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Enhancing Tuff Properties with Hydraulic and Organic Binders for Advancements in Desert Pavement Technology

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Abstract:

This study aims to valorize local materials to meet the needs of regions deficient in noble materials. The study investigates the effects of processing a tuff from Algeria's Saharan region. Two types of binder were used: hydraulic (cement and/or lime at 3% and 6%) and organic (lignosulfonate at 0.5% and 1%). The effects were observed in both immediate stability (compaction and bearing capacity) and mechanical performance (compressive and shear strength). The results indicate that 1) some raw tuff characteristics are mediocre and do not meet the requirements of various specifications, particularly mechanical performance and sensitivity to water; 2) soaked and unsoaked California Bearing Ratio (CBR) significantly improved after treatment; 3) the treatment with cement or lime-cement considerably reduced the tuff's sensitivity to water; 4) the treatment significantly improves cohesion and even the friction angle, but with smaller gains with increasing binder quantities; and 5) in all tests conducted, cement performed better than the other binders used. Thus, tuff treated with 6% cement or a 6% cement-lime combination may serve as a base or sub-base layer in Saharan road subjected to high traffic volumes and in areas with high rainfall.

Key words: Tuff, Local materials, Saharan road technology, Soil treatment.

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1. Introduction

The Algerian Sahara has seen a significant expansion of road infrastructure as a result of socio-economic development, increased industrial activity (particularly following the discovery of the first oil fields), Saharan tourism, and the influx of new markets. This created a high demand for pavement materials. Initially, European road construction techniques were used, and only materials meeting strict geotechnical criteria (particle size, hardness, cleanliness, or fine grain quality) were accepted. As the demand for pavement construction materials grew, the requirement to use specific materials, particularly "noble" gravels, could not be met, as these materials were scarce or non-existent in some areas. Researchers, engineers and technicians were forced to innovate, leveraging the Saharan region's unique characteristics (climate, lack of high-quality aggregates, local materials and low traffic). They searched for a different technique with its own standards and experience, which opened up a wide range of pavement materials, including fine materials, for cost-effective road construction. A Saharan road construction technique, unique to Saharan regions, was born (Omar et al., 2022).

Tuffs are among the most abundant materials, covering almost half of Algeria's surface area (Daheur et al., 2025). In some regions with abundant aggregates, it is used as substitute materials to conserve noble materials; in others, particularly in Saharan regions, it is the only source of road materials (Bouacha et al., 2023). Overall, its use in its raw form has been positive. However, with increased traffic, particularly during the winter when their water content rises, pavements have shown problems with cracking. However, research into specific treatment processes for these materials to improve their physico-mechanical properties remains one of the most appropriate solutions for generalizing their use in a variety of climatic conditions in pavement bodies with medium to heavy traffic (Jadoon et al., 2023; Komurlu, 2026).

Several techniques have been developed to improve the mechanical properties of tuff, including cost-effective stabilization and reinforcement methods. One technique is to combine tuff with other materials that have a high proportion of coarse constituents but a low proportion of fine material (e.g. gravel or sand) (Akacem et al., 2020; Omar et al., 2022). Another recent technique is to treat tuff with hydraulic binders such as cement and lime (Balegh et al., 2020; Daheur et al., 2023; Demdoum et al., 2021; Kamiloğlu et al., 2024; Khellou et al., 2024).

The Ghardaïa region in the Algerian Sahara is home to a large tuff deposit. This research aims to valorize these local materials and study the influence of different treatment methods using hydraulic binders (lime and/or cement) or organic binders (lignosulfonate) on the mechanical performance of the tuff.

The aim of this study is to generalize the application of tuff in different layers of Saharan road pavements exposed medium to high traffic volumes and moderate rainfall (to ensure the safety of this type of construction in the critical event of sudden rainfall, which the Ghardaïa region was subjected to, for example, during the floods of 2008). The objective was to enhance the mechanical performance and increase the material's water resistance. The experimental study employed various tests, including Modified Proctor, California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS) before and after water immersion, and direct shear tests. Thus, the primary objectives can be summarized in two essential points: (1) improvement of material properties and (2) profitability. It is imperative (1) to enhance the utility of crusted tuffs that are initially inadequate for

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high-traffic pavements, and (2) to conserve high-quality road material resources, mitigate expensive transportation that disrupts the local road network, decrease pavement layer thicknesses, and reduce the overall costs of road projects.

2. Materials

2.1 Base material

The selected material is tuff from the Ghardaïa region, located 600 km south of Algiers (Figure 1). This region has a Saharan climate, characterized by hot summers with extremely high temperatures particularly during the day, and temperate winters. It is characterized by large temperature fluctuations between day and night, as well as between summer and winter. The hot season begins in May and lasts until September (Miara et al., 2022). Table 1 summarizes the geotechnical and mineralogical identification tests of the tuff sample. Chemical analysis was carried out using X-ray fluorescence. Figure 2 shows the grading curve of the studied material. The results indicate that the tuff primarily consists of gypsum and limestone ($CaCO_3$ + $CaSO_4$; $2H_2O$ = 69.6%), exhibiting a diverse particle size distribution. The 0/80µm fraction accounts for about 27%. The assessment of the quality of the fine material indicates that the studied material consists of non-clay gypsum and limestone fine material and does not exhibit any plasticity.

