

# Improvement of the Mechanical Properties of an Encrusting Tuff Treated with Sewage Sludge Bottom Ash and Lime

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## Abstract

The limitations of some mechanical properties of encrusting tuff, a local material abundant in the southern regions of Algeria, prevent its extensive use in different layers of roads. However, treatment or mixing of tuff with other materials or products can overcome this problem. In this context, this work aims to improve the mechanical strength of the encrusting tuff and reduce its water sensitivity through a mixed treatment with sewage sludge bottom ash (BA) and lime. Several formulations composed of encrusting tuff, BA, and lime were tested in both the short and long term. The results showed that the formulation TL4BA12 (84% tuff + 4% lime + 12% BA) has the best strength in simple compression (Rc) and indirect tension (Rtb) compared to tuff alone and the other tested formulations. This improvement in strength is observed for both short- and long-term periods. At 7 days, the Rc of TL4BA12 reached double that of tuff alone, and it was triple at 180 days. Additionally, the Rtb of TL4BA12 was approximately four times that of tuff alone at 7 days and more than double at 180 days. The water sensitivity study revealed that the specimens prepared from the treated tuff remain intact after 24 hours of immersion in water. In contrast, those prepared from tuff alone dissolved within 8 to 10 minutes.

## 1. Introduction

Encrusting tuffs, commonly referred to as tuffs, are abundant road materials found in the southeastern regions of Algeria. These tuffs are extensively utilized in Saharan road construction for capping or foundation layers. Originating from various dissolution and precipitation processes, tuffs are soft, porous, lightweight, friable, and light-colored rocks dating back to the Quaternary period [1]. Based on their chemical composition, tuffs are categorized into three types: calcareous, gypsum, and mixed tuffs (gypsum-limestone). Tuffs exhibit significant

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cohesion after undergoing wet compaction and desiccation; however, this cohesion diminishes at high saturation levels. Additionally, these materials harden over time without any treatment, a characteristic known as self-stabilization or the slab effect, making them suitable for pavement construction [2-3].

Certain types of tuffs are not very usable because of their mediocrity in geotechnical and mechanical characteristics, which do not meet the recommended technical requirements. To overcome this problem, engineers suggest treating these materials with binders (lime, cement, fumed silica, fly ash) or mixing them with other materials and waste from various sources (mines, industries, metallurgy). The treatment of encrusting tuffs by combining them with other granular materials or hydraulic binders has been the subject of numerous research works and publications [4-16]. These works focused on the study of the mechanical performance of different types of tuffs over time by incorporating various proportions of additives, such as dune sand [4-6], calcareous sand [7-9], ash from date palm by-products [11] and Sandy Residues [15] to valorize these additives and the potential use of the formulated mixtures as materials for road construction. Overall, the results obtained indicate that an improvement in the mechanical properties of the mixtures (tuff + additive) is possible, and in some cases, treatment with a low percentage of hydraulic binder can give even better results.

In Algeria, the production of residual sewage sludge is estimated at more than 2 million tons per year [17], which is expected to increase with the construction and commissioning of new treatment facilities. The incineration of this sludge remains the least harmful disposal route for the environment and human health compared to other routes, such as those used in agriculture as fertilizer and soil amendments. The incineration of sewage sludge generates bottom ash (BA). This by-product can be valorized instead of disposed of in landfills. The utilization of by-products in civil engineering activities is an area that has been actively researched. For instance, Zabielska-Adamska [17] and Chang et al. [18] found that the physical and mechanical properties and the chemical composition of sewage sludge BA suggest its potential for sustainability applications related to civil engineering aspects. In addition, several other research works have shown that it can be used as an additive in the production of cement mortars and concrete [19-22], in the preparation of lightweight bricks [23], and in bituminous mixtures as filler [24].

This work is a continuation of research in the field of the valorization of local materials and industrial wastes. It aims to improve the mechanical strengths in compression and tension of encrusting tuff and its water sensitivity by adding sewage sludge BA. For this purpose, simple compression and indirect tensile tests were carried out on cylindrical specimens prepared from formulations composed of Tuff-BA and tuff-lime-BA.

## 2. Materials and Methods

### 2.1 Materials

This section focuses on presenting the geotechnical aspects of the materials utilized in the study. Table 1 summarizes the various characterization tests conducted and the associated standards for each test.

**Table 1** Different types of characterization tests

Types of Tests	Standard
Chemical analysis	NF P 15-461; BS 1377; NF P 94-048
Granular size analysis	NF P 94-056
Atterberg limits test	NF P 94-051
Methylene blue value test	NF P 94-068
Modified Proctor test	NF P 94-093
Immediate bearing index (IBI)	NF P 94-078

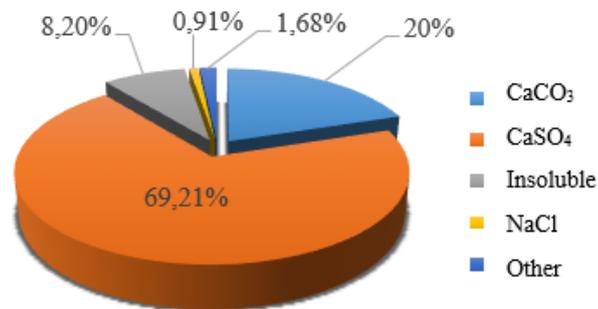
#### 2.1.1 Tuff

The tuff (see Fig. 1) used in this study was extracted from a deposit in the Ouargla region. It was approximately 758 km southeast of Algiers, Algeria. An arid climate characterizes this region.



