Mechanical behavior of calcareous tuff and coal mine tailings mixture as an embankment material for road construction

Comportamento mecânico da mistura de tufo calcário e rejeitos de mineração de carvão como material de aterro para construção de estradas

Comportamiento mecánico de la mezcla de toba calcárea y relaves de mina de carbón como material de terraplén para la construcción de carreteras

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ABSTRACT

The construction of embankments requires available and suitable material that sounds to the imposed load. The selection of materials that provide slope stability and maintain pavements is made through specific test control. This research aims to analyze the mechanical behavior of a mixture of 75% calcareous tuff and 25% coal mine tailings (CMTs) used on embankment foundations. The impact of particle size characteristics and the compaction on the mechanical behavior of the mixture are studied. The direct shear test was conducted on different material states, granular and uncompressed states, compaction at the Maximum Practical Optimum (MPO), and MPO compaction post a 30-day curing period at 40 degrees Celsius. The normal stress applied ranging from 50 to 500 KPa, with a constant shear rate displacement of 0.5 mm/min. The results show a substantial influence of compaction on both friction angle (φ) and cohesion (C) values. A remarkable increase in
cohesion values after the curing period, attributed to the cementitious compound formation from the interaction between calcareous tuff and coal mine tailings. This investigation emphasizes coal mine tailings potential as a sustainable and cost-effective embankment material for road construction, especially in arid regions. The material exhibits significant shear strength, with a marked increase in cohesion values post-curing state. These results are conducted to consider coal mine tailings as an appealing alternative to traditional materials of road engineering.

**Keywords:** Coal Mine Tailings. Tuff. Embankment. Compaction. Shear Strength.

**RESUMO**

A construção de aterros requer materiais disponíveis e adequados que resistam à carga imposta. A seleção de materiais que proporcionem estabilidade de taludes e mantengam pavimentos é feita através de testes específicos de controle. Esta pesquisa tem como objetivo analisar o comportamento mecânico de uma mistura de 75% de tufo calcário e 25% de rejeitos de mineração de carvão (CMTs) utilizados nas fundações de aterros. Estudam-se as características do tamanho das partículas e a compactação no comportamento mecânico da mistura. O ensaio de cisalhamento direto foi realizado em diferentes estados do material: estado granular e não compactado, compactação no Ótimo Prático Máximo (MPO) e compactação MPO após um período de cura de 30 dias a 40 graus Celsius. A tensão normal aplicada variou de 50 a 500 KPa, com uma taxa de deslocamento de cisalhamento constante de 0,5 mm/min. Os resultados mostram uma influência substancial da compactação nos valores de ângulo de atrito (φ) e coesão (C). Observou-se um aumento notável nos valores de coesão após o período de cura, atribuído à formação de compostos cimentícios resultantes da interação entre o tufo calcário e os rejeitos de mineração de carvão. Esta investigação enfatiza o potencial dos rejeitos de mineração de carvão como um material sustentável e econômico para aterros em construção de estradas, especialmente em regiões áridas. O material exibe uma resistência ao cisalhamento significativa, com um aumento marcado nos valores de coesão após o estado de cura. Esses resultados são conduzidos para considerar os rejeitos de mineração de carvão como uma alternativa atraente aos materiais tradicionais da engenharia rodoviária.