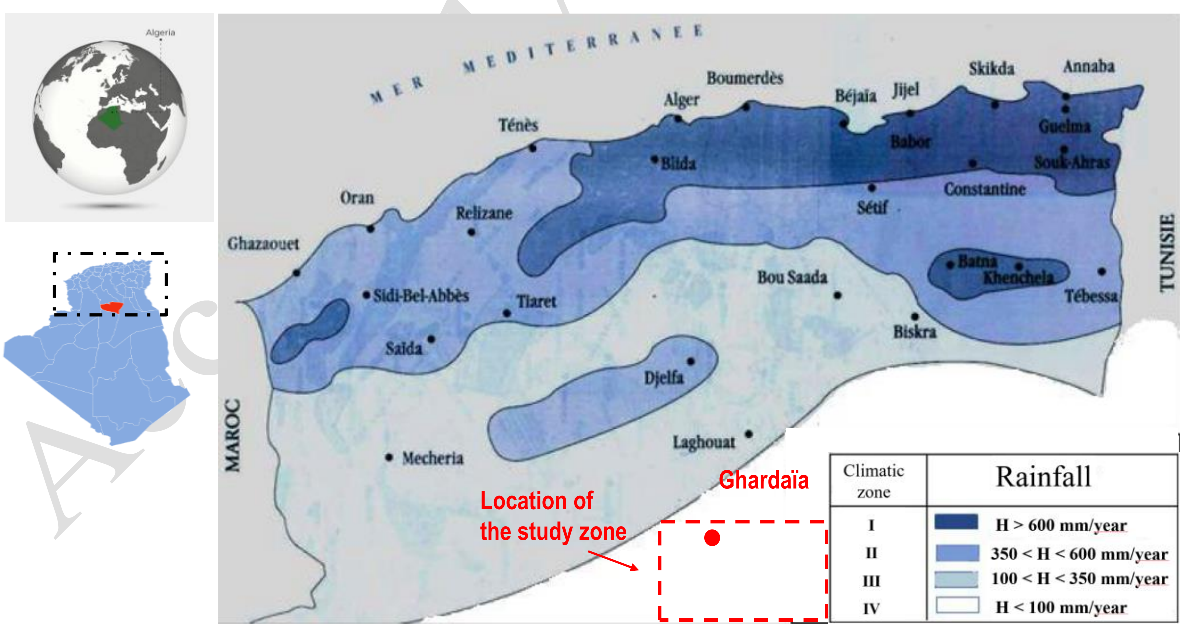

Figure 1. Location of study area.

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Table 1. Results of geotechnical and mineralogical identification tests on tuff from the Ghardaïa region.

Test	Results
Particle size analysis	
D_{10}	0.009 mm
D_{30}	0.09 mm
D_{60}	0.6 mm
Uniformity Coefficient (Cu)	66.66 %
Coefficient of Curvature (Cc)	1.5 (-)
Atterberg limits	
w_l	28.5 %mas
w_p	Not measurable
I_p	Not measurable
Sand equivalent test	9.65 %
Methylene blue test	0.35 (-)
Compaction characteristics	
Maximum dry density γ_{dmax}	1.79 g/cm^3
Optimum moisture content	11.85 %mas
Bearing capacity	
CBR immediate	42 %
CBR after 4 days of immersion	35 %
Unconfined Compressive Strength (UCS)	2.5 MPa
Chemical analysis by X-ray fluorescence	
Gypsum ($CaSO_4$; $2H_2O$)	52.61 %mas
Calcium carbonate ($CaCO_3$)	17.02 %mas
Silica (SiO_2)	9.29 %mas

Based on the Saharan Road Technique (SRT) (Fenzy, 1966), this material is suitable for pavement applications due to the following criteria: fine content (27% < 30%), IP is negligible (< 13%), γ_{dmax} = 1.79 g/cm^3 > 1.7 g/cm^3, ICBR immediate = 42% > 40%, UCS = 2.55 MPa > 2 MPa. SRT categorizes the analyzed material as gypsum-limestone tuff, family III, with a grading curve above the spindle of specification. According to the specifications presented in Algeria by Struillou and Alloul 1984, the use of tuff for pavement layers is limited to the base layer in climate zone IV, noted for its low traffic and the necessity for careful management during rainy seasons. In addition, based on the classification of fine soils in the Technical Road Guide (GTR) (GTR, 1992), the sample can be categorized as B5, which denotes "sandy or gravelly soils with fines."

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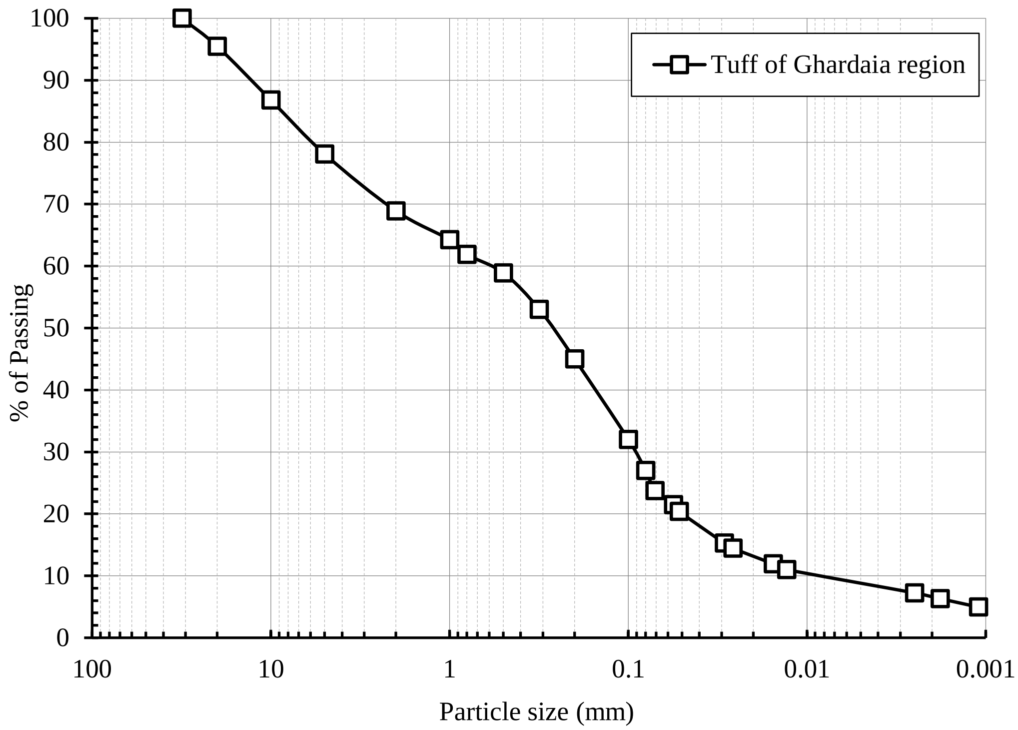