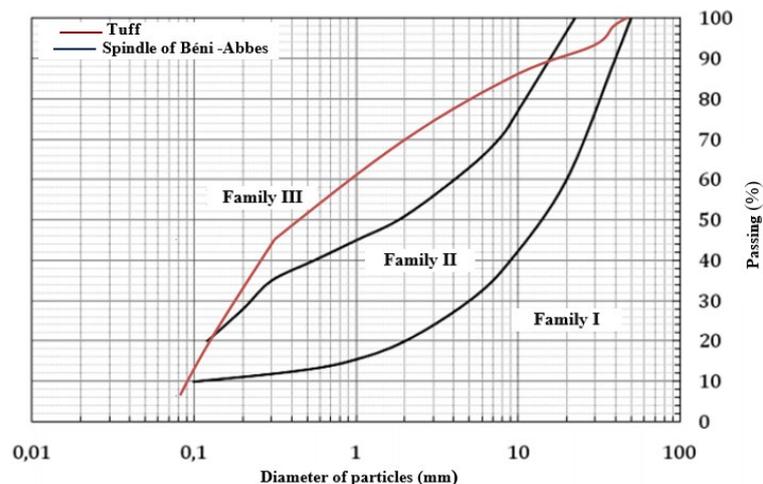
**Fig. 1** Sample of tuff extracted

The chemical analysis aims to quantify various components in the tuff material, including insoluble substances such as calcium sulfate ( $\text{CaSO}_4$ ), quartz, calcium carbonate ( $\text{CaCO}_3$ ), and salts. The result of the analysis, illustrated in Fig. 2, shows that  $\text{CaSO}_4$  predominates within the tuff material. This component constitutes about 70% of the overall composition of the material, which indicates the gypsum nature of the tuff.



**Fig. 2** Chemical analysis results

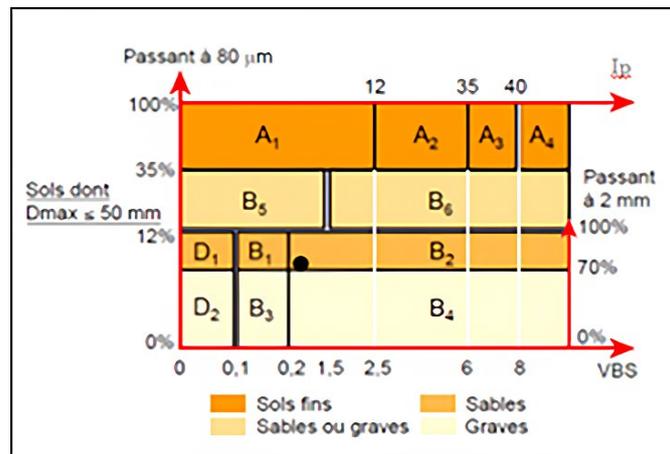
The granulometric analysis (Fig. 3) indicates that the tuff exhibits a maximum diameter ( $D_{\text{max}}$ ) of 31.5 mm, with a sand fraction ( $< 2$  mm) comprising approximately 70.17% of the total material. The fine content ( $< 0.80$  mm) constituted about 8.44%. The grain size curve falls outside the Saharan spindle of Beni-Abbès and is classified within family III, categorizing this tuff as fine material. Additional results from the geotechnical characterization are detailed in Table 2. According to the GTR1992 classification [25], the tuff under investigation classified as class B2, which is recognized as sandy soil (see Fig. 4).



**Fig. 3** Grain size distribution curves for tuff compared to the spindle of Beni-Abbès

**Table 2** Geotechnical characteristics of tuff

Parameter	Tuff
Dmax (mm)	31.5
% < 2 mm	70.17%
% < 80 µm	8.44%
Uniformity Coefficient: Cu (%)	11.25
Hazen Coefficient (curvature): Cc (%)	0.40
Limits of liquidity: WL	26.85 %
Limit of plasticity: Wp	not measurable
Blue value: VB (0/D)	0.93
Absolute density (gr/cm <sup>3</sup> )	1.16
Optimum water content: Wopm	12%
Maximum dry density γd (gr/cm <sup>3</sup> )	1.68
Immediate bearing index, IBI	69.14%



**Fig. 4** Classification of tuff according to GTR 1992

### 2.1.2 Sewage Sludge BA

As shown in Fig. 5, the sewage sludge sample was collected from the N'GOUSSA wastewater treatment facility in the Ouargla region. Initially, the sludge was incinerated in an open-air metal drum and subsequently in a muffle furnace, where it was subjected to a temperature of up to 800 °C for 45 minutes. Following the incineration process, the resulting bottom ash (BA) underwent a ball milling procedure for 45 minutes for each batch of 400 g. The resulting BA powder obtained is black, as illustrated in Fig. 6. The particle diameter of this material is less than 630 µm (Table 3), with approximately 69.7% of the particles measuring less than 80 µm.