**RESUMEN**

La construcción de terraplenes requiere materiales disponibles y adecuados que resistan la carga impuesta. La selección de materiales que proporcione estabilidad de taludes y mantengan los pavimentos se realiza mediante pruebas específicas de control. Esta investigación tiene como objetivo analizar el comportamiento mecánico de una mezcla de 75% de toba calcárea y 25% de relaves de mina de carbón (CMTs) utilizados en las fundaciones de terraplenes. Se estudia el impacto de las características del tamaño de las partículas y la compactación en el comportamiento mecánico de la mezcla. La prueba de corte directo se realizó en diferentes estados del material: estados granulares y no compactados, compactación en el Óptimo Práctico Máximo (MPO), y compactación MPO después de un período de curado de 30 días a 40 grados Celsius. La tensión normal aplicada varió de 50 a 500 KPa, con una tasa de
desplazamiento de corte constante de 0.5 mm/min. Los resultados muestran una influencia sustancial de la compactación en los valores del ángulo de fricción (φ) y la cohesión (C). Se observó un notable aumento en los valores de cohesión después del período de curado, atribuido a la formación de compuestos cementantes resultantes de la interacción entre la toba calcárea y los relaves de mina de carbón. Esta investigación enfatiza el potencial de los relaves de mina de carbón como un material de terraplén sostenible y rentable para la construcción de carreteras, especialmente en regiones áridas. El material exhibe una resistencia al corte significativa, con un aumento marcado en los valores de cohesión después del estado de curado. Estos resultados se llevan a cabo para considerar los relaves de mina de carbón como una alternativa atractiva a los materiales tradicionales de la ingeniería vial.

**Palabras clave:** Relaves de Mina de Carbón. Toba. Terraplén. Compactación. Resistencia al Cizallamiento.

1 INTRODUCTION

Coal mining processes produce massive quantities of waste materials [1,2]. The coal mine tailings (CMTs) are a significant material that continues to captivate researchers’ attention, particularly in the context of current climate challenges [3]. These tailings have traditionally been known as a substantial environmental issue [4–8] and their study remains important to the scientific community. In the southwest of Algeria, a large accumulation of old Coal Mine Tailings, estimated at 3,7 million cubic meters deposited in Kneads near the Becher district. It is a constant source of pollution that has harmful effects on the environment and human health. To help reduce this solid waste, several studies have been carried out. The study by examined the potential for using coal mine tailings as base material on road construction. The use of mine waste in road constructions and embankment foundations back to 1990, but it still is challenging due to the huge quantities produced annually in various countries around the world [9–14].

In Algeria, the public works sector is witnessing a great recovery, in light of the authorities’ interest in expanding the road infrastructure and linking villages together, especially in desert areas [15]. Tuffs are among the materials available in huge quantities. It covers about 300,000 square kilometres. In arid and semi-arid regions, they represent 90% of road materials used in the pavement construction [16]. Tuff can be used alone or in combination with other materials. In the arid region
researches focuses on valorisation of natural tuff utilized road technology by mixing it with local materials such as dune sand [17,18]. Akcem et al. (2022) investigated a pavement in the Adrar region in southern Algeria design and construct by tuffs combined with different percentage of dunes sand [19]. While the mixture of 20 % dune sand and 80 % tuff shows optimum geotechnical results. In the study of Guesmia et al. 2019, a mixture of 35% dune sand and 65% tuff from Ouargla district, 800 km south of Algiers, was shown the optimal geotechnical properties [20], also through a number of drying-wetting and triaxial tests, the study examines the optimized mixture's hydro-mechanical properties [21] and using hydraulic binders (sulphate resistant binders), an experimental investigation was also carried out to assess the same optimal mixture for pavement design for medium to high traffic road. It was found that the mixture met the requirements appears to be an appropriate compromise for the valuation of regional resources and meets the specifications of road pavement design in desert regions [22]. The geotechnical properties of tuff from Mascara in northwest Algeria treated by cement with different mixing of ceramic powder, the results demonstrate that the ceramic powder may be utilized to reinforce and enhance the tuffs modification [23]. The capacity of limestone tuff from Djelfa semiarid region, when subjected to low or quick drying, analogous to the pavements constructed with wet calcareous tuff or crust, was experimentally studied and the morphological changes in the tuff microstructure during drying process was studied using SEM analysis to enhance understanding of the mechanisms involved in suction, as well as the processes of tuff skeleton hardening and stiffening. [24].

