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Research Article

Effect of The Combined Addition of Brick Waste Powder And Dune Sand Powder on The Mechanical Performance of A Lime-Treated Gypsiferous Tuff

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Abstract:

This study investigates the improvement of mechanical performance and water durability of a gypsiferous tuff from southeastern Algeria, with the aim of its application in road infrastructure. The natural material, characterized by low cohesion and high water sensitivity, was treated through the combined addition of lime, finely ground brick waste powder, and dune sand powder. Several mix formulations were developed to assess the individual and synergistic effects of these additions on the mechanical behavior of the tuff.The experimental program included unconfined compressive strength, indirect tensile strength, water sensitivity, durability under wetting–drying cycles, and direct shear strength parameters. The results indicate that lime treatment significantly enhances material cohesion, while the incorporation of brick waste powder leads to a substantial mechanical gain attributed to the development of pozzolanic reactions. The contribution of dune sand powder is mainly associated with a granular densification effect, resulting in an improvement of the internal friction angle and overall structural stability.Microstructural analysis using scanning electron microscopy corroborates these macroscopic findings by revealing the formation of secondary cementitious products and a marked reduction in porosity for the most efficient mixtures.

1. Introduction

In recent years, Algeria has experienced significant economic development accompanied by a substantial expansion of its road network, particularly in desert regions. However, these areas suffer from a shortage of standardized high-quality materials traditionally used in road construction. This situation has prompted engineers and researchers to focus on the valorization of locally available materials in order to overcome this deficiency [1–3].

Among the materials available in large quantities are calcareous crust tuffs, which cover nearly 50% of the Algerian territory [4]. Despite their abundance, their use in Saharan road infrastructures remains limited due to their low mechanical performance and high sensitivity to water [5].

The use of tuff in its natural state has yielded generally acceptable results in certain contexts. Nevertheless, with increasing traffic loads and the low bearing capacity of tuff used in pavement layers—particularly under wet conditions—numerous forms of distress have been observed, including cracking and loss of bearing capacity [6]. Previous studies have shown that compacted and dried tuff may develop a certain degree of cohesion [7]; however, this cohesion almost completely disappears after full saturation [8,9].

To address these limitations, several treatment techniques have been proposed to improve the physico-mechanical properties of tuffs, in

accordance with the specifications recommended in Algeria by Struillou and Alloul [8]. These approaches are based either on the combination of tuff with other materials or on its treatment using various binders [10,11].
Furthermore, Saharan regions are also characterized by the abundance of dune sand, a material that is widely available but poorly exploited in road construction in its natural form due to its fine granulometry and low bearing capacity. However, when used in powder form, dune sand may play a beneficial role as a granular filler and as a potential source of reactive silica.
Within the framework of sustainable development, the recycling of construction waste represents a promising alternative for producing more economical and environmentally friendly materials. In this respect, red brick waste, available in large quantities from demolition sites and brick manufacturing plants, constitutes an attractive supplementary material [12].
The combined use of brick waste powder and dune sand with tuff therefore appears to be an innovative solution from technical, economic, and environmental perspectives. Brick waste is known for its pozzolanic activity, reacting with calcium hydroxide $Ca(OH)_2$ to form hydrated calcium silicate and aluminate compounds, which enhance the cohesion and strength of composite materials [13,14].In this context, the objective of the present study is to improve the mechanical performance of a gypsiferous tuff through the combined addition of brick waste powder and dune sand, in conjunction with lime treatment. This approach aims to promote pozzolanic reactions and
granular densification effects, leading to an increase in unconfined compressive strength and a reduction in water sensitivity, thereby opening new prospects for the use of these materials in road construction in arid environments.

2. Materials and methods

2.1. Materials

2.1.1. Tuff

The base material investigated in this study is a tuff collected from the Ouargla region, located in southeastern of Algeria.(photo.1)

2.1.1.1. Characteristics

The physical, chemical, and mechanical characteristics of the tuff from the Ouargla region were determined through a series of laboratory tests in order to assess its suitability for road construction applications. These characterizations included particle size distribution, Proctor compaction parameters, California Bearing Ratio (CBR), methylene blue value, and mineralogical and chemical analyses.

Particle Size Distribution Analysis [15]
According to the Béni Abbés gradation band, the tuff from the Ouargla region, characterized by a proportion of fine elements exceeding 20%, belongs to Family III. This family comprises
fine-grained materials that are highly water-sensitive, whose use in road infrastructure imperatively requires preliminary treatment.
Analysis of the particle-size distribution curve for the Ouargla tuff reveals a predominantly fine sandy material containing a significant proportion of fines.

Modified Proctor [16]
The Modified Proctor compaction curve of the tuff from the Ouargla region reveals a relatively moderate maximum dry density, on the order of 1.63 t/m³, achieved at a relatively high optimum water content of approximately 14.8%. The general shape of the curve is characterized by a gentle peak and a limited variation in dry density around the optimum, indicating the material's low sensitivity to compaction energy and a low-reactive granular structure. Beyond the optimum water content, a pronounced decrease in dry density is observed, revealing the tuff's heightened sensitivity to excess water.
The observed gap between the experimental curve and the saturation line reflects the material's high porosity and underscores the impossibility of achieving a dense, mechanically stable structure in a saturated state.

The California Bearing Ratio (CBR) [17]The CBR tests conducted on the tuff from the Ouargla region reveal a high bearing capacity in the dry state, with a CBR value of approximately 58.5%, indicating good resistance to penetration and an apparently satisfactory cohesion under favorable moisture conditions. In contrast, after soaking, the CBR index decreases significantly to about 24.4%, corresponding to a loss of bearing capacity exceeding 50%. This pronounced mechanical degradation reflects a high sensitivity of the material to water, mainly associated with the partial dissolution of the natural binding phases and the progressive disruption of the internal structure under saturation conditions. This behavior confirms that, despite its relatively good mechanical performance in the dry state, the Ouargla tuff cannot be used in its natural form for road infrastructure without prior treatment aimed at improving its water stability and ensuring long-term mechanical durability.

Methylene Blue Value [18]

The methylene blue value (VB_S), equal to 0.5, indicates that the studied tuff contains a low proportion of active clay minerals. This low clay activity limits swelling and shrinkage phenomena associated with variations in moisture content. Such a result complies with the
requirements of certain specifications applicable to road construction in Algeria, particularly those defined in GTR 92 [19].
According to the Road Earthworks Guide (GTR, 1992), and considering a fines content passing the 0.08 mm sieve greater than 20% together with a low methylene blue value ($VB_S < 1$), the studied material is classified within the B2 family. This class corresponds to a fine soil with low clay activity but exhibiting sensitivity to water (Figure 5) [19].

2.1.1.2 Chemical and Mineralogical Composition of the Ouargla Tuff

The chemical and mineralogical characterization of the Ouargla tuff was carried out using reference analytical techniques in order to accurately identify the constituent mineral phases and quantify the overall chemical composition of the material. X-ray diffraction (XRD) was employed for the qualitative and semi-quantitative determination of the mineralogical assemblages, while X-ray fluorescence spectrometry (XRF) was used to assess the distribution of major and minor oxides. The results obtained from these analyses are presented in Figure 6 and Table 1, respectively.The mineralogical and chemical analyses carried out using X-ray diffraction (XRD), complemented by X-ray fluorescence spectrometry (XRF), as presented in Figure 6 and Table 1, indicate that the Ouargla tuff is mainly composed of gypsum ($CaSO_4 \cdot 2H_2O$). A secondary proportion of calcite ($CaCO_3$) was also identified, along with the presence of trace amounts of quartz (SiO_2), alumina (Al_2O_3), and iron oxides. This composition confirms the gypsum-rich nature of the investigated tuff.

2.1.2 Brick waste and dune sand powders

The brick waste used in this study (Photo 3) was sourced from the SBT brick factory located in Touggourt, in southeastern Algeria. The waste materials were crushed using a blade mill and subsequently sieved to 0.08 mm to obtain a powder form (Photo 4).
The dune sand employed in this research was collected from the Sidi Khouiled area (Ouargla) (Photo 5). This material is abundantly available in southern Algeria; however, its direct use in road construction remains limited due to its fine particle size distribution and low bearing capacity.Within the scope of this study, the dune sand was first dried, then ground and sieved to 0.08 mm in order to be used in powder form (Photo 6).density indicate that brick waste and dune sand powders exhibit physical characteristics comparable to those of conventional mineral additions.