**Fig. 5** Sewage sludge sample



**Fig. 6** BA sample

**Table 3** Particle size of BA powder

Diameter (mm)	Passing (%)
630 $\mu\text{m}$	100
315 $\mu\text{m}$	92.9
160 $\mu\text{m}$	89.8
80 $\mu\text{m}$	69.7

Several studies have revealed that the main components of BA are silica ( $\text{SiO}_2$ ), alumina ( $\text{Al}_2\text{O}_3$ ), lime ( $\text{CaO}$ ), ferric oxide ( $\text{Fe}_2\text{O}_3$ ), and magnesium oxide ( $\text{MgO}$ ). The proportions of these elements may vary depending on the initial compositions of the sludge and the incineration conditions, particularly the calcination time and temperature. These components commonly found in ordinary Portland cement can act as sources of hydration products and make BA an excellent pozzolanic material. While a specific mineralogical analysis of the BA used in this study has not been conducted, it is reasonable to assume that its composition aligns closely with findings reported in the existing literature (Table 4). More specifically, the ash composition of the BA in this study is comparable to that of sludge from a wastewater treatment plant in the Boumerdès region of northern Algeria [26]. This similarity arises from the wastewater treatment methods employed in both regions, suggesting that the pozzolanic properties of the BA may be similar as well.

**Table 4** Typical chemical composition of Sewage sludge BA

Content (%)	Algeria [26]	Egypt [27]	China [28].	France [28]	South Korea [23]
$\text{SiO}_2$	44.10	39.03	54.1	48.43	30.8
$\text{Al}_2\text{O}_3$	13.97	15.13	8.5	6.63	13.3
$\text{Fe}_2\text{O}_3$	12.23	17.05	4.6	6.73	0.36
$\text{CaO}$	11.79	5.80	14.8	15.43	47.0
$\text{MgO}$	2.75	1.93	1.5	1.73	4.67
$\text{Na}_2\text{O}$	0.74	0.43	4	5.13	0.16
$\text{K}_2\text{O}$	2.50	0.62	0.6	0.23	
$\text{P}_2\text{O}_5$	3.15	13.12	-	-	0.01
$\text{TiO}_2$	0.61	-	-	-	-
$\text{MnO}$	0.25	-	-	-	-
$\text{Cl}$	--	-	0.5	0.57	-
$\text{SO}$	-	4.04	2.8	0.47	2.28
Other	-	2.11	-	-	-

### 2.1.3 Lime

The lime used in this study is slaked lime ( $\text{Ca}(\text{OH})_2$ ), produced by the Saïda factory located in the western region of Algeria. It has a low concentration of oxide elements such as silicates ( $\text{SiO}_2$ ) and aluminates ( $\text{Al}_2\text{O}_3$ ) and a high concentration of basic elements such as free lime ( $\text{CaO}$ ). The chemical and physical properties of the lime are presented in Table 5.

**Table 5** Chemical and physical properties of Saïda extinct lime [29]

CaO (%)	MgO (%)	Fe <sub>2</sub> O <sub>3</sub> (%)	Al <sub>2</sub> O <sub>3</sub> (%)	SiO <sub>2</sub> (%)	SO <sub>3</sub> (%)	Na <sub>2</sub> O (%)	CO <sub>2</sub> (%)	CaCO <sub>3</sub> (%)	Over 90 μm (%)	Over 630 μm (%)	Specific density (g/cm <sup>3</sup> )
> 83,3	< 0,5	< 2	< 1,5	< 2,5	< 2,5	4,7 - 0,5	< 5	< 10	< 10	0	2

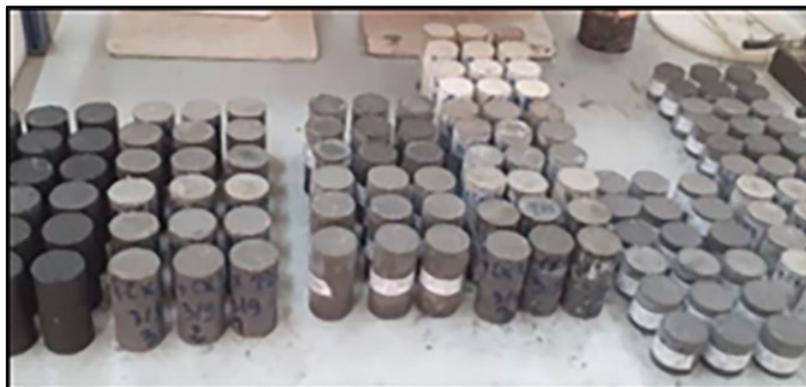
## 2.2 Methods

This experimental study focuses on developing compressive and indirect tensile strength and sensitivity to the water of tuff treated with sewage sludge BA and lime. Several mixture formulations were prepared to achieve this objective, as shown in Table 6. From these formulations, cylindrical specimens (Fig. 7) were made. For the compression testing, specimens with dimensions of H 10 Ø 5 cm (H is height and Ø is diameter) were utilized, in accordance with NF P 98-232-1, while specimens with dimensions of H 5 Ø 5 cm were employed for the indirect tensile testing, in accordance with NF P 98-232-3.