Shear strength evaluation is one of the important geotechnical properties in the study of the base layer of roads [25], where the soil shear strength consists of two important properties: Cohesion C and friction angle φ which are considered as basic indicators for determining the soil shear strength. However, in the base layer, which is an absorption layer for the force resulting from the passage of vehicles, which leads to slips and deformations, it must be evaluated in advance. However, there is a scarcity of comprehensive research available in the published literature that aims to clarify the impact of compaction, maximum particle size characteristics, and curing time on the mechanical properties of coal mine tailings mixed with tuff. In order to address this research gap, we undertook the present study.
2 MATERIALS AND METHODS

2.1 MATERIALS

The material under examination is a mixture of 75% tuff and 25% Coal Mine Tailings T75-CMT25, the two raw materials are available in Bechar region, southwest of Algiers (Figure 1). The CMTs was taken from the old coal mines in Kenadsa near Bechar cities, which had known mining activity since the thirties of the last century, and then stopped after Algeria’s independence a few years later. Limestone is a source of tuff formation [26], the CaO it is the most predominant mineral in the chemical composition of tuff, and it is widely used in the design of road projects in the south of Algeria. The average of chemical composition of the two materials, coal mine tailings and tuff are discussed below.

Figure 1. The site’s locations

Source: The authors.

Figure 2 displays the grain size distribution of tuff, coal mine tailings, and the T75-CMT25 mixture. Table 1 presents the geotechnical properties of the T75-CMT25 mixture, varying based on maximum particle diameters $D_{\text{max}}$ of 5 mm, 2.5 mm, and 1 mm. Specific gravity $G_s$ values range from 0.43 to 0.49. Atterberg limits include liquid limit $W_L$ at 25.45%, plastic limit $W_P$ at 16.27%, and plasticity index $I_P$ at 9.18%. Volume-based stability VBS is less than 1.5. Dry density $\gamma_{\text{dmax}}$ varies from 1.86 g/cm³ to 1.94 g/cm³. Optimum water content ranges from 12.00% to
13.00%. Coefficient of uniformity $C_u$ ranges from 26.67 to 52.27, and coefficient of curvature $C_c$ varies from 1.35 to 2.53.

![Figure 2. Grain size distribution curves of Tuff, Coal Mine tailings, CMT25 mixture.](image)

Table 1. Geotechnical properties and mechanical properties of the T75-CMT25.

<table>
<thead>
<tr>
<th>Properties</th>
<th>$D_{\text{max}}$</th>
<th>CMT25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5mm</td>
<td>0.45</td>
<td></td>
</tr>
<tr>
<td>1mm</td>
<td>0.49</td>
<td></td>
</tr>
<tr>
<td>$W_L$ (%)</td>
<td>/</td>
<td>25.45</td>
</tr>
<tr>
<td>$W_P$ (%)</td>
<td>/</td>
<td>16.27</td>
</tr>
<tr>
<td>$I_P$ (%)</td>
<td>/</td>
<td>9.18</td>
</tr>
<tr>
<td>VBS</td>
<td>/</td>
<td>1.5 &lt;</td>
</tr>
<tr>
<td>$\gamma_{\text{max}}$ (g/cm3)</td>
<td>2.5mm</td>
<td>1.89</td>
</tr>
<tr>
<td>1mm</td>
<td>1.86</td>
<td></td>
</tr>
<tr>
<td>5 mm</td>
<td>12.00</td>
<td></td>
</tr>
<tr>
<td>$W_{\text{opt}}$ at MPO (%)</td>
<td>2.5mm</td>
<td>12.50</td>
</tr>
<tr>
<td>1mm</td>
<td>13.00</td>
<td></td>
</tr>
<tr>
<td>5 mm</td>
<td>52.27</td>
<td></td>
</tr>
<tr>
<td>Coefficient of uniformity, $C_u$</td>
<td>2.5mm</td>
<td>43.57</td>
</tr>
<tr>
<td>1mm</td>
<td>26.67</td>
<td></td>
</tr>
<tr>
<td>5 mm</td>
<td>1.35</td>
<td></td>
</tr>
<tr>
<td>Coefficient of curvature, $C_c$</td>
<td>2.5mm</td>
<td>1.41</td>
</tr>
<tr>
<td>1mm</td>
<td>2.53</td>
<td></td>
</tr>
</tbody>
</table>

Source: The authors.