Figure 2. Grading curve of tuff from Ghardaïa region

2.2 Binders

2.2.1 Cement and lime

The cement used is a Portland cement designated CEM II/A 42,5 N. The lime used is hydrated lime. The percentages of binders used (3% and 6 %) are within a reasonable economic range. The proportion of lime for the mixed treatment known as (CLMix) is twice that of cement. Table 2 summarizes the results of the chemical analysis for the cement and lime used. The CaO content of the lime (52.5%) exceeds 50%, and MgO (0.312%) is less than 6%. The lime used therefore meets the specifications of the AFNOR standard for road construction (NF P 98-101 1991).

Table 2. Chemical composition of cement and lime used.

Features	***Formula***	***Cement (%)***	***Lime (%)***
Calcium oxide	CaO	41.088	52.503
Magnesium oxide	MgO	0.791	0.312
Sodium oxide	Na_2O	0.710	0.698
Alumina	AL_2O_3	1.909	0.183
Silica	SiO_2	8.927	-
Phosphorus pentoxide	P_2O_5	0.113	0.022

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Sulfur trioxide	SO_3	1.792	0.077
Potassium oxide	K_2O	0.311	0.029
Iron oxide	Fe_2O_3	1.294	0.087
Strontium oxide	SrO	0.040	0.007
Chlorine	Cl	0.310	0.412

2.2.2 Lignosulfonate

Lignosulfonates are surface-active amino derivatives, resins combined with hardeners or plant extracts of the lignosulfonate or sulfonated lignin type. They are by-products of wood pulp production and are renewable, biodegradable and non-toxic, but readily soluble in water. These additives are supplied in liquid, dilutable paste or dispersible powder form. Table 3 shows the characteristics of the lignosulfonate used in the study. Given the current high cost of lignosulfonates, low doses of 0.5%mas and 1%mas of the total tuff weight were selected.

Table 3. Physical and chemical properties of the lignosulfonate used.

Physical condition	Color	pH	Density	Solubility in water	Chlorine content	Dry extract	Solidification temperature
Liquid	Brown	9.5	1.19 g/cm³	Soluble	< 1 g/l	40 %	0 °C

3. Methods

In this study, the tuff was treated with two types of binders, one hydraulic (cement and/or lime) and the other organic (lignosulfonate), to determine the best technical-economic option for a road project. The formulation study was carried out using the flow chart shown in Figure 3.

3.1 Compaction and bearing capacity tests

The Modified Proctor Test was performed in accordance with standard ASTM D1557. Its purpose is to determine the best soil compaction conditions for maximum compactness, cohesion, and stability while maintaining a standardized energy intensity. The CBR test is performed according to ASTM D1883 (immediately after compaction and four days of immersion). The test consists of punching into CBR mold specimens with water contents equal to the Modified Proctor test's optimum. To calculate the CBR index, first plot the curves representing the piston pressure as a function of piston indentation, then CBR index = Sup {P (2.5) / 0.68, P (5) /1.02}, where, P (2.5) and P (5) represent the piston pressures at indentations of 2.5 and 5 mm, respectively.

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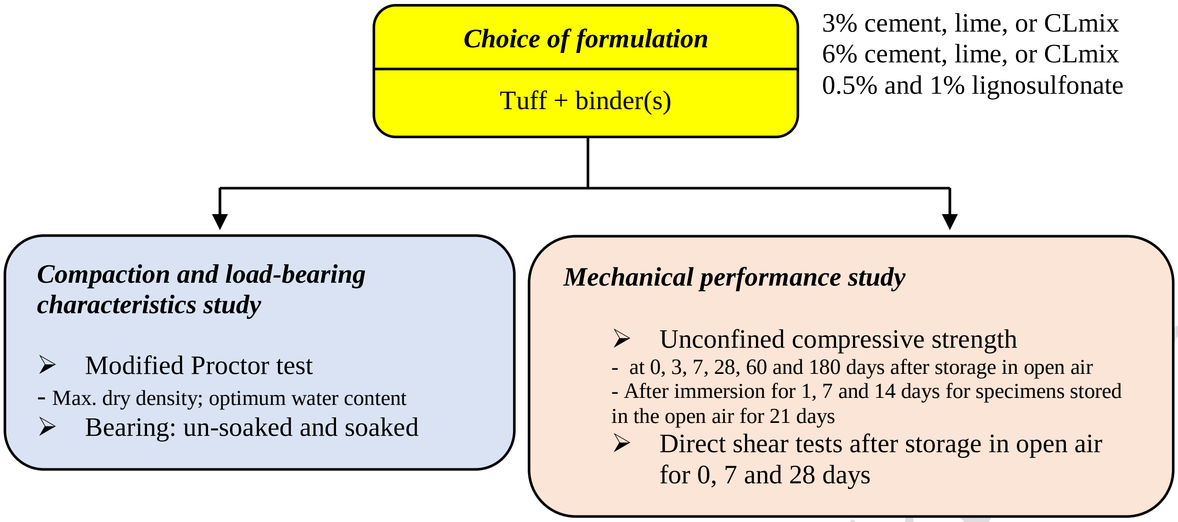

Figure 3. Flow chart for conducting a formulation study.