**Table 6** Different formulations prepared

Mixture	Tuff (%)	Lime (%)	BA (%)
Tuff	100	0	0
TL4	96	4	0
TBA4	96	0	4
TBA8	92	0	8
TBA12	88	0	12
TL4BA4	92	4	4
TL4BA8	88	4	8
TL4BA12	86	4	12

The specimens were statically compacted and stored under laboratory conditions at 25 ± 3 °C for two different curing periods. The short-term period of 7 days was selected based on guidelines from the French soil treatment manual, which indicates that this duration is sufficient to achieve acceptable strength levels for circulation on treated layers. In contrast, the long-term period of 180 days was chosen to evaluate the overall effectiveness of the treatment over an extended curing time, allowing for a comprehensive assessment of strength development. The crushing of the specimens was performed by hydraulic press at a constant speed of 1.6 mm/min. The final strength result was determined by calculating the average strength obtained from three specimens, ensuring statistical reliability in our findings.



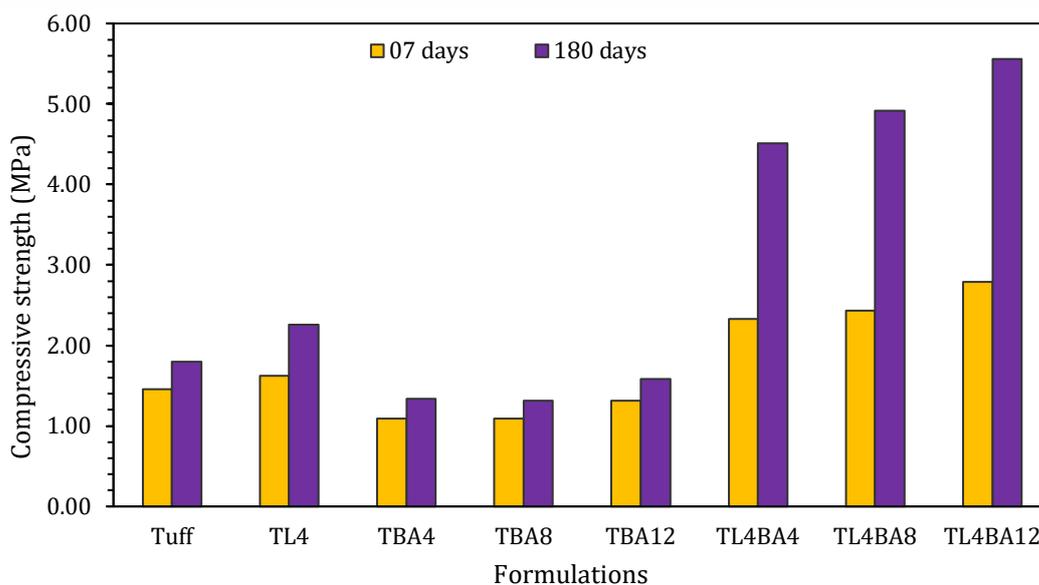
**Fig. 7** Type of specimens prepared

The compressive strength of the specimens prepared from the different formulations was initially observed for a compaction water content equal to that of the optimum Proctor modified " $W_{optm}$ " and at 95% of the maximum dry density of the tuff. Subsequently, water contents equal to  $W_{optm}-1$  and  $W_{optm} +1$  were evaluated for the formulations which gave better results. The evolution of the indirect tensile strength was observed only for the specimens prepared from formulations having the best compressive strength. The sensitivity to water was studied by measuring the compressive strength of test specimens aged 180 days and then immersed in water for 24 hours.

### 3. Results and Discussion

#### 3.1 Evolution of the Compressive Strength ( $R_c$ )

Compressive strength is considered an important index in selecting encrusting tuffs in Saharan pavement construction to appreciate the cohesion within the material. Fig. 8 illustrates the compressive strength of the specimens prepared from the adopted formulations at two ages: 7 and 180 days.



**Fig. 8** Compressive strength of different formulations

Initially, the histograms showed that the compressive strength ( $R_c$ ) at 180 days was significantly higher than the values observed at 7 days for all the tested formulations. This observation aligned with previous findings reported in the literature [1-5], which indicated that the compressive strength of tuffs and treated tuffs increases with age. The treatment of tuff with 4% lime (TL4) increased strength by approximately 11% at 7 days and 26% at 180 days. However, the  $R_c$  of specimens from formulations composed of tuff + Bottom Ash (TBA4, TBA8, and TBA12) is lower than that of tuff alone and TL4 for both ages. This indicated that adding ash alone to tuff does not effectively improve the strength of the material.

