as of September 2019.The percentage of the dry mass of each blend are presented in Table 3. Therefore, the percentage reduction in the cost based on the percentage of the soil replacement with CW, MD, OPC, and CW–OPC are listed in Table 5.

5 Conclusion

To the best of our knowledge, this is the first study that attempted to use CW and MD in the road construction in Algeria. The study sought to identify suitable mixtures of the CW–soil, and the MD–soil combined with small amounts of OPC by assessing the MDD and CBR values of the different mixtures. Furthermore, we calculated the resilient modulus of the different mixtures. Based on the analysis of the results of the tests we note that MDD increases with increasing CW and MD added to the soil. Moreover, the CBR values increase with the addition of CW and MD, however, the results also indicated that the addition of 1.5–2%

OPC to the blend gave the highest CBR values. Based on the CBR results, 5–10% CW added to the soil can be used for rural roads, while the addition of 1.5–2% OPC to the blends can be used as a sub-base layer for highways. The resilient modulus was calculated from the correlation between M_R and CBR, based on proposed model in the literature and the results indicate that the M_R varied from 300 to 750 MPa when the OPC was used; however, it was around 100 MPa for mixtures without OPC. This study shows that CW and MD combined with small amounts of OPC could act as alternative soil stabilization for use in road sub-base layers. In the future, more analysis should be conducted on the UCS to obtain a greater understanding of the sub-base material.

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

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