2.1.2.1 Bulk density [20] [21]

By comparing the densities of the powders derived from brick waste and dune sand with those of commonly used mineral additions, it can be observed that their absolute densities, equal to 2.31 g/cm³ and 2.53 g/cm³ respectively, are comparable to those of silica fume (2.2–2.5 g/cm³) and natural pozzolana (2.4–2.6 g/cm³), while remaining lower than that of blast furnace slag (2.8–3.0 g/cm³).
Moreover, their apparent densities, approximately 1.20 g/cm³ for brick powder and 1.27 g/cm³ for dune sand powder, fall within the range of values reported for mineral additions such as natural pozzolana (0.9–1.2 g/cm³) and fly ash (1.0–1.3 g/cm³). These similarities in terms of In recent years, Algeria has experienced significant economic development accompanied by a substantial expansion of its road network, particularly in desert regions. However, these areas suffer from a shortage of standardized high-quality materials traditionally used in road construction. This situation has prompted engineers and researchers to focus on the valorization of locally available materials in order to overcome this deficiency [1–3].Among the materials available in large quantities are calcareous crust tuffs, which cover nearly 50% of the Algerian territory [4]. Despite their abundance, their use in Saharan road infrastructures remains limited due to their low mechanical performance and high sensitivity to water [5].The use of tuff in its natural state has yielded generally acceptable results in certain contexts. Nevertheless, with increasing traffic loads and the low bearing capacity of tuff used in pavement layers—particularly under wet conditions—numerous forms of distress have been observed, including cracking and loss of bearing capacity [6]. Previous studies have shown that compacted and dried tuff may develop a certain degree of cohesion [7]; however, this cohesion almost completely disappears after full saturation [8,9].To address these limitations, several treatment techniques have been proposed to improve the physico-mechanical properties of tuffs, in accordance with the specifications recommended in Algeria by Struillou and Alloul [8]. These approaches are based either on the combination of tuff with other materials or on its treatment using various binders [10,11].Furthermore, Saharan

regions are also characterized by the abundance of dune sand, a material that is widely available but poorly exploited in road construction in its natural form due to its fine granulometry and low bearing capacity. However, when used in powder form, dune sand may play a beneficial role as a granular filler and as a potential source of reactive silica.Within the framework of sustainable development, the recycling of construction waste represents a promising alternative for producing more economical and environmentally friendly materials. In this respect, red brick waste, available in large quantities from demolition sites and brick manufacturing plants, constitutes an attractive supplementary material [12].The combined use of brick waste powder and dune sand with tuff therefore appears to be an innovative solution from technical, economic, and environmental perspectives. Brick waste is known for its pozzolanic activity, reacting with calcium hydroxide $Ca(OH)_2$ to form hydrated calcium silicate and aluminate compounds, which enhance the cohesion and strength of composite materials [13,14].In this context, the objective of the present study is to improve the mechanical performance of a gypsiferous tuff through the combined addition of brick waste powder and dune sand, in conjunction with lime treatment. This approach aims to promote pozzolanic reactions and granular densification effects, leading to an increase in unconfined compressive strength and a reduction in water sensitivity, thereby opening new prospects for the use of these materials in road construction in arid environments.

2**.1.2.2 Blaine specific surface area** [22]

The Blaine specific surface area is a fundamental parameter for assessing the fineness of powdered materials and plays a decisive role in evaluating their chemical, mechanical, and rheological properties. Within the framework of this study, the specific surface area of brick waste and dune sand powders (Table 4) was measured using an automatic Blaine permeameter (Photo 7).The measured Blaine specific surface areas of the brick waste and dune sand powders indicate a relatively high fineness, comparable to that of certain commonly used mineral additions, such as fly ash (3,500–5,500 cm²/g), natural pozzolana (4,000–6,000 cm²/g), and blast furnace slag (4,000–6,000 cm²/g). This level of fineness is favorable for the development of physicochemical reactions.

2.1.2.3 Chemical and mineralogical compositions

The chemical and mineralogical compositions of the powders derived from brick waste and dune sand were determined by X-ray diffraction (XRD), complemented by X-ray fluorescence spectrometry (XRF) (Figures 7 and 8; Table 5).The brick waste powder exhibits a predominantly silico-aluminous composition, characterized by high contents of amorphous SiO_2 and Al_2O_3, which are favorable for the development of pozzolanic reactions. In contrast, the dune sand powder is mainly composed of crystalline silica (quartz), with very low proportions of other oxides, thereby conferring primarily a physical role as a fine filler material.

2.1.3 Lime

The lime used in the present study was supplied by the BMS plant in Saïda (Photo 8). It is a hydrated lime characterized by a low content of siliceous (SiO_2) and aluminous (Al_2O_3) oxides, and by a high proportion of basic constituents, particularly free lime (CaO), which gives it an essentially air-hardening character. The main chemical and physical properties of this lime, according to the manufacturer's technical data sheets, are presented in Table 6.

2.1.4 Mixing water

The water used for conducting the tests and preparing the different mixtures, particularly those containing hydraulic binders (lime), must meet strict purity requirements. It should be clean and free from harmful salts, organic matter, and any impurities likely to adversely affect the properties of the materials constituting the mixtures. In the present study, the water employed was potable water supplied by the public distribution network. The main chemical characteristics of this water are presented in Table 7.The chemical analyses indicate that the water used complies with the requirements of Standard XP P 18-303, which relates to the quality of mixing water [24]. In accordance with this standard, the water does not exhibit any chemically aggressive characteristics that could adversely affect the mechanical performance or the physicochemical properties of the materials employed.

2.2 Experimental methodology

2.2.1 Mix design

The mix design was defined in order to evaluate the effect of lime treatment and the influence of mineral additions, considered both individually and in combination, on the mechanical behavior of the studied tuff. The selected dosages were based on recommendations reported in the literature, as well as on preliminary results related to the material reactivity and its geotechnical classification.

Natural tuff was used as the reference material. A lime content of 4% (by mass of dry soil) was

adopted, as this dosage is commonly considered effective for the improvement of low-activity fine soils of type B2 according to the GTR (1992) classification [19]. The mineral additions, namely brick waste powder and dune sand powder, were incorporated to enhance the water stability and mechanical performance of the treated tuff.
Five formulations were therefore investigated, as summarized below:
M1: Natural tuff (reference)
M2: Tuff + 4% lime
M3: Tuff + 4% lime + 10% brick waste powder
M4: Tuff + 4% lime + 10% dune sand powder
M5: Tuff + 4% lime + 5% brick waste powder + 5% dune sand powder
The percentages of lime and mineral additions are expressed by mass relative to the dry tuff. The brick waste and dune sand powders were previously dried, ground, and sieved to obtain a fine and homogeneous particle size distribution, ensuring good dispersion within the mixture.
The preparation of the mixtures was carried out by dry mixing the tuff with lime and the mineral additions, followed by the addition of mixing water corresponding to the optimum water content (Wopm). The resulting mixtures were then used to perform the various mechanical tests, in accordance with the applicable standardized procedures.

2.2.2 Test methods

2.2.2.1 Unconfined compressive strength test (Rc)

The unconfined compressive strength test aims to evaluate the bearing capacity and mechanical behavior of the studied mixtures under a monotonic axial load applied without lateral confinement. This test makes it possible to assess the effect of lime treatment and the incorporation of mineral additions on the development of the mechanical strength of the tuff, as well as the evolution of this strength as a function of curing time.
The specimens used for the unconfined compression test were cylindrical in shape (H = 10 cm, ϕ = 5 cm) (Photo 9). The specimens were prepared by static compaction at the optimum water content and the maximum dry density determined from the Modified Proctor test, using a hydraulic press (Photo 10).After preparation, the specimens were carefully demolded and stored under laboratory climatic conditions (Photo 11).
The unconfined compression tests were carried out after representative curing periods (7, 28, and 60 days), allowing the evaluation of the time-dependent evolution of mechanical strength.
The test was performed using a compression testing machine equipped with a controlled loading-rate system. The specimens were placed between two rigid and parallel platens and then subjected to an increasing axial load applied at a constant deformation rate (1.27 mm/s) (Photo 12).
The load was applied until failure of the specimen, which was identified by the appearance of cracks or by a sudden drop in the recorded load (Photo 13).

2.2.2.2 Indirect Tensile Strength Test (Rt)

The indirect tensile test (Brazilian test) was used to evaluate the tensile strength of the studied mixtures, making it possible to analyze the effect of lime treatment and mineral additions on the cohesion and cracking behavior of the material. This test is particularly suitable for assessing the tensile behavior of soils treated with hydraulic binders.
The specimens used in the Brazilian test were cylindrical in shape, in accordance with common practices adopted for lime-treated materials (Photo 14). The specimens were prepared by static compaction using a hydraulic press (Photo 10), at the optimum water content and the maximum dry density determined from the Modified Proctor test. After demolding, the specimens were stored under laboratory climatic conditions (35 ± 3 °C) for curing periods identical to those adopted for the unconfined compression tests (7, 14, and 28 days), in order to ensure the comparability of the mechanical results.
After the curing period, the specimens were subjected to the indirect tensile test using a compression testing press equipped with a diametral loading device.
The specimen was placed horizontally between two loading strips or linear platens, ensuring a uniform distribution of the load along the diameter. The load was applied continuously and at a constant rate until failure of the specimen, which was characterized by the appearance of a clear diametral crack developing in the loading plane (Photo 15).