3.2 Mechanical testing

3.2.1 Compressive strength

Two series of samples were prepared to investigate the effect of treatment on compressive strength. The first is intended to demonstrate the evolution of strength as a function of specimen storage time, both with and without treatment. The specimens in this series were stored in open air (T= 25∓ 2 °C) for 0, 3, 7, 28, 60, and 180 days. The second series aims to investigate the effect of different binders on immersion resistance. The specimens in this series were kept in the open air (T= 25∓ 2 °C) for 21 days, then immersed in water for 1, 3, and 7 days (~~Chauvin, 1984;~~ Ghrieb et al., 2014). All cylindrical specimens (∅= 5 cm, H=10 cm) were prepared with the modified Proctor water content and a theoretical compactness of 98% of the maximum Proctor density. The preparation of the specimens consists of three phases: 1) preparation of a homogeneous mixture of tuff + binder + water, 2) static compaction and 3) demolding and storage in the open air. Compaction is carried out with a CBR press and double-piston molds at a rate of 1.27 mm/min. The material is compressed in a single operation in the mold (Gueddouda et al., 2010). At the end of the storage time for the first series is completed, and after each immersion time for the second series, the specimens are subjected to compressive stress parallel to the cylinder axis using a CBR press at a constant speed of 1.27 mm/min until failure, and readings are taken (ASTM D5102). The results for each test are the average of three replications.

3.2.2 Shear strength

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The direct shear test (ASTM D3080) was performed on samples treated with different binders after outdoor storage for 0, 7, and 28 days at T= (25∓ 2 °C) was carried out to observe the impact of treatment on the evolution of cohesion (C) and friction angle (φ). The test samples were statically compacted using a CBR press set to the optimum water content of the modified Proctor test and a theoretical compaction of 98%. The dimension of the shear box are 6x6x3 cm^3. The normal stresses used are 100, 200, and 300 kPa.

4. Results and discussion

4.1 Influence of treatment on compaction and load-bearing characteristics

Figure 4 shows the results of the Modified Proctor test. These results demonstrate that treatment with hydraulic binders increases the optimum water content. This increase is proportional to binder dosage, peaking at 14.4 % when treated with 6 % lime. The curves are therefore shifted to the right. Furthermore, the maximum dry density decreases. The increase in optimum water content is mainly attributed to the higher proportion of fine particles introduced by cement and/or lime. These fine fractions exhibit a large specific surface area, resulting in an increased water absorption capacity. Furthermore, the incorporation of binders requires additional water to facilitate hydration and pozzolanic reactions (Chompoorat et al., 2021). Similar trends have been widely reported for hydraulically stabilized soils (Regasa et al., 2023; Wassie et al., 2024). Concurrently, the decrease in maximum dry density can be explained by microstructural changes induced by binder addition. The formation of cementitious bonds, combined with clay flocculation and aggregation, leads to a more open soil fabric that restricts particle rearrangement under compaction energy, thereby reducing the achievable dry density (Consoli et al., 2007; Du et al., 2014). This effect is particularly pronounced in lime-treated soils, where cation exchange and pozzolanic reactions prevail during the early stages of stabilization.

The results also show a flattening of the Proctor curve, which is most pronounced with lime treatment (reduced sensitivity of maximum dry density to optimum water content). This behavior reflects the development of a more stable and less moisture-sensitive soil structure, which is typically associated with lime stabilization and has been widely reported in recent studies on lime-treated clays (Ahmadullah et al., 2024).

Contrary to hydraulic binders, lignosulfonate treatment lowers the optimum water content (from 12.85% to 11.20 % in the case of 1% lignosulfonate treatment), increases the maximum dry

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density (from 1.79 g/cm^3 to 1.84 g/cm^3), and does not affect the shape of the curves. These results suggest an improvement in compaction efficiency without significant alteration of the soil fabric. The unchanged shape of the Proctor curves further indicates that lignosulfonate primarily acts through physical mechanisms, such as particle lubrication and improved packing, rather than through chemical reactions that significantly modify the soil structure.

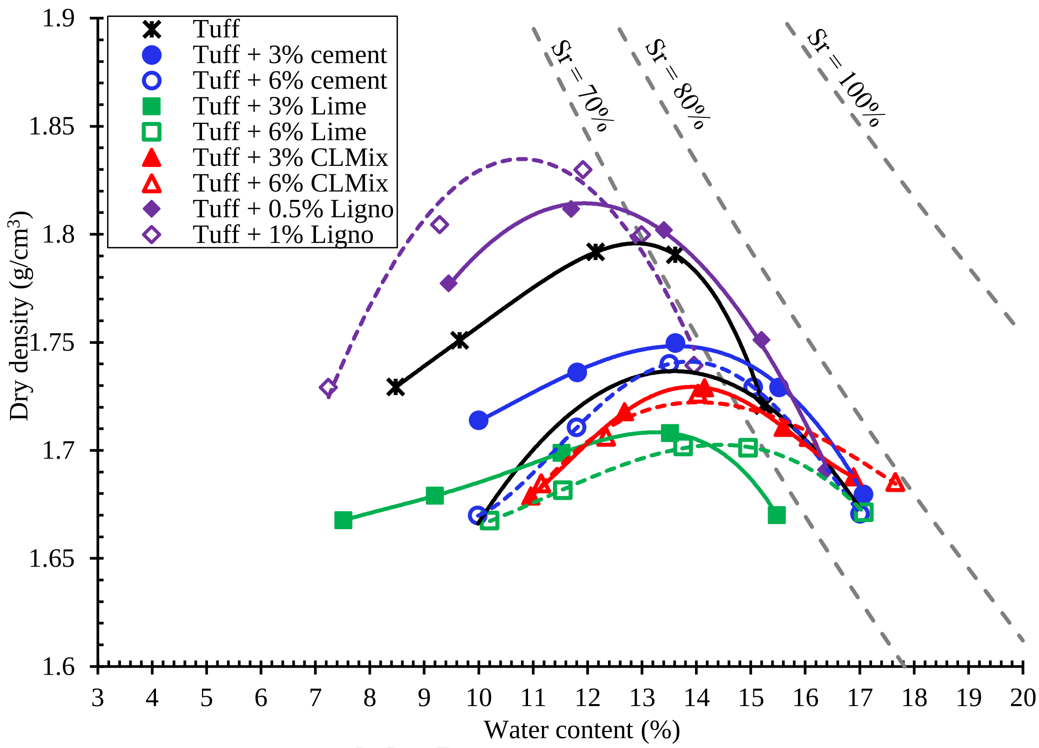

Figure 4. Modified Proctor curve for tuff from the Ghardaïa region, with and without treatment.