2.2 SCANNING ELECTRON MICROGRAPH (SEM)

The SEM micrograph in Figure (3-a) illustrates the granular state of tuff, while Figure (3-b) represents the coal mine tailings. Both materials have a maximum grain size of 0.5 mm $D_{\text{max}} = 5$ mm. The presented scanning electron micrograph SEM provides a detailed view of two distinct materials: coal mine tailings and tuff, with a
magnification of 200 µm. This SEM analysis offers valuable insights into the microstructural characteristics and surface features of these materials.

Upon closer examination, it is evident that the tuff exhibits elements of smaller sizes compared to the CMTs. The tuff contains smaller-sized elements distributed throughout its composition. These smaller elements are likely indicative of fine particles or grains within the tuff structure. Conversely, the CMTs primarily consist of larger elements. However, it also contains a small quantity of smaller elements. These smaller elements within the CMTs are comparable in size to fly ash particles[27,28]. Fly ash particles are typically known to have a relatively small size range.

![Figure 3. SEM micrograph analysis](image)

(a) Calcareous tuff
(b) Coal Mine Tailings

Source: The authors.

Table 2 presents the major oxide compositions of calcareous tuff and coal mine tailings, which are essential for understanding their chemical properties and the potential for forming cementitious materials when these two materials are mixed together. In calcareous tuff, CaO is the predominant oxide, comprising 43.89% of the composition. This high silica content suggests that the tuff can contribute to the formation of silicate-based cementitious compounds. Al₂O₃ and SiO₂ are also significant components, accounting for 3.67% and 16.73%, respectively. These oxides are crucial for the formation of aluminosilicate and calcium silicate hydrates, which are fundamental in cementitious reactions. The presence of Fe₂O₃ (1.15%) further contributes to the reactivity potential of the tuff. Additionally, minor amounts of MgO, Na₂O, SO₃, K₂O, and CO₂ are present,
ranging from 0.01% to 0.81%. These oxides may influence the overall chemical composition and reactivity of the tuff.

CMTs exhibits higher percentages of SiO$_2$ (23.54%) and Al$_2$O$_3$ (10.30%), suggesting a higher potential for forming cementitious compounds. However, the presence of CaO is significantly lower, constituting only 1.79% of the CMTs composition. The presence of Fe$_2$O$_3$ (8.46%) in the CMTs indicates a higher iron content, which may contribute to the reactivity of the mixture.

<table>
<thead>
<tr>
<th>Oxide</th>
<th>tuff</th>
<th>CMTs</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>16.73</td>
<td>23.54</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>3.67</td>
<td>10.30</td>
</tr>
<tr>
<td>CaO</td>
<td>43.89</td>
<td>1.79</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>1.15</td>
<td>8.46</td>
</tr>
<tr>
<td>MgO</td>
<td>0.81</td>
<td>1.52</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>0.01</td>
<td>0.11</td>
</tr>
<tr>
<td>SO$_3$</td>
<td>0.43</td>
<td>7.94</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>0.44</td>
<td>1.63</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>33.85</td>
<td>44.15</td>
</tr>
</tbody>
</table>

Source: The authors.

2.3 X-RAY DIFFRACTION (XRD)

Figure 4 illustrates the X-ray Diffraction XRD spectra of the tuff sample, revealing a composition dominated by 88% calcite (CaCO$_3$). Additionally, 12% of quartz SiO$_2$. These findings align seamlessly with the results obtained from the X-ray Fluorescence (XRF) analysis, as detailed in Table 2.