2.2.2.3 Water Sensitivity Test

The water sensitivity test aims to evaluate the influence of immersion on the mechanical behavior of the studied materials. It makes it possible to assess the hydraulic stability of tuff treated with lime and mineral additions by quantifying the loss of mechanical strength induced by saturation. This test is particularly relevant for materials intended for road infrastructures, which are subjected to variable moisture conditions. Water sensitivity is evaluated through a strength retention index, expressing the ability of the material to maintain its mechanical performance in a wet environment.
The specimens used for the water sensitivity test are identical to those employed in the unconfined compressive strength tests, in order to ensure the comparability of the results.After demolding, the specimens were cured for 28 days under laboratory

climatic conditions, allowing the development of the physicochemical reactions associated with lime and mineral additions.

At the end of the curing period, the specimens intended for the water sensitivity test were fully immersed in potable water at ambient temperature (20 ± 3 °C) for 4 days. The immersion was carried out in such a way as to ensure complete saturation of the material (Photo 16).At the end of the immersion period, the specimens were surface-dried to remove free water and then immediately subjected to the unconfined compression test.

Water sensitivity is evaluated based on the ratio of unconfined compressive strength, according to the following expression:

$$Is = \frac{\text{Rc immersed}}{\text{Rc dry}}$$

where:

Rc immersed: is the compressive strength measured after immersion,

Rc dry: is the compressive strength measured in the dry (non-immersed) state.

An Is value close to 1 indicates good hydraulic stability, whereas a low value reflects high sensitivity to water.

2.2.2.4 Wetting–Drying Cycles Test

The wetting–drying cycles test aims to evaluate the hydraulic durability and mechanical stability of the studied tuff when subjected to repeated alternations of wet and dry conditions, representative of the environmental stresses encountered in situ. This test makes it possible to assess the behavior of mixtures treated with lime and mineral additions with respect to progressive degradation mechanisms, such as cracking, surface disintegration, and loss of internal cohesion.

The principle of the test consists of subjecting specimens to a succession of cycles comprising a water immersion phase followed by a drying phase.The specimens used are identical to those employed in the unconfined compressive strength tests, thereby ensuring consistency in the comparisons (h = 10 cm, ϕ= 5 cm).

After demolding, the specimens were subjected to an initial curing period of 7 days, which is necessary for the development of the physicochemical reactions induced by lime and mineral additions.

Each cycle consisted of complete immersion of the specimens in potable water at ambient temperature (20 ± 3 °C) for 24 hours, ensuring full saturation of the material. The specimens were then removed from the water, surface-dried, and subsequently air-dried for 24 hours.

This operation was repeated over 7 days, corresponding to a total duration of 14 days. The impact of the wetting–drying cycles was evaluated through the evolution of the unconfined compressive strength, in comparison with that of specimens cured under controlled laboratory climatic conditions for a period of 14 days.

2.2.2.5 Direct Shear Test

The direct shear test was conducted in order to determine the fundamental shear strength parameters of the studied tuff, namely cohesion (c) and the internal friction angle (φ)**.** These parameters are essential for evaluating the mechanical behavior of materials intended for pavement layers and geotechnical applications, particularly when lime treatment and mineral additions are involved.

The direct shear test consists of subjecting a specimen to a constant normal stress while applying an increasing tangential force until failure occurs. Failure takes place along a predefined shear plane located at the interface between the two halves of the shear box apparatus (Photo 17).

The obtained results make it possible to define the failure envelope according to the Mohr–Coulomb criterion, expressed by the following relationship:

$$\tau = c + \sigma \tan(\varphi)$$

where τ represents the shear stress at failure and σ the applied normal stress.

The test was carried out using a motorized direct shear apparatus equipped with a normal load application system, a horizontal shearing mechanism, and force and displacement sensors connected to a digital data acquisition unit (Photo 18).

The specimens (ϕ =60 mm) were prepared from the different studied mixtures in accordance with the selected formulation conditions. They were compacted at the optimum water content and the maximum dry density, as determined by the Modified Proctor test.

After molding, the specimens were subjected to a controlled curing period of 7 days, which is necessary for the development of the stabilization reactions induced by lime and mineral additions.

2.2.2.6 Scanning Electron Microscopy (SEM) Analysis

Scanning Electron Microscopy (SEM) analysis was carried out to investigate the microstructure, morphology, and texture of the studied materials at the micrometric scale. This technique makes it possible to highlight the evolution of particle arrangement, the nature of interparticle bonds, as well as the reaction products formed as a result of lime treatment and the incorporation of mineral additions.

The specimens were subjected to a targeted analysis of the surface layer, which was considered representative of the microstructural changes induced by the treatment.SEM observations were performed on specimens taken from the unconfined compressive strength test after 60 days of curing under laboratory climatic conditions.

3. Results and discussion

3.1 Unconfined Compressive Strength

Figure 9 illustrates the evolution of the unconfined compressive strength (Rc) of mixtures M1 to M5 as a function of curing age (7, 28, and 60 days). The results highlight a progressive increase in mechanical strength for all formulations, reflecting the development of consolidation mechanisms and the physicochemical reactions induced by the treatment.At 7 days, mixture M1 (natural tuff) exhibits the lowest strength values, confirming the low cohesive nature of the raw material. The incorporation of 4% lime (M2) leads to a moderate improvement in strength, which can be attributed to the initial hydration reactions and the flocculation of fine particles. In contrast, mixtures M3, M4, and M5, which include mineral additions, display significantly higher strength values even at early ages, indicating a combined effect of particle size optimization and the onset of pozzolanic reactions.

At 28 days, the differences between the various formulations become more pronounced. Mixture M3 (tuff + lime + brick waste powder) achieves the highest strength, which can be explained by the high pozzolanic reactivity of brick powder, rich in amorphous silica and alumina. Mixtures M4 and M5 show intermediate performance, reflecting respectively the filler effect of dune sand and the synergistic effect resulting from the combination of both mineral additions. Although mixture M2 shows a significant improvement compared to M1, it remains less effective than the formulations enriched with mineral additions.At 60 days, the observed trend is confirmed by a continued increase in strength, indicating the persistence of carbonation and long-term pozzolanic reactions. The ranking of mechanical performance remains unchanged (M3 > M5 > M4 > M2 > M1), highlighting the stability of the mechanical behavior of the treated mixtures. The relatively high and stable strength of mixture M5 suggests that a balanced combination of brick powder and dune sand contributes to the formation of a dense microstructure.

3.2 Indirect Tensile Strength

The indirect tensile strength results of the different formulations exhibit a trend similar to that observed for unconfined compressive strength, with a progressive increase as a function of curing age. The mixtures treated with lime and enriched with mineral additions show significantly higher tensile strength values compared to the untreated tuff (control), reflecting a marked improvement in the internal cohesion of the material.

Mixture M3 records the highest indirect tensile strength values at all curing ages, confirming the beneficial effect of brick waste powder, which is rich in reactive silica and alumina and promotes the formation of secondary cementitious products. Mixtures M4 and M5 display intermediate performance, indicating respectively the filler effect of dune sand and the synergistic effect arising from the combined use of sand and brick powder. The control mixture M1 remains the least efficient, due to the absence of an active binding agent.Overall, the indirect tensile strength results confirm the effectiveness of lime treatment combined with mineral additions particularly brick waste powder in enhancing internal cohesion and improving the mechanical performance of the studied tuff.

3.3 Water Sensitivity

Figure 11 illustrates the variation of the water sensitivity index (Is) for mixtures M1 to M5, allowing the assessment of the mechanical stability of the materials after immersion relative to their dry state. A higher Is value indicates greater resistance to water action.The untreated tuff (M1) exhibits a null water sensitivity index, as the specimens collapsed a few minutes after immersion, indicating extremely high vulnerability to water. This poor performance is attributed to the gypsiferous and highly porous nature of the untreated tuff, which is characterized by low cohesion and rapid degradation upon contact with water.The addition of lime (M2) leads to a noticeable improvement in the Is index, reaching approximately 0.50. This enhancement is associated with the development of flocculation–agglomeration reactions and the formation of initial pozzolanic reaction products, which improve material cohesion. However, water sensitivity remains relatively high due to a still-open microstructure.Mixture M3 (tuff + 4% lime + 10% brick waste powder) exhibits the highest water sensitivity index (Is ≈ 0.78), reflecting excellent resistance to water. This behavior is attributed to the high pozzolanic reactivity of brick waste powder, which promotes the formation of secondary cementitious compounds (C–S–H and C–A–H), leading to matrix densification and reduced water penetration.The Is index of mixture M4 (≈ 0.54) is higher than that of mixture M2 but lower than those of the brick powder–containing mixtures. The observed improvement is mainly due to the physical filling effect of dune sand, which partially reduces porosity without providing significant chemical contribution. Mixture M5 (tuff + 4% lime + 5% brick powder + 5% dune sand) presents a relatively high intermediate Is value (≈ 0.70). The combined effect of brick powder, providing chemical reactivity, and dune sand, enhancing granular compactness, results in a dense microstructure with improved resistance to water action. In conclusion, the results clearly demonstrate that lime treatment combined with mineral additions particularly brick waste powder significantly enhances the resistance of the mixtures to water action. Mixture M3 emerges as the most effective in terms of hydraulic durability, whereas untreated tuff remains extremely water-sensitive. These findings are consistent with the mechanical performance results obtained from both compressive and tensile strength tests.