Table 4 lists the different compaction and bearing capacity characteristics of studied samples both immediately and after 4 days of immersion. Figure 5 shows the ICBR gains immediately and after immersion, as expressed by the following relationship:

$$G = ((CBR_{AI} - CBR_{BI})/CBR_{BI}) \times 100 \qquad (1)$$

where, CBR_{BI} is the CBR index before treatment and CBR_{AI} is the CBR index after treatment.

Table 4. Summary results of compaction characteristics and bearing capacity.

Tests	***Modified Proctor***		***Bearing***	
Formula	Optium Proctor water content	Maximum Proctor density γ_{dmax} (g/cm^3)	*CBR Unsoaked (%)*	*CBR soaked* (%)

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	w_{MPO} (%mas)			
Tuff	12.85	1.79	42	35
Tuff + 3% lime	13.34	1.71	49	41
Tuff +6% lime	14.35	1.70	50	43
Tuff +3% cement	13.45	1.75	55	96
Tuff +6% cement	13.86	1.74	60	130
Tuff +3% CLMix	13.95	1.73	52	81
Tuff +6% CLMix	14.10	1.73	57	94
Tuff +0.5% lignosulfonate	12.20	1.81	51	42
Tuff +1% lignosulfonate	11.20	1.84	64	49

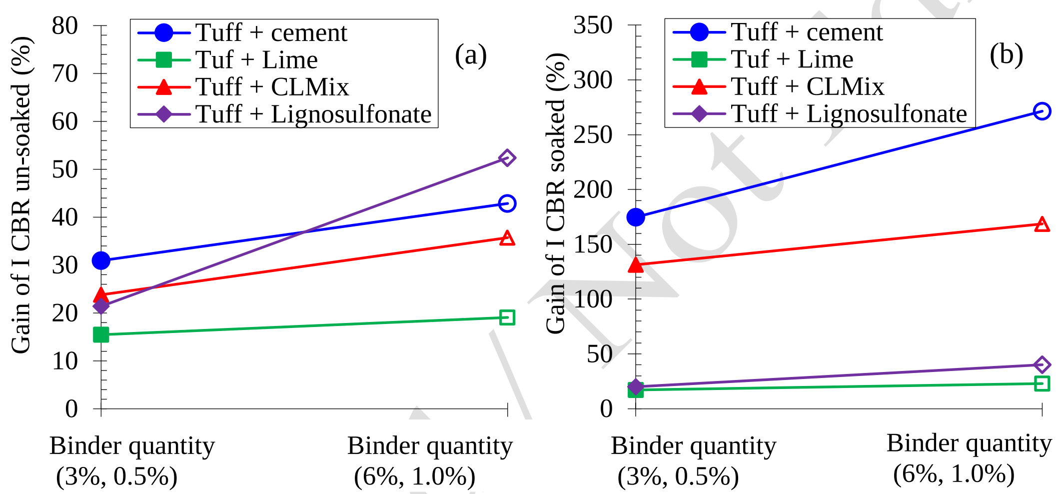

Figure 5. Gain of (a) ICBR unsoaked and (b) ICBR soaked versus the binder amount.

These results show that the dosage of hydraulic binders has a direct and positive effect on the CBR index, particularly after immersion in the case of cement and CLMix treatments. For example, after treatment with 6% cement, the soaked CBR index increased by more than threefold (a gain of 271%), rising from 35% to 130% (Fig.6b). Treatment with 1% lignosulfonate significantly improves the unsoaked CBR index (a gain of 53%). The marked improvement in bearing capacity following cement treatment can be attributed to the low clay content of the sample (approximately 6%), which facilitates the coating and binding of grains by hydrated cementitious compounds, leading to the formation of increasingly numerous and stronger interparticle bonds. In contrast, in the case of lime treatment, the low clay content limits the occurrence of cation exchange reactions between alkali cations (Na^+, K^+) and calcium ions (Ca^{2+}), resulting in no significant improvement in bearing capacity. These findings are consistent with (Abu-Farsakh et

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al., 2015; Firoozi et al., 2017; Yong et al., 2007). The reduction in CBR soaked compared to CBR unsoaked in the case of lignosulfonate treatment (a decrease of approximately 25% with 1% lignosulfonate treatment) is explained by the water sensitivity of lignosulfonate, which limits its effectiveness in conditions where moisture exposure is significant.

4.2 Influence of treatment on compressive strength

Figure 6 illustrates the evolution of the compressive strength of the samples as a function of curing time. For comparative purposes, the evolution of the compressive strength of gravel treated with 4% cement is also presented in this figure. The curves are very similar. The evolution of the compressive strength is rapid in the first few days of storage (0 to 7 days) but weakens after 28 days. The results also show that the water content changes are very similar independent of the treatment: it decreases rapidly during the first storage phase (0-7 days), followed by a slow decrease. Water loss favors compressive strength. Furthermore, the treatment effect was immediately apparent from the beginning of the treatment, resulting in a greater gain. The sample treated with 6% cement retained good compressive strength throughout the storage period; at 180 days, the gain was 90%. Figure 6 confirms that treatment with hydraulic binders and lignosulfonate significantly improves the mechanical properties of tuff, and that curing time further enhances these improvements. However, this enhancement appears to be less pronounced than that observed in gravel treated with 4% cement, particularly for curing periods exceeding two months.