The mixed treatment of tuff with sewage sludge BA and lime, as seen in the formulations TL4BA4, TL4BA8, and TL4BA12, demonstrated a significant improvement in compressive strength as the percentage of added ash increased. This strength enhancement was observed in the short term (7 days) and long term (180 days). At 7 days, the compressive strength of the TL4BA12 formulation was approximately twice that of tuff alone. As the curing period extends to 180 days, the compressive strength of TL4BA12 further increases, becoming three times that of tuff alone. This indicated that the mixed treatment with Bottom Ash and lime has a positive and substantial impact on the mechanical performance of the tuff.

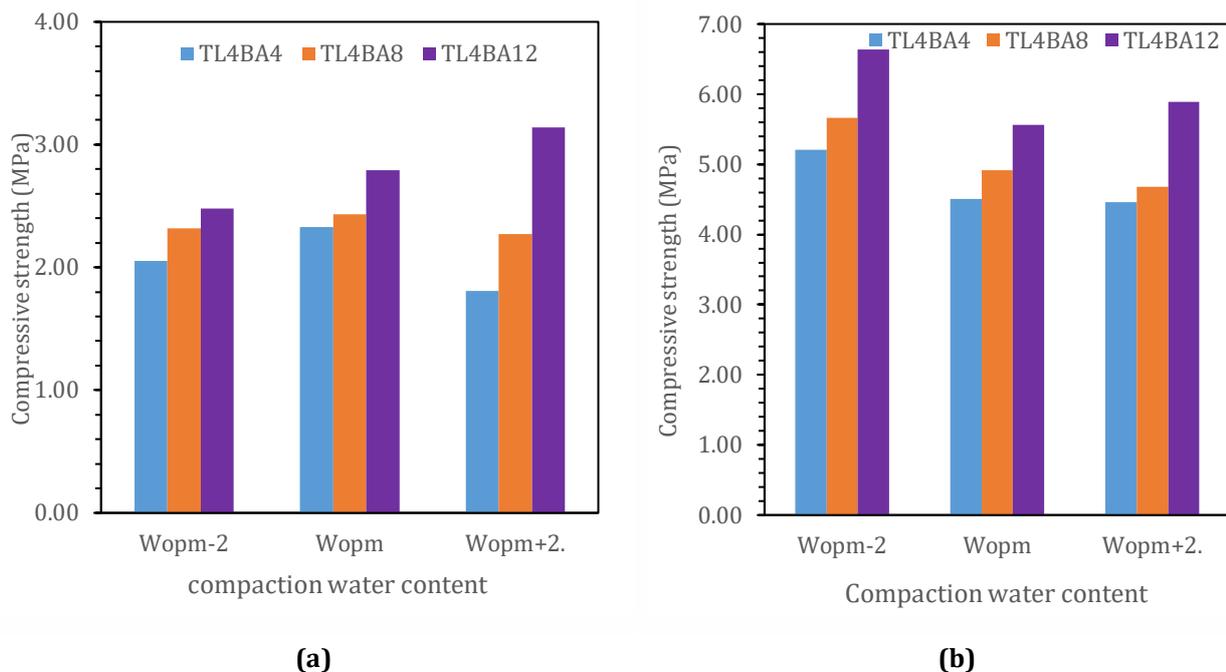
The obtained result supports the conclusion that the presence of lime in the mixture triggered the pozzolanic reaction of the ash, resulting in additional strength development. The pozzolanic reaction between lime and ash contributes to the formation of cementitious compound, such as calcium silicate hydrates (C-S-H) and calcium aluminate hydrates (C-A-H), indicating improved compressive strength.

From the perspective of using the prepared mixtures in Saharan roads, and according to the Algerian road specifications established by Struillou and Alloul (cited by Goual [8]), which consider compressive strength ( $R_c$ ) as one of the selection criteria for road materials, treated tuffs based on sewage sludge ash and lime, particularly

formulations TL4BA8 and TL4BA12, can be used in the base layer, as the recorded strength exceeds 2.5 MPa. In contrast, untreated tuff remains limited to the foundation layer.

### 3.2 Effect of Compaction Water Content on Compressive Strength

The mechanical strength of tuffs and treated tuffs is often affected by the amount of water added during the compaction process. In this study, MORSLI (2007), focusing on the hardening of tuffs, demonstrated the existence of an optimal water content for compaction that is lower than that of Proctor, ensuring optimal hardening and, therefore, better compressive strength. In this context, a series of specimens were prepared from the formulations TL4BA4, TL4BA8, and TL4BA12, which exhibited superior strength. These specimens were compacted using three different water contents:  $W_{0pm-2}$ ,  $W_{0pm}$  (optimum Proctor water content), and  $W_{0pm+2}$ . Fig. 9 illustrates the variation in compressive strength according to the compaction water content of the specimens at 7 and 180 days for the formulations TL4BA4, TL4BA8, and TL4BA12.