3.4 Wetting–Drying Cycles

The results of the wetting–drying cycles test, compared with those obtained under normal curing conditions for an identical duration of 14 days, reveal contrasting behaviors depending on the mixture formulation. The untreated tuff (M1) exhibits an almost complete loss of strength after immersion, indicating extremely high water sensitivity associated with its gypsiferous nature and high porosity. The addition of lime (M2) partially improves material stability; however, the post-cycle strength remains lower than that measured under normal curing conditions.

In contrast, mixtures incorporating mineral additions (M3, M4, and M5) demonstrate a marked improvement in hydromechanical behavior. Mixture M3, containing brick waste powder, shows a significant increase in strength after wetting–drying cycles, which can be attributed to the activation and enhancement of pozzolanic reactions promoted by repeated immersion phases. Mixtures M4 and M5 also exhibit higher post-cycle strength compared to that obtained under normal curing conditions, reflecting improved material structuring and reduced sensitivity to water.Overall, these results confirm the effectiveness of mineral additions, whether used individually or in combination, in enhancing the performance of lime-treated tuff when subjected to alternating wet and dry conditions.

3.5 Direct Shear Strength

The direct shear strength of the studied materials can be analyzed through the Mohr–Coulomb strength parameters, namely cohesion (c) and internal friction angle (φ).

The untreated tuff (M1) exhibits very low cohesion (17 kPa), reflecting a weakly bonded structure and high sensitivity to water, while the internal friction angle remains moderate (29°), which is characteristic of a predominantly frictional material.

The incorporation of 4% lime (M2) leads to a significant increase in cohesion, reaching 53 kPa, as a result of the initial stabilization reactions, accompanied by a slight increase in the internal friction angle (31°).

Mixtures incorporating mineral additions show a more pronounced improvement in shear strength parameters. Mixture M3, containing 10% brick waste powder, presents the highest cohesion value (94 kPa), indicating the formation of secondary cementitious products generated by pozzolanic reactions. The internal friction angle is also enhanced (33°), reflecting improved material structuring and interparticle bonding.

Mixture M4, incorporating 10% dune sand powder, is characterized by moderate cohesion (72 kPa) but a relatively high internal friction angle (37°), which can be attributed to the granular effect and improved particle interlocking.

Finally, mixture M5, combining brick waste powder and dune sand, offers an optimal balance between cohesion (86 kPa) and internal friction angle (35°), reflecting a dense and homogeneous structure. This behavior confirms the complementarity of the two mineral additions and their effectiveness in enhancing the overall mechanical performance of the treated tuff.

3.6 Scanning Electron Microscopy (SEM) Observations

3.6.1 Untreated Tuff (M1)

The scanning electron microscopy (SEM) observation of untreated tuff (M1), conducted at a magnification of 50×, reveals a heterogeneous and weakly cohesive microstructure. The image shows an assemblage of particles with irregular shapes, predominantly angular to sub-angular, and exhibiting a wide range of particle sizes, confirming the fragmented and poorly consolidated nature of the material.

The grains appear poorly arranged and are separated by large intergranular voids, indicating high porosity and low compactness. This open microstructure promotes water circulation through the material, which explains the high water sensitivity observed during mechanical and durability tests. The particle surfaces exhibit a rough and locally cracked texture, characteristic of

gypsiferous and carbonate materials subjected to dissolution and recrystallization processes.
No continuous binding phase is observed between the grains, confirming the absence of natural cementitious products capable of providing significant internal cohesion. This microstructural configuration accounts for the low unconfined compressive strength and indirect tensile strength measured for mixture M1, as well as its rapid degradation when subjected to wetting–drying cycles.

3.6.2 Tuff + 4% Lime (M2)

The scanning electron microscopy (SEM) observation of mixture M2, performed at a magnification of 50×, reveals a significant evolution of the microstructure compared to untreated tuff. The matrix appears more compact, with a noticeable reduction in intergranular voids, reflecting the effect of lime treatment on particle organization.
The image highlights the presence of partially cemented zones, where grains are interconnected by reaction products forming intergranular bridges. Higher-magnification details show a fibrous and locally lamellar texture, characteristic of hydrated phases resulting from the initial physicochemical reactions between lime and the fine constituents of the tuff. These products contribute to the enhancement of the internal cohesion of the material.
Despite this improvement, the microstructure remains heterogeneous, with residual porous zones and a non-uniform distribution of binding products. This microstructural configuration explains the intermediate mechanical performance of mixture M2, which exhibits higher compressive and tensile strengths than untreated tuff but lower values than those of mixtures incorporating pozzolanic mineral additions.

3.6.3 Tuff + 4% Lime + 10% Brick Waste Powder (M3)

The scanning electron microscopy (SEM) observation of mixture M3, carried out at a magnification of 50×, reveals a markedly denser and more homogeneous microstructure than those observed for mixtures M1 and M2. The granular assembly appears highly consolidated, with a significant reduction in intergranular voids and improved continuity of the matrix.
The image shows an abundant presence of secondary reaction products forming a continuous binding phase that partially coats the tuff grains. Higher-magnification details reveal a compact and massive texture, locally microcrystalline, which is characteristic of products resulting from pozzolanic reactions between lime and the silico-aluminous constituents of brick waste powder. These products contribute to the formation of effective intergranular bridges, thereby enhancing the internal cohesion of the material.
The progressive disappearance of angular grain boundaries observed in certain areas indicates advanced integration of particles within a cemented matrix, which limits crack propagation and improves overall mechanical strength. This dense and well-bonded microstructure accounts for the high unconfined compressive strength and indirect tensile strength values measured for mixture M3, as well as its excellent performance with respect to water sensitivity and wetting–drying cycles.

3.6.4 Tuff + 4% Lime + 10% Dune Sand Powder (M4)

The scanning electron microscopy (SEM) observation of mixture M4, performed at magnifications of 50× and 500×, reveals a microstructure that differs from those observed for mixtures incorporating pozzolanic additions. The matrix appears overall denser than that of untreated tuff, with a noticeable reduction in intergranular voids, mainly resulting from the granular effect of dune sand.
At low magnification (50×), the image shows a relatively well-interlocked particle assembly, where dune sand grains with more regular morphology promote mechanical interlocking and enhance material compactness. However, the structure remains heterogeneous, with locally weakly bonded zones, indicating a non-uniform distribution of reaction products.
At higher magnification (500×), the grain surfaces appear to be coated with a thin and discontinuous deposit corresponding to lime hydration products. Unlike mixture M3, no continuous binding matrix is observed. The formed products mainly occur as films or localized clusters, which limits the development of significant chemical cohesion.
This microstructural configuration explains the mechanical behavior of mixture M4, which is characterized by a notable improvement in the internal friction angle due to optimized granular arrangement, but lower cohesion compared to mixtures containing brick waste powder. Nevertheless, the reduction in porosity and the improved structural stability provide mixture M4 with enhanced resistance to water action and wetting–drying cycles relative to untreated formulations.

3.6.5 Tuff + 4% Lime + 5% Brick Waste Powder + 5% Dune Sand Powder (M5)

The scanning electron microscopy (SEM) observation of mixture M5, performed at a magnification of 50×, reveals a relatively dense and homogeneous microstructure resulting from the synergistic combination of lime, brick waste powder, and dune sand. The image shows a well-structured granular assembly in which coarse and fine particles are closely interlocked, contributing to improved overall compactness of the material.

Secondary reaction products are clearly observed in the form of a partially continuous binding matrix that coats and connects the tuff particles. These products, generated by pozzolanic reactions between lime and the silico-aluminous phases of brick waste powder, provide a significant increase in internal cohesion. In addition, dune sand grains with a more regular morphology promote granular interlocking and contribute to the reduction of intergranular voids.