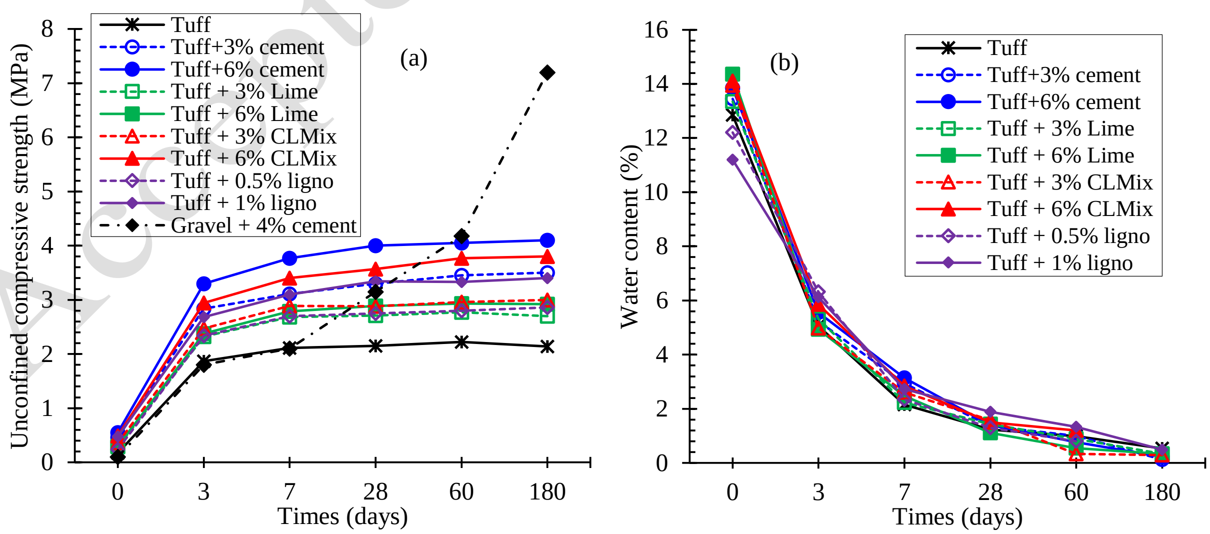

Figure 6. Evolution of (a) compressive strength and (b) water content as a function of shelf life.

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4.3 Influence of immersion on compressive strength

During the immersion of the test specimens, we discovered that the untreated specimens showed a very high sensitivity of the tuff to imbibition because the structure of the tuff was destroyed immediately. Water comes in contact with the walls, destroying them instantly. Water penetrates the specimens and destroys the interior. Specimens treated with lignosulfonate are destroyed quickly (after 2 minutes), whereas specimens treated with 3% lime are destroyed after 24 hours of immersion. Thus, treating the tuff with lime alone or with lignosulfonate does not improve its water sensitivity. Because lignosulfonates are water soluble, rain can wash them away or cause them to sink too deeply into the pavement, rendering them ineffective. In fact, a single downpour can significantly reduce or eliminate their effectiveness. Figure 7a and 7b) show the variation of UCS and resistance to immersion (R_{imm}) as a function of immersion time for treated and untreated samples. Because the UCS and Rimm values for the 3% lime and the lignosulphonate mixtures decreased extremely quickly, they are not displayed in Figure 7. R_{imm} is defined as follows (Ghrieb et al., 2014, Ikhlef et al., 2015):

$$R_{imm} = \frac{UCS_i}{UCS_{28}} \times 100 \qquad (2)$$

where, UCS_i represents the unconfined compressive strength of specimens stored in air for 21 days followed by immersion for 1, 3 and 7 days, and UCS_{28} is the compressive strength curing in air for 28 days without immersion.

A significant improvement in water sensitivity was observed in the cement treated specimens. The UCS of CLMix-treated tuff was moderately affected by immersion, whereas the UCS of 6% lime-treated specimens was significantly affected. R_{imm} of the specimens treated with 3% and 6% cement and 6% CLMix exceeded the 60% threshold required by the Soil Treatment Guide (Daheur et al., 2023) for all immersion periods. Rimm of the 3% CLMix exceeds the 60% threshold only before the third day of immersion. For all immersion periods, the 6% lime treatment does not meet the immersion resistance requirement. To meet the immersion resistance requirement, the samples must be treated with 3% or 6% cement or 6% CLMix. This result agrees with previous research (Ghrieb et al., 2014; Ikhlef et al., 2015).

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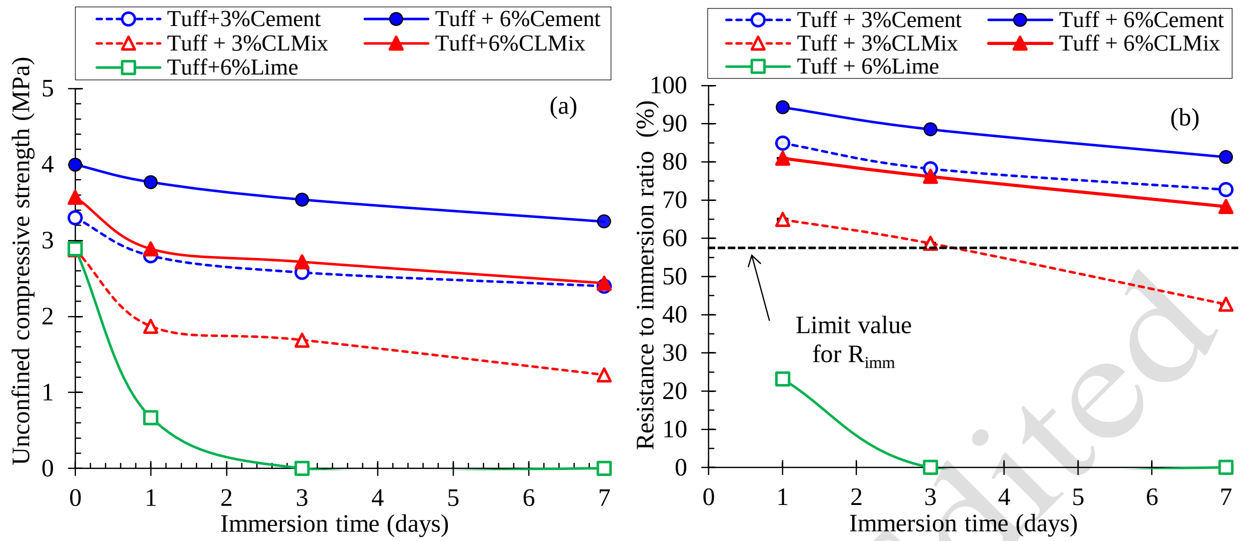

Figure 7. Evolution of a) UCS and b) R_{imm} versus the immersion time.