**Fig. 9** Compressive strength according to the compaction water content for the formulations TL4BA4, TL4BA8, and TL4BA12 (a) At 7 days; (b) At 180 days

#### At 7 days (Figure 9-a)

The trend of strength improvement with the incorporation rate of BA was observed regardless of the compaction water content of the specimens, with the highest strength recorded for the TL4BA12 formulation. For the two water contents,  $W_{0pm-2}$  and  $W_{0pm}$ , the strengths of the formulations TL4BA4 and TL4BA8 were higher than those recorded for the same formulations at  $W_{0pm+2}$ . However, the strength of TL4BA 12 was higher at  $W_{0pm+2}$ . This illustrates the existence of an appropriate water content proportional to the rate of ash added, providing better strength.

#### At 180 days (Figure 9-b)

In the long term, the TL4BA12 formulation exhibited the best strength. The strength of this formulation reached its maximum value when using the lowest water content of  $W_{0pm-2}$ . This is contrary to what was observed in the short term, where the maximum strength was associated with the higher water content at  $W_{0pm+2}$ . Indeed, the observed difference in strength between the short-term and long-term can be attributed to the contribution of suction, which was closely linked to the initial water content. In the long term, the lower initial water content ( $W_{0pm-2}$ ) resulted in higher suction. This increased suction contributed to the improvement of the mechanical strength of the material. In contrast, in the short term, the higher water content ( $W_{0pm+2}$ ) may lead to reduced suction and a different response in terms of mechanical strength.

### 3.3 Evolution of the Indirect Tensile Strength (RTB)

For treated soils, the direct tensile strength ( $R_t$ ), where  $R_{tb} = 0.8 R_t$ , is one of the parameters considered to determine the appropriate thickness and design requirements for the subgrade soil, ensuring its stability and long-term performance. The evaluation utilized the indirect tensile (Brazilian) test on cylindrical specimens by applying a load along two opposite generators. The indirect tensile strength ( $R_{tb}$ ) was observed for the three formulations with the highest compressive strength. From Fig. 10, it is observed that the evolution of the indirect tensile strength of the tuff follows a similar trend to the compressive strength ( $R_c$ ) for the tested formulations. The effect of the mixed treatment with BA and lime on indirect tensile strength was visible for 7 and 180 days, increasing indirect tensile strength with the rate of ash incorporation. The TL4BA12 formulation recorded the highest strength among the formulations tested. At 7 days, the indirect tensile strength of the TL4A12 formulation was approximately four times that of tuff alone, and it was more than twice at 180 days.

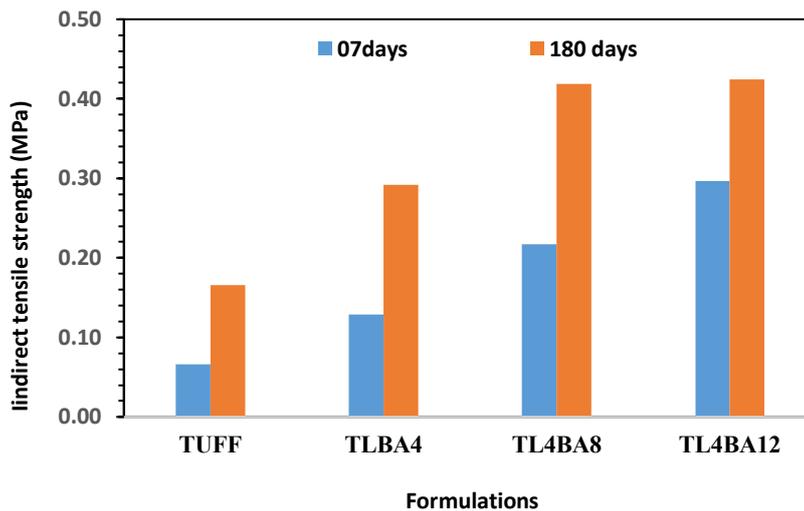
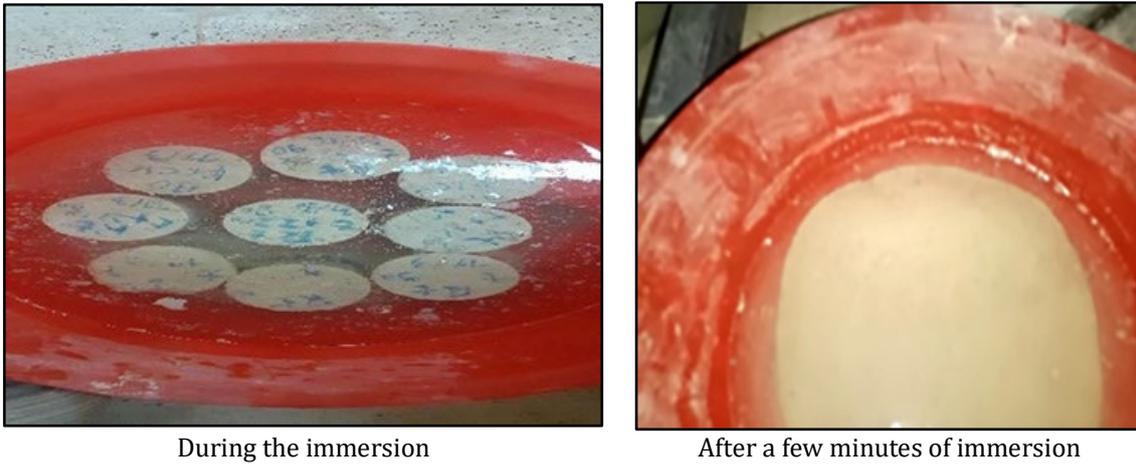