Compared with mixtures M3 and M4, the microstructure of mixture M5 represents a well-balanced compromise between matrix densification and granular structure optimization. The pores appear finer and more uniformly distributed, which limits crack propagation and enhances resistance to both mechanical and hydraulic loading. This microstructural organization accounts for the high mechanical performance observed for mixture M5, particularly in terms of unconfined compressive strength, indirect tensile strength, and durability under wetting–drying cycles.

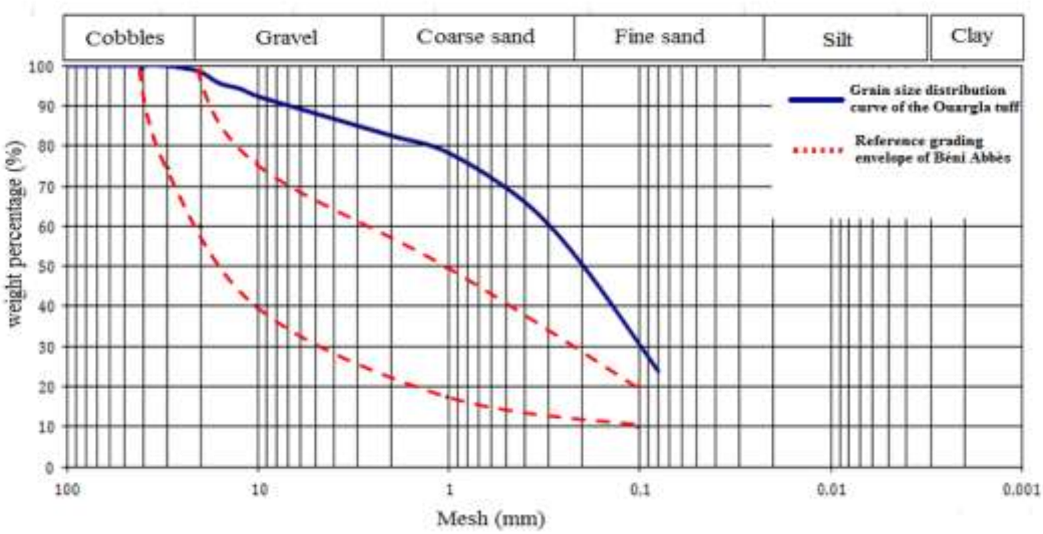


Figure .1 *Particle-size distribution curve of the tuff*

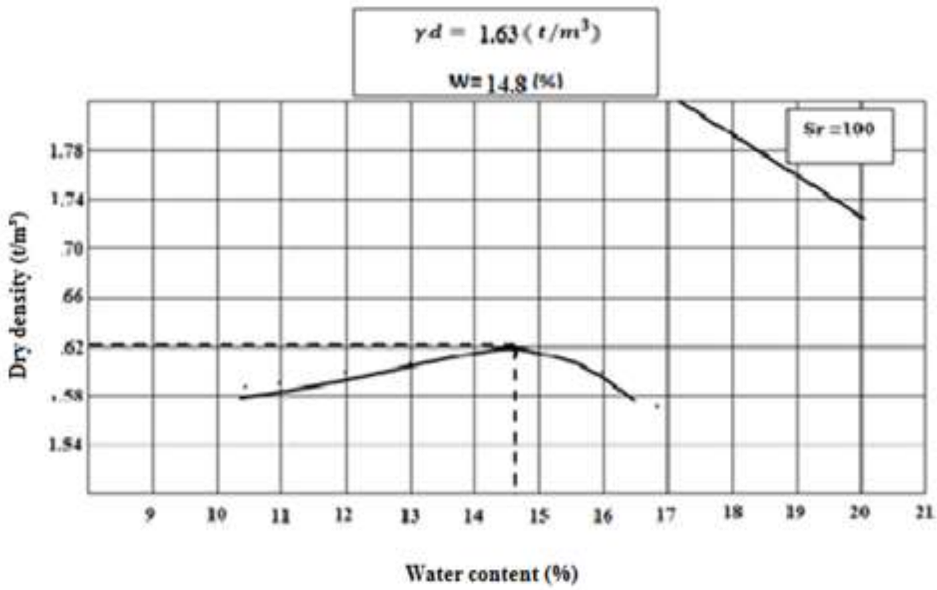


Figure .2 *Modified Proctor curve of the Ouargla tuff*

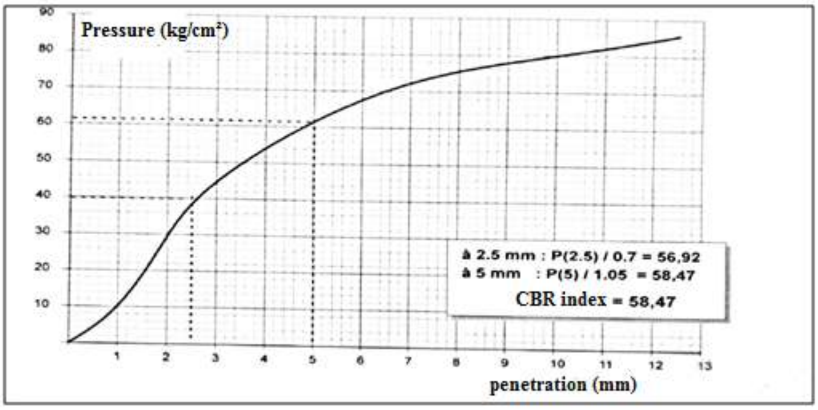


Figure 3. *Immediate CBR index of the Ouargla tuff*

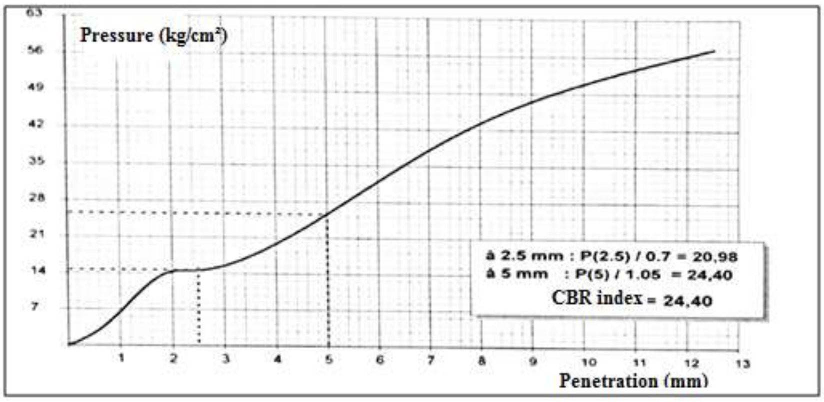


Figure 4. *Soaked CBR index of the Ouargla tuff*

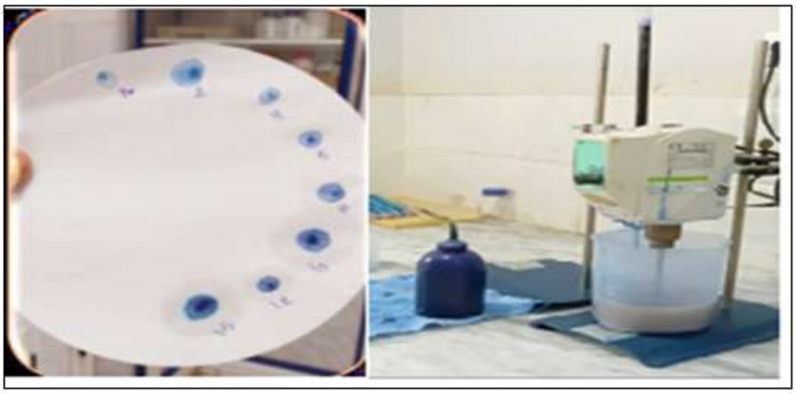


Photo 2. *Methylene blue test*

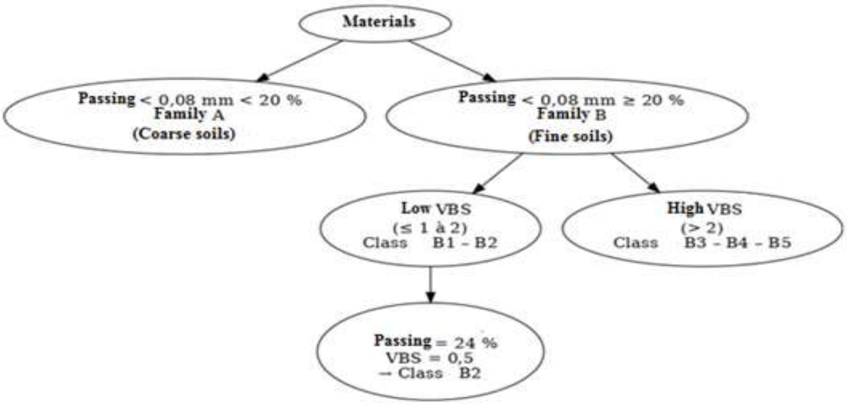


Figure 5. *Classification of the Ouargla tuff according to GTR 1992*

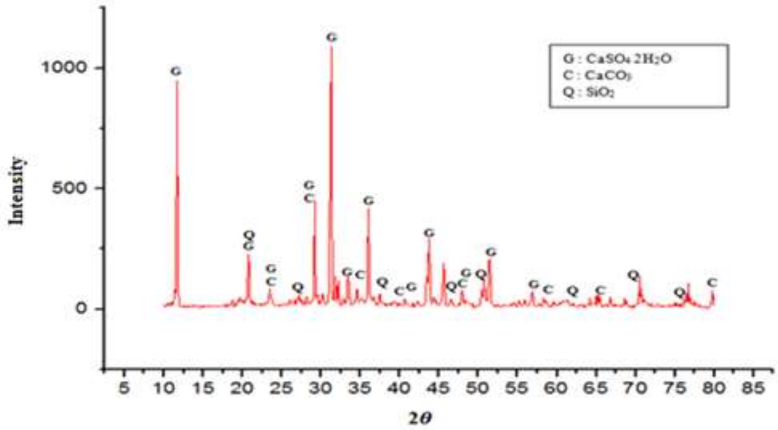


Figure 6. *XRD pattern showing the main mineralogical constituents of the Ouargla tuff.*

Table 1. *Overall chemical composition of the Ouargla tuff determined by X-ray fluorescence (XRF)*

Elements	$CaSo_42H_2O$	$CaCO_3$	SiO_2	AL_2O_3	FeO_2	Cl	MgO
Percentage (%)	76.5	8.8	4.36	1.3	0.72	0.52	3.38

Table 2. *Summary of the geotechnical and chemical characteristics of the studied tuff*

Test		Results	Recommended limits according to Algerian specifications			
			TRS	CTTP	GTR	Struillou et Alloul(1984)
Particle size analysis	D max (mm)	20	-	20-40	<50	-
	$\leq 2mm$(%)	80	-	-	-	-
	$\leq 80mm$ (%)	24	<30	22-32	<35	$\leq$ 30