4.4 Influence of treatment on shear strength

Figure 8 (a and b) shows the evolution of apparent cohesion C_{app} and apparent friction angle φ_{app} as a function of conservation time. Figure 9 shows the gains in shear parameters for each conservation time with and without treatment, expressed using the following formula:

$$G = ((V_{at} - V_{bt})/V_{bt}) \times 100 \qquad (3)$$

where, V_{at} is the value of C_{app} and φ_{app} with treatment and V_{bt} is the value of C_{app} and φ_{app} of the pure tuff without treatment.

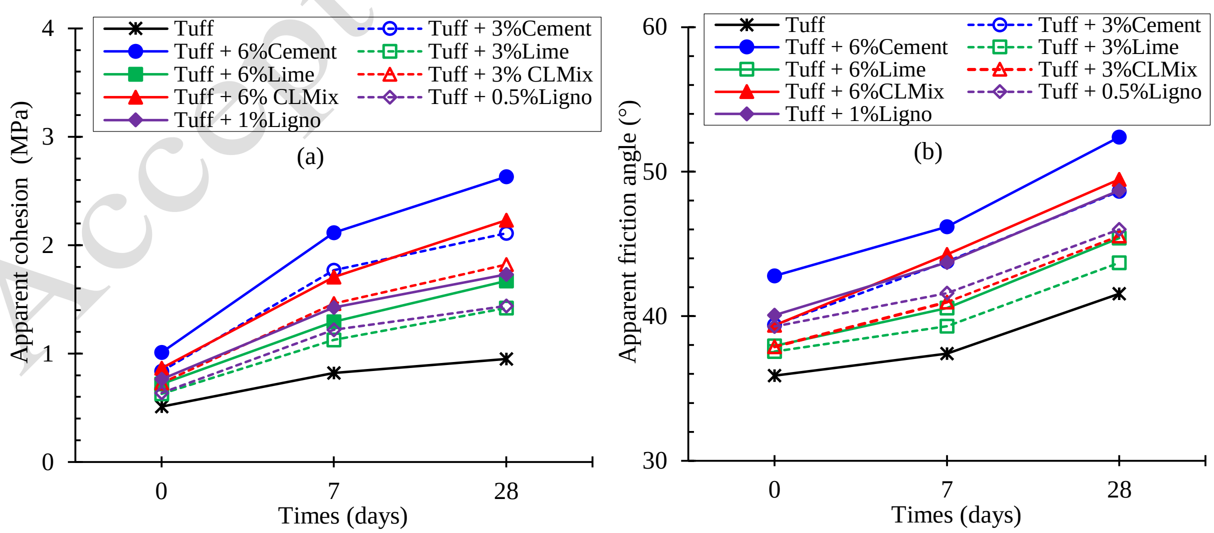

Figure 8. Variation of (a) apparent cohesion; (b) apparent friction angle versus conservation time.

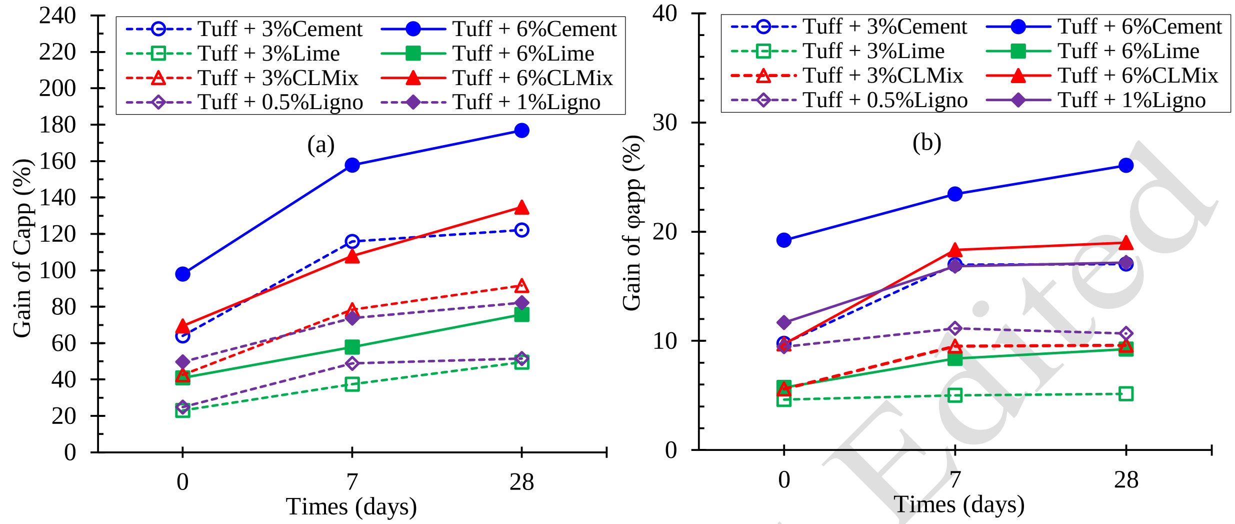

Figure 9. Variation of the gain of (a) apparent cohesion and (b) apparent friction angle versus conservation time.