Figure 5 presents the X-ray Diffraction XRD spectra of Coal Mine Tailings, revealing a diverse mineral composition. The major components identified are as follows: Muscovite 2M1: Constituting 47% of the sample, Muscovite is a prominent mineral with a distinct crystal structure, as denoted by its chemical formula. Quartz (SiO$_2$, 17%) comprising 17% of the sample, exhibits characteristic diffraction peaks. The intensity of these peaks is proportionate to the concentration of quartz in the sample. Gypsum is present, and its identity is confirmed through specific diffraction peaks in the XRD pattern, indicative of its unique crystal structure. Illite As a clay mineral, Illite is identified in the sample, with its distinctive XRD peaks corresponding to its crystal structure. Numerous studies have substantiated the existence of the previous minerals in several researches [29–31]. Jarosite Present
in a minor amount, jarosite's presence is discerned by characteristic XRD peaks associated with its crystal structure. While jarosite itself is not typically found directly in coal mines tailings, the presence of jarosite or other Sulfate minerals in coal mine environments can indicate specific geochemical and mineralogical conditions. The formation of jarosite is typically a result of the oxidation of iron Sulfide minerals, such as pyrite, in the presence of water and air. [32]
3 EXPERIMENTAL METHODS

3.1 COMPACTION TESTS

The compaction test is commonly used in geotechnical practice and construction to design and control road embankments, earth dams, and other earthworks in order to make soil more dense and less air void content [33]. In this context, the compaction characteristics response ($\gamma_{d_{\text{max}}}$, $w_{\text{opt}}$) was evaluated as function of largest grain size ($D_{\text{max}}$) of the T75-CMT25 mixture, Figure 6 shows the three compaction curves according to the different diameters ($D_{\text{max}} = 5 \text{ mm}, 2.5 \text{ mm and } 1 \text{ m}$).

Figure 6. Dry density versus water content of T75-CMT25 with different maximum diameter

![Graph showing compaction curves](image)

The tests were carried out according to the standard Modified Proctor compaction test (ASTM D698-91 1995; NF P94-093 1999). The tested materials have been prepared through the combination of 75% Tuff mixed with 25% of Coal Mine Tailings considering different water contents ranging from $w = 4 \%$ to $w = 15 \%$ and subjected to compaction energy in order to estimate the different optimum modified Proctor coordinates (maximum dry density ($\gamma_{d_{\text{max}}}$), optimal water content ($w_{\text{opt}}$). For the T75-CMT25 mixture with a $D_{\text{max}}$ of 5 mm, the optimum water content is determined to be 12 %. This means that, for this particular grain size, the best moisture content required for achieving maximum compaction is 12 %. The corresponding maximum dry unit weight is found to be 1.941 g/cm$^3$. This indicates
the density that can be achieved when the material is compacted under optimum conditions. When the $D_{\text{max}}$ is increased to 2.5 mm, the optimum water content slightly increases to 12.5 %. This suggests that a slightly higher moisture content is needed to achieve the maximum compaction for this larger grain size. The resulting maximum dry unit weight decreases to 1.898 g/cm$^3$, indicating a lower achievable density compared to the mixture with a $D_{\text{max}}$ of 5 mm. In the case of the largest grain size analysed, which is 1 mm, the optimum water content further increases to 13 %. This implies that a higher moisture content is necessary to attain the maximum compaction for this size fraction. The maximum dry unit weight is found to be 1.860 g/cm$^3$, indicating a further decrease in the achievable density compared to the previous grain sizes.

3.2 DIRECT SHEAR TEST

The direct shear test is a geotechnical testing method used to determine the shear strength properties of soil or rock[33]. It is a laboratory test that involves applying a vertical normal load and a horizontal shear load to a soil sample confined within a shear box. To assess the shear properties of T75-CMT 25 mixture, a series of direct shear tests were carried according with NF P94-071-1 using an advanced automated direct shear testing system (SHEARMATIC EmS)[34].