Compaction and bearing capacity	Wopm (%)	14.8	-	-	-	-
	γd (t /m^3)	1.63	>1.7	-	-	-
	Immediate CBR index	58.47	>40	-	-	-
	Soaked CBR index (4 days)	24.4	-	-	-	30-100
Fines quality	VB_S	0.5	-	-	<1.5	-
Chemical composition	$CaSo_{4,}$ 2H2O(%)	76.5	-	-	-	<5

Photo 3. *Brick waste*

Photo 4. *Brick waste powder*

Photo 5. *Saharan dunes*

Photo 6. *Dune sand powder*

Photo 7. *Automatic Blaine permeameter (Biskra cement plant, Algeria)*

Table 4. *Blaine specific surface areas of brick waste powder and dune sand powder*

	Blaine specific surface area (cm^2/g)
Brick waste powder	5100
Dune sand powder	5300

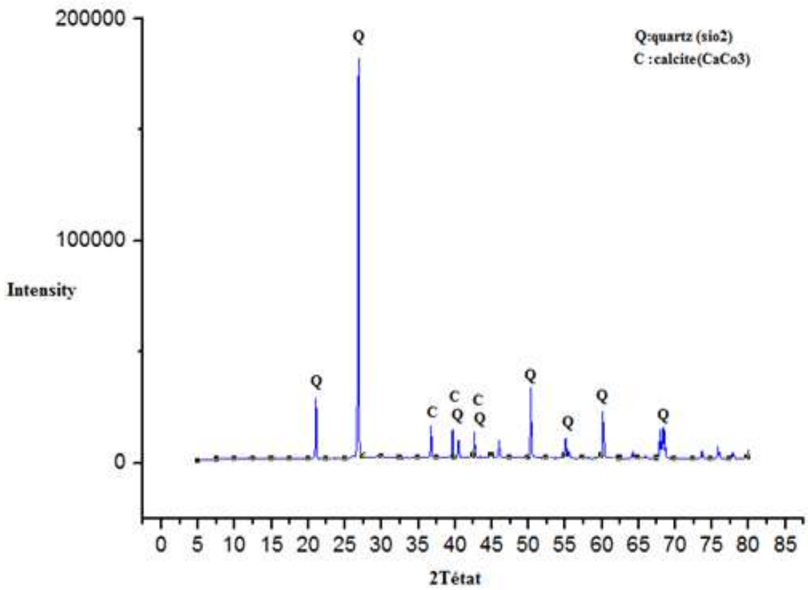


Figure 7. *XRD pattern of dune sand powder*

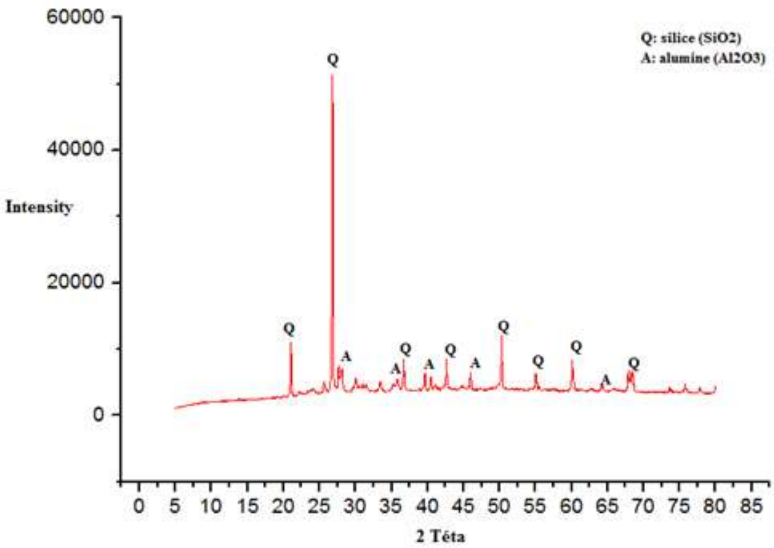


Figure 8. *XRD pattern of ground brick waste*

Table 5. *Chemical compositions of brick waste and dune sand powders*

Elements	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	Cl^-
Brick waste powder (%)	61.56	13.85	6.1	5.75	2.87	2.21	0.51	2.73	0.064
Dune sand powder (%)	93.55 2.56 0.97 1.25 0.84 0.74 0.47 1.22 0.046								

Photo 8. *Bag of ground (hydrated) lime from the BMS Saïda plant*

Table 6. *Physical and chemical properties of BMS Saïda lime [23]*

Physical appearance	Dry white powder
Absolute density (g/cm³)	2.2_ 2.4
Apparent density (g/cm³)	0.5_0.65
Specific surface area (cm²/g)	8000_12000
CaO (%)	> 73,3
MgO (%)	<0,5
Fe2O3 (%)	< 2
Al2O3 (%)	< 1,5
SiO2 (%)	< 2,5

SO3 (%)	< 0,5
Na2O (%)	0,4 – 0,5
CO2 %)	< 5
CaCO3 (%)	< 10
Specific gravity	2
More than 90 µm (%)	< 5
More than 630µm (%)	0
Insoluble material (%)	< 1
Bulk density (g/L)	600-900

Table 7. *Chemical composition of the mixing water used (mg/L)*

Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	Cl^{-}	$NO3^{-}$	$SO4^{-}$	$HCO3^{-}$
241	126	32	539	753	14,7	567.8	123

- Total salinity: 2796 mg/L.
- pH : 7,74.