The results show that cohesion is significantly improved after treatment and outdoor storage. The same is true for the friction angle, which also increased significantly, although with smaller gains. For example, after 28 days of open-air storage and treatment with 6% cement, the cohesion increased from 0.95 MPa to 2.63 MPa (an increase of 177%), while the angle of friction increased from 41.56° to 52.39° (an increase of 26%). These high values are due to the hardening of the cement and the formation of a number of hydrated cement constituents that coat and bind the grains. This suggests that the improvement in UCS is primarily due to the increased cohesion of the treated samples. These results are consistent with the work of (Amini et al., 2014; Wang et al., 2013).

4.5 The use of the treated materials in pavement construction

The results of the treatment of tuff with hydraulic or organic binders have shown the superiority of certain formulations over others. Several local, national, and international criteria must be carefully considered before using the obtained materials in the construction of Saharan road pavements. The standards used are the “Technical Roads in the Sahara TRS” describing the design of Algerian Saharan roads (Fenzy, 1966), the GTS (Daheur et al., 2023) (French acronym for 'Soil Treatment Guide'), and the AASHTO Pavement Design Guide (ASTM D3282). The TRS requires that the UCS at 28 days of curing time (UCS_{28}) be greater than 2 MPa (Fenzy, 1966; Omar

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et al., 2022). The GTS recommends a 60% Rimm threshold. The AASHTO requires UCS_{28} to be greater than 1.7 MPa for a stabilized subbase and 5.2 MPa for a stabilized base (Jamsawang et al., 2021). As shown in Table 5, the stabilization of the subbase layer in pavement construction necessitates a binder treatment containing either cement or a cement-lime mixture. According to the AASHTO Pavement Design Guide, neither tuff or any of the treatments can be used as a base layer in pavement construction.

Table 5. Mechanical parameters for the different binder treatments.

	Tuff	Tuff +3% Lime	Tuff +6% Lime	**Tuff + 3% Cement**	**Tuff + 6% Cement**	Tuff +3% CLMix	**Tuff + 6% CLMix**	Tuff +0.5% Ligno	Tuff +1% Ligno
UCS_{28} (MPa)	2.15	2.71	2.89	**3.3**	**4**	2.88	**3.57**	2.75	3.34
R_{imm} (%)	0	0	0	**72.72**	**81.25**	42.7	**68.35**	0	0
Compliance with standards (TRS, GTS and AASHTO)	No	No	No	**Yes**	**Yes**	No	**Yes**	No	No

Table 6 shows the suitability of materials derived from tuff for pavement layers in the Sahara region depending on traffic density, according to the criteria established by Struillou and Alloul 1984, as evaluated by the UCS at 180 days hardening (UCS180) and the soaked CBR index. Raw tuff is only suitable as a base course for low traffic pavements (< 130 trucks/day). Similar, tuff+lime and tuff+lignosulfate mixtures are only suitable for base and subbase layers under low traffic. Only tuff treated with 6% cement or a 6% cement-lime mixture is suitable for use as a base layer for all traffic conditions and as a sub-base layer for light to moderate traffic (< 600 trucks/day). The selection of a combination requires a technical-economic analysis depending on the size of the project and the anticipated traffic.

Table 6. The use of treated materials in Sahara pavement construction (Struillou and Alloul 1984).

		truck/day				
Formulation	UCS_{180} (MPa)	< 130	130 300	300 600	600 1200	> 1200
Tuff	2.14	B	N.U.	N.U.	N.U.	N.U.
Tuff + 3% lime	2.7	B and S	N.U.	N.U.	N.U.	N.U.
Tuff +6% lime	2.92	B and S	N.U.	N.U.	N.U.	N.U.
Tuff +3% cement	3.4	B and S	B and S	B and S	B	N.U.

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Tuff+6% cement	**4.1**	**B and S**	**B and S**	**B and S**	**B**	**B**
Tuff +3% CLMix	3	B and S	B and S	B	B	N.U.
Tuff +6% CLMix	**3.8**	**B and S**	**B and S**	**B and S**	**B**	**B**
Tuff +0.5% lignosulfonate	2.86	B and S	N.U.	N.U.	N.U.	N.U.
Tuff +1% lignosulfonate	3.35	B and S	N.U.	N.U.	N.U.	N.U.

B: for base layer; S: for subbase layer; N.U.: not usable.

5. Conclusion

This study investigated the effects of treatment with hydraulic binders (cement and/or lime) or lignosulfonate on the compaction characteristics, bearing capacity, and compressive and shear strength of tuff. The objective was to improve mechanical performance and make the material relatively impervious to water, thus ensuring its applicability in pavements located in harsh climatic regions with medium to heavy traffic. The results obtained lead to the following conclusions:

- Once exposed to water, untreated tuff quickly loses its bearing properties. Although readily available, it is not recommended for use on pavements in areas with high rainfall or capillary-rise of water.
- The study of the effect of treatments on mechanical performance demonstrates that binder dosage exerts a direct and positive influence on the properties of the studied sample. On the other hand, the type of binder influences the mechanical performance of the samples (cement provides superior performance). Resting period after treatment also improves these characteristics.
- Compactibility and trafficability generally improved after treatment.
- Treatment with cement and/or lime significantly improves the sensitivity of tuff to water.
- Treatment with lime or lignosulfonate is not sufficient to make tuff water-resistant. It is necessary to take precautions against water infiltration when building pavements. In the case of rainwater, it is necessary to accelerate runoff and prevent any water stagnation on the pavement. For capillary water, proper drainage must be ensured and the rise of water must be limited, e.g. by building the road on a small anti-capillary embankment.
- The binders used improved shear parameters, particularly cohesion, and resting period after treatment supports these improvements.

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It is recommended to treat tuff with 6% cement or with a mixture of 6% cement and lime, since this treatment allows it to be used as a base or subbase layer on desert highways exposed to heavy traffic (e.g. National north-south Highway No. 1) and in areas with high rainfall events.

Finally, further investigations are strongly recommended on a broader and more diverse range of tuff samples treated with alternative binders such as fly ash and other pozzolanic materials. The objective is to compare the performance obtained with that achieved using the binders considered in this study, as well as with high-quality road materials.

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