Test specimens was placed at the square direct shear box with 60 * 60 * 20 mm, The normal load is applied to the soil sample using a loading device. The normal load applied in increments until the desired normal stress is reached with values of $(\sigma_n) = 50, 100, 200, 300, 400, \text{ and } 500 \text{ KPa}$. The horizontal shear load is applied in increments until the desired shear stress is reached with shear rate of 0.5 mm/min. The horizontal shear load should be applied in a direction perpendicular to the normal load. Test results are recorded and displayed in real time then processed using Wykeham Farrance (WF) geo-analysis models which allows remote control of our tests (Figure 7).
To analyse the shear stress-horizontal displacement curves obtained from the shearing experiments on the mixture of calcareous tuff and coal mine tailings, we will examine the results under three different conditions: the granular and uncompressed state, the optimized Proctor condition, and the optimal Proctor condition after thirty days of preservation at a temperature of 40 degrees Celsius. Additionally, we will consider the varying diameters tested, including $D_{\text{max}}$ values of 5 mm, 2.5 mm, and 1 m. Furthermore, we will take into account the range of normal stresses applied, which cover $\sigma_n$ values of 50, 100, 200, 300, 400, and 500 kPa. The horizontal displacement used for plotting the curves is fixed at 10 mm. This chosen displacement ensures that the curves are presented without distortion, maintaining a consistent spacing between the different normal stress.
4 RESULTS AND DISCUSSION

4.1 SHEARING EXPERIMENTS ON GRANULAR AND UNCOMPRESSED STATE

In this condition, the mixture is in its loosest form without any compaction. The shearing experiments were conducted for different diameters. The shear stress-horizontal displacement curves obtained for each diameter and normal stress can provide insights into the material's behaviour in its loosest state. The curves will indicate the shear strength and deformation characteristics of the mixture under various loading conditions (Figure 8).

The reduction in particle size is clearly evident through the decreasing trend observed in the curve magnitudes. This observation confirms the influential role of particle size in the shearing process. The curves exhibit a clear relationship between the values of Shear Stress and the change in maximum particle size $D_{\text{max}}$.

Figure 8. shear-displacement, granular materials

Source: The authors.
4.2 SHEARING EXPERIMENTS ON OPTIMIZED PROCTOR CONDITION

The optimized Proctor condition involves compacting the mixture to achieve a specific compaction density. The shearing experiments under optimized Proctor condition for different diameters and normal stresses will provide information about the shear strength and deformation properties of the compacted mixture (Figure 9).

As the maximum particle size increases, the Shear Stress values also increase. Furthermore, there is an evident change in the curve shapes, characterized by a distinct peak occurring at a bias of less than 0.6 mm.

Source: The authors.

4.3 SHEARING EXPERIMENTS ON OPTIMAL PROCTOR CONDITION AFTER 30 DAYS PRESERVATION AT 40 C°

This experimental condition aims to examine the influence of preservation time on the shear strength characteristics of the mixture. By conducting shearing experiments on the mixture following a thirty-day preservation period at 40°C,
mimicking conditions similar to arid zones (Bechar city), and under optimal Proctor condition, we can evaluate the long-term stability and variations in shear strength over time. The shear stress-horizontal displacement curves obtained under this condition will provide insights into the progression of shear strength in relation to the duration of preservation (Figure 10).

The figures present the results of shear stress-horizontal displacement for the T75-CMT25 mixture after a 30 days preservation period at 40°C. It is evident that the values of the curves have been influenced, though in a contrasting manner compared to the previous observation. Specifically, as the maximum particle size $D_{\text{max}}$ decreases, the shear stress values increase. Another noteworthy observation is the significant drop in shear stress values after reaching the peak, particularly when the horizontal displacement is less than 4 millimetres. This decrease is accompanied by a distinct breaking sound during the shearing process, which confirms the hardening of the samples following the preservation periods.