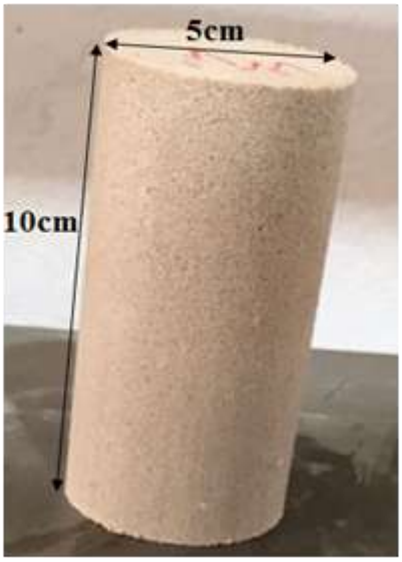


Photo 9. *Specimen for the unconfined compression test*

Photo 10. *Hydraulic press used for the static compaction of specimens*

Photo 11. *Demolding and curing of specimens*

Photo 12. *Compression testing press* ***Photo 13.*** *Specimen after crushing*

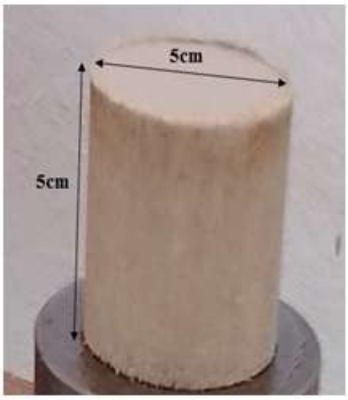


Photo 14. *Specimen for the indirect tensile test*

Photo 15. *Specimen subjected to the indirect tensile test*

Photo 16. *Immersion of the specimens in water*

Photo 17. *Components of the shear box used for the direct shear test (LTPS Laboratory, Ouargla, Algeria).*

Photo 18. *Direct shear box apparatus (LTPS Laboratory, Ouargla, Algeria).*

Photo 19. *Scanning electron microscope (CRAPC Laboratory, Ouargla, Algeria)*

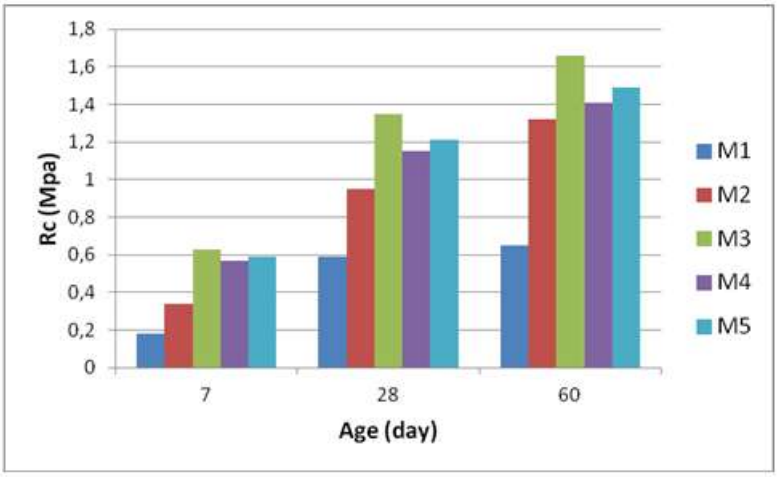


Figure 9. *Evolution of unconfined compressive strength (Rc) as a function of curing age for untreated tuff and treated mixtures*

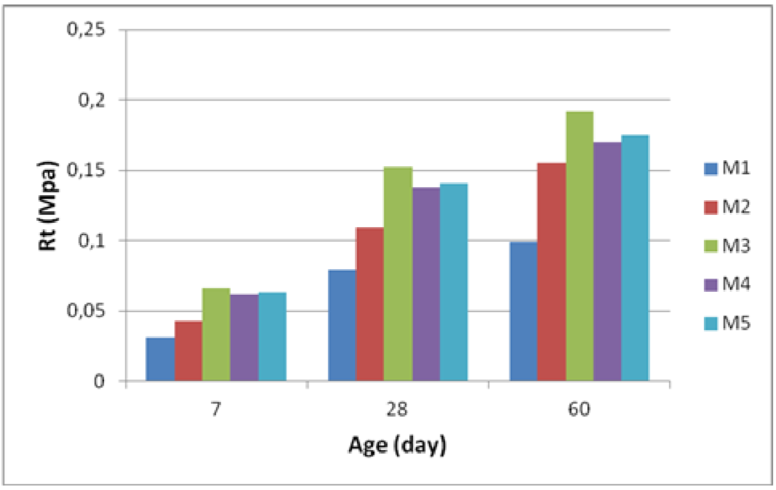


Figure 10. *Evolution of indirect tensile strength (Rt) as a function of curing age for untreated tuff and treated mixtures*

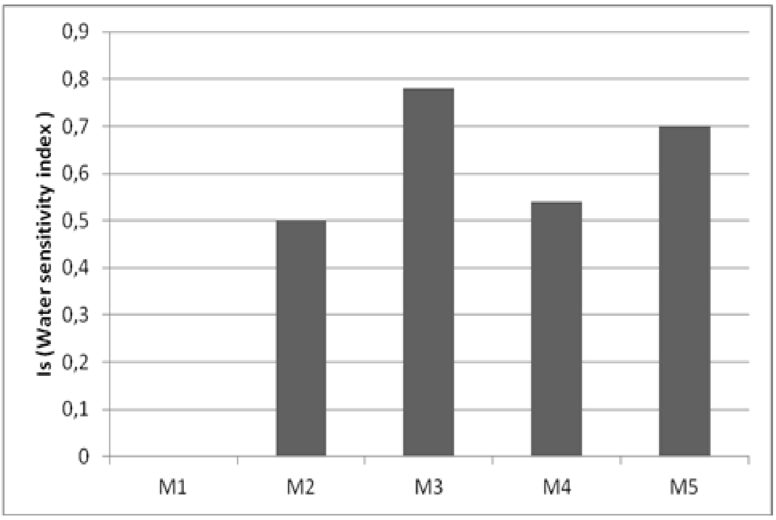


Figure 11. *Water sensitivity index (Is) of the different mixtures*

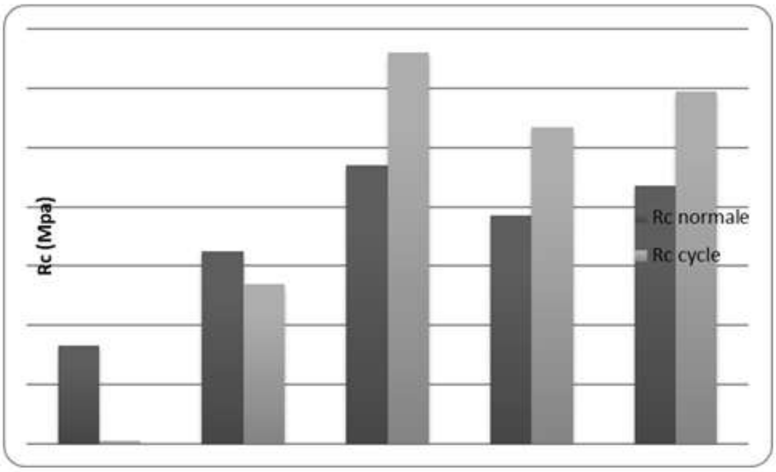
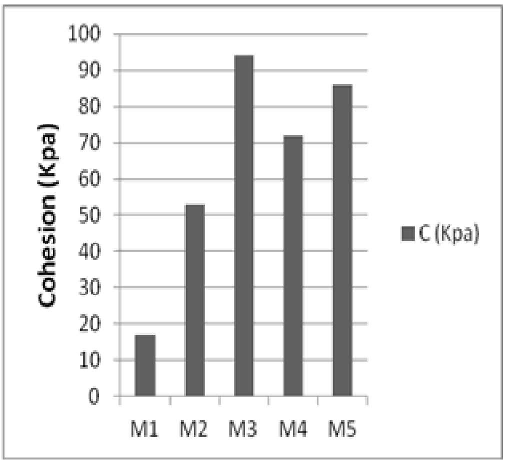


Figure 12. *Unconfined compressive strength of mixtures subjected to wetting–drying cycles compared with those cured under normal climatic conditions*



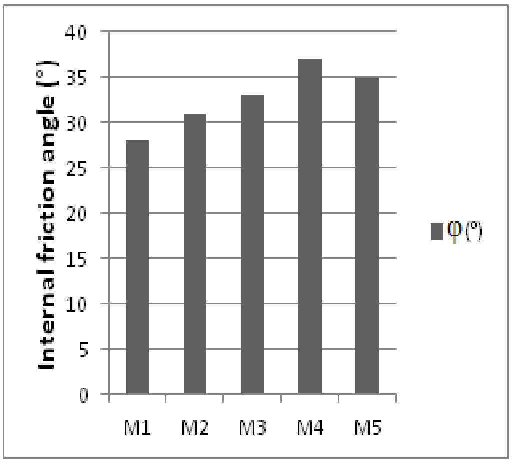


Figure 13*. Cohesion of the studied mixtures* ***Figure 14.*** *Internal friction angle of the studied mixtures*