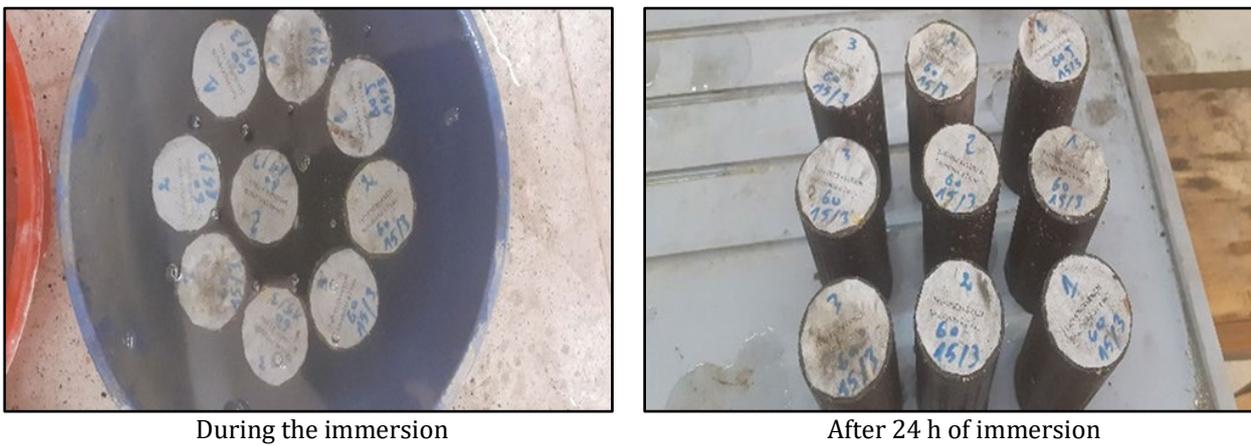
Fig. 10 Indirect tensile strength for the formulations TL4BA4, TL4BA8, and TL4BA12

### 3.4 Sensitivity to Water

Cohesion of the tuffs decreases with the increase in the degree of saturation, and it disappears completely at total saturation. This disadvantage limits their use in humid zones. To assess the water sensitivity of the treated tuff, cylindrical specimens were produced from the formulations TL4BA4, TL4BA8, and TL4BA12. The specimens were stored for 180 days under laboratory conditions and then immersed in water. Fig. 11 shows that the specimens made from tuff are completely dissolved when immersed in water within 8 to 10 minutes, indicating their high sensitivity to water. In contrast, specimens made from the treated tuff formulations (TL4BA4, TL4BA8, and TL4BA12) remained intact after 24 hours of immersion, as shown in Fig. 12, demonstrating their enhanced resistance to water-induced deterioration.



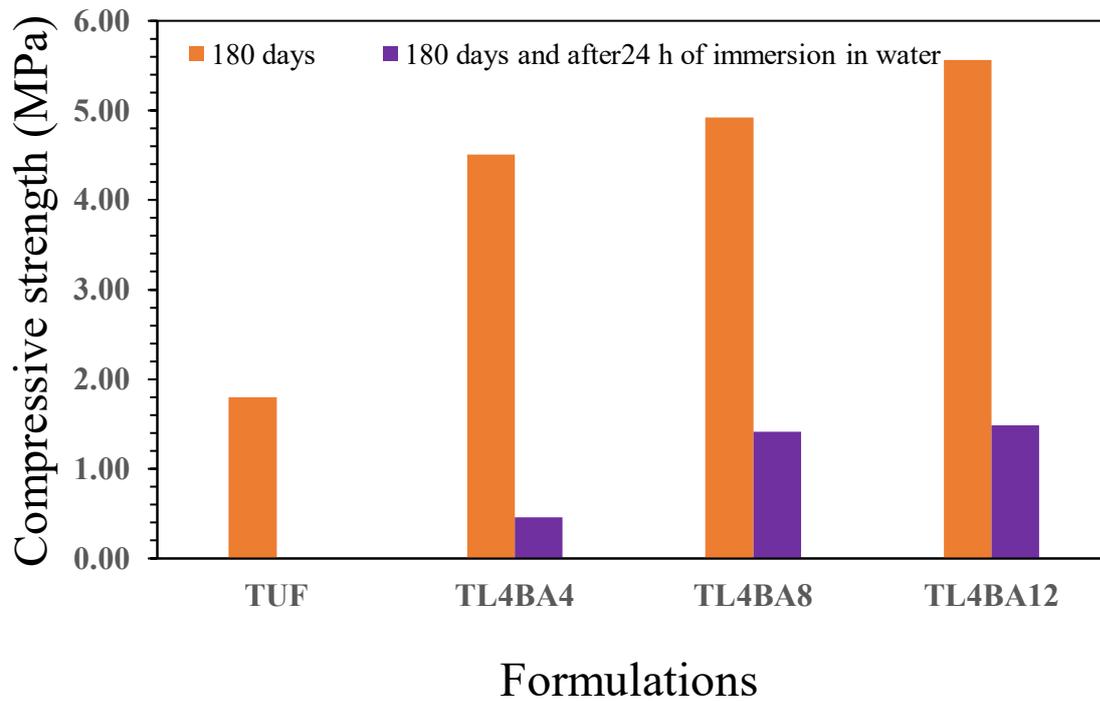
**Fig. 11** Specimen prepared from tuff alone and conserved for 180 days, then immersed in water