Figure 10. shear-displacement, after 30 days curing time

Source: The authors.
4.4 SHEARING FAILURE ENVELOPE PARAMETERS

The strength envelopes of the T75-CMT25 mixture in three states (granular and uncompressed), optimized Proctor condition, and after 30 days of curing at 40°C) are detailed in Figures 8, 9, and 10. Table 3 presents peak shear strengths at various normal stresses, friction angle, and cohesion for all samples tested. For different states and a maximum particle size (Dmax) of 5 mm, shear strengths ranged from 82.5 KPa at 50 KPa normal stress to 44.22 KPa at 500 KPa normal stress, with low cohesion values (2.5 to 41.42 KPa) and friction angles (43.69° to 75.64°). With a Dmax of 1 mm, shear strengths were slightly lower, and friction angles varied widely. Compaction at MPO increased shear strengths significantly, with cohesion values up to 75.46 KPa and friction angles up to 167.32°. After 30 days of curing, shear strengths and cohesion values increased further, indicating that compaction and curing time significantly enhance the shear resistance of the mixture. Higher normal stresses generally resulted in higher shear strengths, highlighting the impact of particle size and compaction on the material's shear behavior.

Table 3. shear strengths at different normal stresses (KPa), Cohesion and Friction angle in terms of different materials state

<table>
<thead>
<tr>
<th>Materials state</th>
<th>Dmax (mm)</th>
<th>30</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>Cohesion (KPa)</th>
<th>Friction angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granular and Uncompressed State</td>
<td>5</td>
<td>82.3</td>
<td>137.47</td>
<td>244.36</td>
<td>345.03</td>
<td>428.61</td>
<td>512.33</td>
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<td>2.5</td>
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<td>401.64</td>
<td>492.14</td>
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<td></td>
<td>1</td>
<td>68.78</td>
<td>121.75</td>
<td>218.17</td>
<td>294.02</td>
<td>375.14</td>
<td>449.08</td>
<td>37.76</td>
<td>40.20</td>
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<tr>
<td>Compacted at MPO</td>
<td>5</td>
<td>120.94</td>
<td>167.32</td>
<td>263.44</td>
<td>355.10</td>
<td>445.93</td>
<td>526.34</td>
<td>78.59</td>
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<td></td>
<td>2.2</td>
<td>107.19</td>
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<td>244.42</td>
<td>319.70</td>
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<td>Compacted at MPO and 30 days curing time</td>
<td>5</td>
<td>319.61</td>
<td>380.25</td>
<td>461.14</td>
<td>548.13</td>
<td>604.84</td>
<td>677.56</td>
<td>297.19</td>
<td>38.30</td>
</tr>
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<td></td>
<td>2.1</td>
<td>331.63</td>
<td>401.90</td>
<td>510.00</td>
<td>575.94</td>
<td>646.50</td>
<td>765.84</td>
<td>303.31</td>
<td>43.98</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>341.81</td>
<td>422.11</td>
<td>541.14</td>
<td>636.03</td>
<td>748.36</td>
<td>805.44</td>
<td>314.85</td>
<td>45.86</td>
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</table>

Source: The authors.
5 CONCLUSION

In the field of geotechnical engineering, the search for alternative materials in road construction has become increasingly prominent owing to the growing concerns regarding the environment and economics. Among the materials being explored, coal mine tailings have shown potential for utilization in various geotechnical applications.

In conclusion, the results demonstrate that increasing the maximum particle size $D_{\text{max}}$ generally improves the shear strength behavior of the calcareous tuff mixed with coal mine tailings as an embankment material. The densification achieved during compaction and the development of cementitious materials during the curing process contribute to the enhanced shear strength properties. These findings provide valuable insights for the design and construction of embankments using T75-CMT25 mixture as material for road construction, highlighting the importance of particle size and the effect of curing time on the material's shear strength behavior. Further studies are needed to investigate the long-term behavior and environmental impact of this study. Nonetheless, our study provides a strong foundation for the use of coal mine tailings CMT and Tuff as an embankment material for road construction in arid zones, which can have a significant impact on reducing the cost and environmental impact of road construction projects.

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REFERENCES


[21] GUESMIA, E.; TAIBI, S.; GOUAL, I.; LI, Z. Hydro-mechanical behavior from small strain to failure of tuffs amended with dune sand – Application to