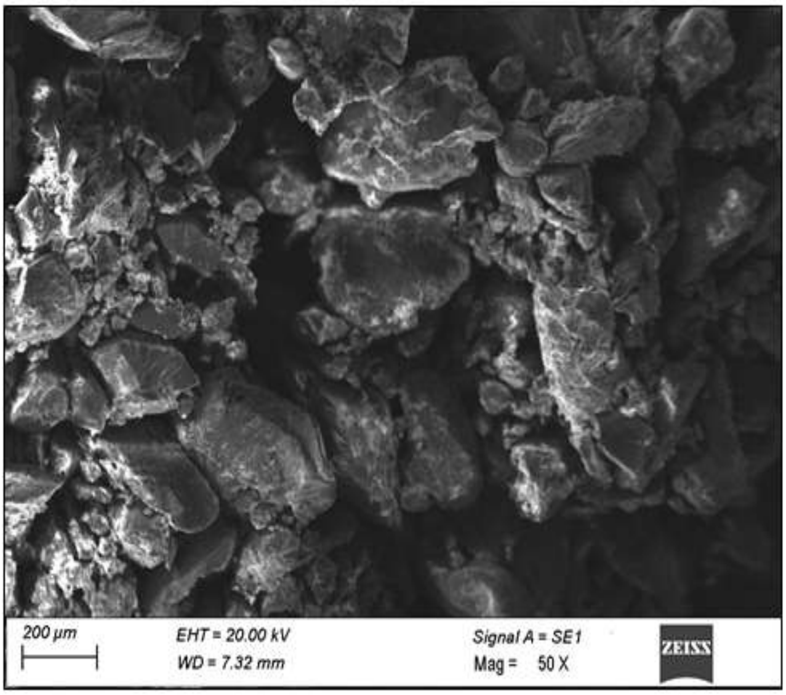


Photo 20. *SEM observation of untreated tuff (M1)*

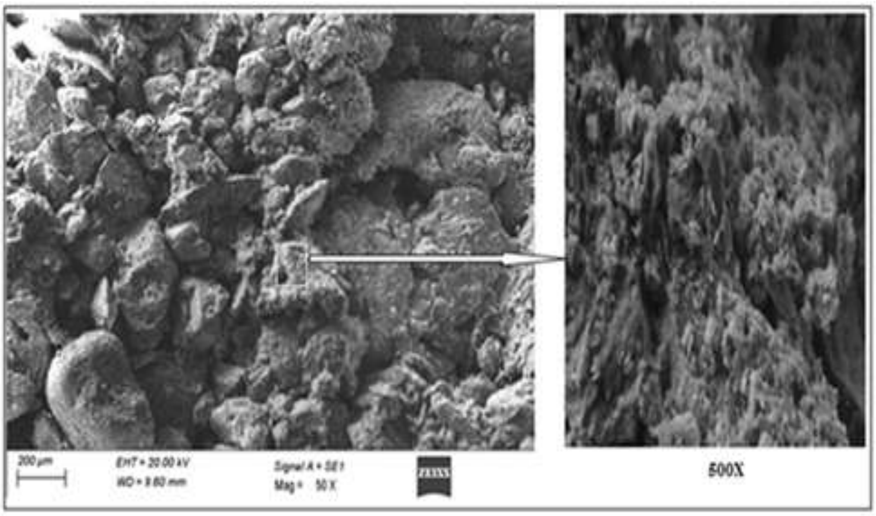


Photo 21. *SEM observation of mixture M2*

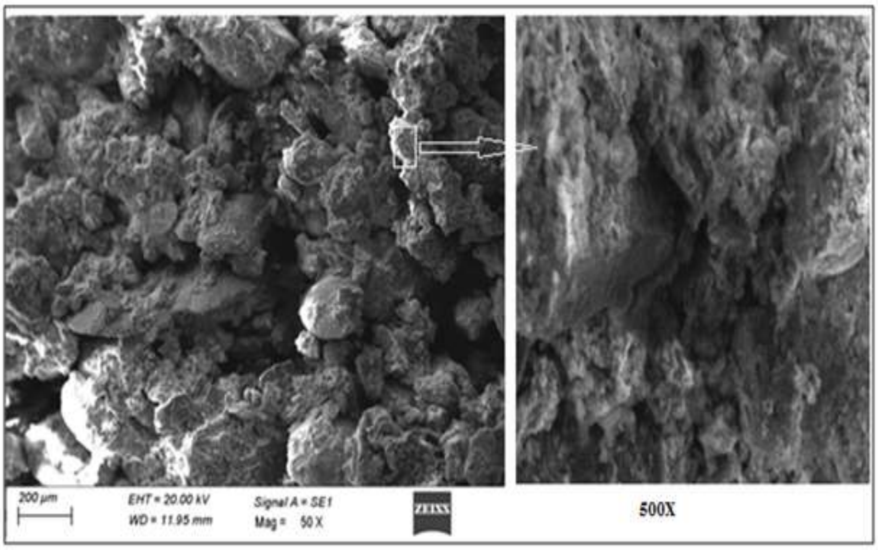


Photo 22. *SEM observation of mixture M3*

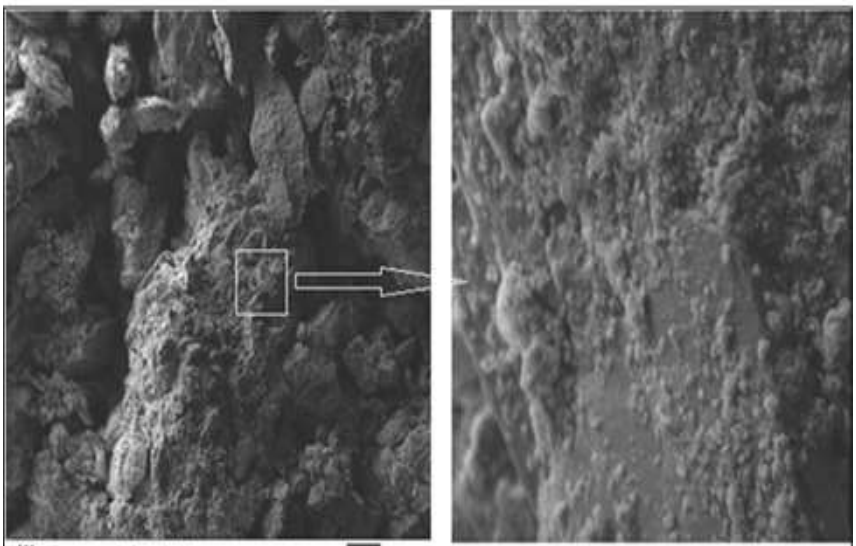


Photo 23. *SEM observation of mixture M4*

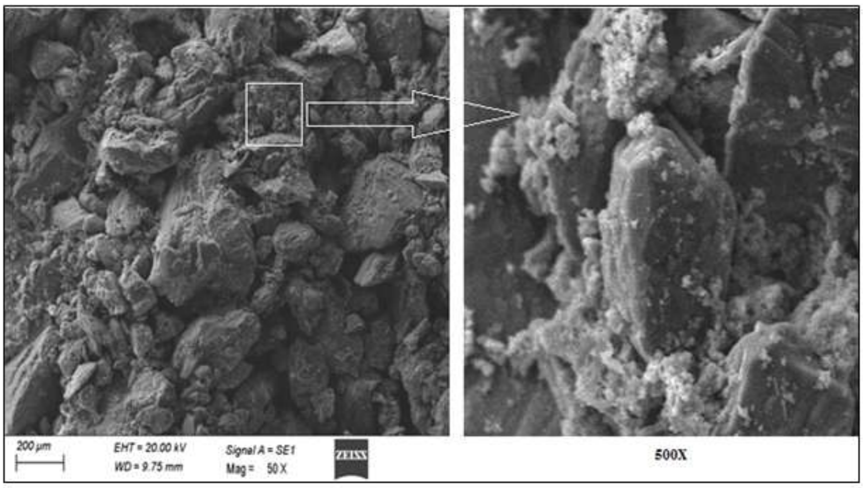


Photo 24. *SEM observation of mixture M5*

4. Conclusions

The results of this study clearly demonstrate that the investigated gypsiferous tuff cannot be used in its natural state for road construction applications due to its low mechanical strength and high sensitivity to water. Lime treatment leads to a noticeable improvement in cohesion and bearing capacity; however, it remains insufficient to ensure satisfactory long-term hydraulic durability.

The incorporation of mineral powders, particularly brick waste powder, results in a significant enhancement of mechanical performance through the development of pozzolanic reactions that promote the formation of a dense and continuous cementitious matrix. Dune sand powder plays a complementary role by improving material compactness and granular interlocking, which leads to an increase in the internal friction angle and enhanced stability under cyclic hydraulic loading.

The formulation combining lime, brick waste powder, and dune sand provides the most favorable balance between mechanical strength and hydraulic stability. These findings highlight the potential of simultaneously valorizing local resources and construction waste materials, fully aligning with a sustainable development approach. Future research perspectives may focus on optimizing mixture proportions, investigating long-term performance, and validating the proposed formulations under real field conditions in road infrastructure applications.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **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
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- **Author contributions:** The authors declare that they have equal right on this paper.
- **Funding information:** The authors declare that there is no funding to be acknowledged.
- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.
- **Use of AI Tools:** The author(s) declare that no generative AI or AI-assisted technologies were used in the writing process of this manuscript.

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