**Fig. 12** Specimen prepared from formulation TL4BA4, TL4BA8, and TL4BA12, and conserved for 180 days, then immersed in water for 24 h

Fig. 13 presents the compressive strengths of the specimens tested after 180 days of conservation followed by 24 hours of immersion in water, as well as those not immersed. The results indicate that the conservation of specimen for 180 days, followed by immersion in water for 24 hours, reduced the strength of the formulations TL4BA4, TL4BA8, and TL4BA12 compared to those not immersed. However, this strength remains appreciable considering the highly water-sensitive nature of tuff, which exhibits zero strength after immersion.

The maximum compressive strength ( $R_c$ ) value is approximately 1.5 Mpa, obtained from the formulation TL4BA12. This result demonstrates that by adding ash and lime to the tuff, the mixture benefits from improved cohesion and mechanical strength, which enhances the bonds between the material particles. These rigid bonds created by the pozzolanic reaction provide better stability and resistance to the effects of water.



**Fig. 13** Compressive strength of specimens from the mixed treatment of tuff Conserved for 180 days, then immersed in water for 24 h

#### 4. Conclusion

This paper's main objective is to improve the mechanical strength of encrusting tuff extracted from the Ouargla region in Algeria. The focus is on enhancing both compressive strength and indirect tensile strength, as well as reducing its sensitivity to water, to expand its use in the construction of Saharan roads. This is achieved through mixed sewage sludge (BA) and lime treatment. Based on the obtained results, the following conclusions can be drawn:

- The combined treatment of tuff with sewage sludge BA and lime results in a significant increase in both compressive strength ( $R_c$ ) and indirect tensile strength ( $R_{tb}$ ) in both the short-term (7 days) and long-term (180 days). The optimal formulation, containing 12% sewage sludge BA and 4% lime (TL4BA12), achieves maximum strength. After 180 days, the  $R_c$  of TL4BA12 is three times greater than untreated tuffs, and the  $R_{tb}$  is approximately four times greater.
- The existence of an appropriate compaction water content, different from Proctor's optimum water content, gives better simple compressive strength for the treated tuff.

The study of water sensitivity reveals that the specimens prepared from the treated tuff remain intact after being immersed in water for 24 hours. Furthermore, these specimens exhibit significant compressive strength, with the TL4BA12 formulation reaching the highest value at 1.48 MPa. Conversely, specimens prepared from tuff alone dissolve rapidly within minutes.

From the perspective of using treated tuff in Saharan pavements, and according to the Algerian road specifications established by Struillou and Alloul, treated tuff made from sewage sludge ash and lime, particularly formulations TL4BA8 and TL4BA12, can be used in the base layer, as the recorded compressive strength ( $R_c$ ) exceeds 2.5 MPa. In contrast, untreated tuff is limited to the foundation layer.

Although the study showed promising results regarding improving the mechanical properties of tuff treated with sludge ashes from sewage treatment plants, an environmental impact study, including the leaching of heavy metals, must be carried out to ensure sustainable and responsible use.

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## Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Author Contribution

All authors contributed to the study conception and design. The authors confirm contribution to the paper as follows: **study conception and design:** Abderrezak Khellou, Lokmane Abdeldjouad, Abdessamed Mokhtari, Mohammed Dehmani; **analysis and interpretation of studies:** Abderrezak Khellou, Lokmane Abdeldjouad, Abdessamed Mokhtari, Mohammed Dehmani, Muhammad Aminuddin Khalid, Aziman Madun; **draft manuscript preparation:** Abderrezak Khellou, Muhammad Aminuddin Khalid, Firdaus Md Dan, Aziman Madun. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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