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STABILISATION OF MARL SOIL FOR USE IN COMPACTED EMBANKMENTS BY EGGSHELL QUICKLIME AND ZEOLITE

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Abstract

Chemical soil stabilisation is an established technique in road construction. However, it is constantly evolving to discover novel treatment agents that reduce environmental impact. Traditional agents such as cement and lime, while effective, have drawbacks in terms of cost and environmental impact compared to novel agents. Furthermore, these two agents are rendered ineffective for certain types of highly plastic soil or when the soil is subjected to frequent drying and wetting cycles. Marls' complex and variable mechanical behavior makes them difficult to use as backfill materials. In this context, this study aims to investigate the mechanical behavior of local clayey marl stabilised by an unconventional binder made up of recycled eggshell quicklime and natural zeolite. Unconfined compression, Californian Bearing Ratio, and rectilinear shear tests were carried out on samples treated with varying dosages (2, 4, 6, 8, and 10%), eggshell quicklime and natural zeolite proportions, and curing times (7, 28, and 56 days. The results show that adding the eggshell quicklime and natural zeolite binders improved the mechanical properties of the marl. The compressive strength ratios increased by 4 to 11 times, the Immediate Bearing Index (IBI) exceeded 20 and the friction angle (φ) increased until 25°. The addition of zeolite to eggshell quicklime for soil stabilisation appears to have a positive effect on the different parameters studied. The admixture of these two materials represents a promising alternative for stabilising clayey marls, providing a more sustainable and environmentally friendly solution for earthworks.

Keywords:

Soil stabilisation;
Eggshell quicklime;
Zeolite;
Compressive strength;
Shear strength.

1 Introduction

Road construction on embankments of low-quality evolving materials frequently causes technical issues in many parts of the world [1]. The traditional method of building these embankments entails replacing the existing fine soil of low strength with more resistant and durable soil [2]. Chemical soil stabilisation is a widely recognized and utilised method in the field of civil engineering [1]. Constructing roads on evolving or poor-quality embankments often presents challenges in various regions worldwide [3]. The traditional method for stabilising these embankments involves removing weak, fine-grained soil and replacing it with a more resilient and durable soil [2]. However, this method is replaced by stabilisation with binders when it is expensive and/or has a negative environmental impact. Soil treatment and stabilisation techniques are currently emerging as viable options for improving mechanical properties to provide solid and long-lasting support for various transportation infrastructures.

Much research has been done over the years to find effective and appropriate solutions for improving fine soils with both conventional and unconventional products. Cement and lime are the most widely used conventional products. Many studies have looked into how lime, either alone or in combination with cement, affects the properties of fine soils. The addition of lime and/or cement has been shown to improve the properties of stabilised soils, allowing them to be reused on-site to build sustainable, ecological, and cost-effective embankments [3]. The addition of lime or cement enhances soil properties, allowing it to be reused on-site for durable embankments, thereby contributing to more eco-friendly and cost-effective construction [3- 4]. Etayeb et al. [5] found that adding lime to local marl from Morocco modifies the soil's physicochemical properties, reduces its adsorption capacity, and increases its optimum water content. Other studies have shown that lime stabilisation of marls increased the compressive strength of the soil reduces swelling potential, improves the rigidity of the soil's solid matrix, increases shear and tensile strength, and lowers secondary consolidation coefficients [6-7]. Cement is also a popular stabiliation material in road construction. It is particularly effective at stabilising plastic clays with a high plasticity index, resulting in long-lasting materials with low plasticity, shrinkage, and permeability [3]. Furthermore, it increases the strength, dry density, stability, and durability of marl soils [1]. The combination of lime and cement offers a promising synergy for soil stabilisation, effectively reducing the free swell index, liquid limit, and plasticity index, while increasing maximum dry density, compressive strength, and bearing capacity, with significant improvements observed after extended curing periods [8]. Stabilising marl soils exhibit higher maximum compressive strength and dry density [1]. However, the use of these two conventional products (lime and cement) has an environmental impact. Their production is energy intensive and accounts for 8% of total CO_2 emissions [2], contributing to global warming. In addition, cement becomes ineffective in soils with a high plasticity index, and lime loses cohesion in areas prone to frequent drying-wetting cycles [2]. To overcome the limitations of conventional soil stabilisation products, researchers have turned to unconventional products that offer promising soil treatment alternatives, particularly in terms of technology, economics, and the environment.

Pai and Patel [9] demonstrated that treating black cotton soil with Ground Granulated Blast Furnace Slag (GGBS) activated with lime significantly increased compressive strength (UCS) and CBR values, yielding higher strength and elasticity modulus for extended curing periods. Soil-GGBS-lime mixtures showed a 55% improvement in CBR compared to soil-GGBS mixtures alone. According to Parhizkar et al. [10], the addition of lime, GGBS, and fly ash improves plasticity, compressive strength, microstructure, and elemental composition, resulting in a more stable and less plastic soil. Bensaifi et al. [11], demonstrated that adding 15% GGBS activated with eggshell quicklime increases the unconfined compressive strength (UCS) by 8.5 times and the immediate bearing index (IBI) by 5 times when compared to natural marl. Noaman et al. [12] found that adding fly ash up to an optimal threshold improves soil stability by up to 25%. Fly ash lowers the liquid limit and plasticity index of expansive soils while increasing their unconfined compressive strength [12]. They also improve the CBR index by increasing interfacial contact and bond interlocking in the soil [13]. Another study [14] demonstrated that the addition of magnesium slag and cement increases the soil's maximum dry density (MDD) and optimum water content. The compressive strength (UCS) increases with curing time, reaching a maximum of 20% magnesium slag and 6% cement [14]. Similarly, Toyeb et al. [15] demonstrated that the stabilisation of soil with polyunsaturated fatty acid alkaline activators (AAP) and palm oil fuel ash (POFA), activated by sodium silicate and sodium hydroxide, enhances densification, reduces deformation and increases bearing capacity (CBR) by 54% in 11 days, due to the formation of C-S-H gels. Salehi et al. [16] found that the CBR index and UCS values increased with curing time and stabilising binder content. To improve soil compressive strength, an optimal mixture of 5% to 7% lime, approximately 10% pozzolan, and 10% to 30% crushed limestone waste is recommended. Wijaya et al. [17] revealed that adding a geopolymer binder based on fly ash and blast furnace slag improves the physical and mechanical properties of the tested soil, particularly by increasing compressive strength, reducing the plasticity index and enhancing the bearing capacity (CBR value). Mola-Abasi et al. [18], discovered that adding cement and zeolite to a low-plasticity clay at the same time reduced the optimum water content while increasing it with zeolite alone. The optimal percentage of zeolite was 15%, which significantly improved compressive strength and durability when compared to samples treated only with cement. Furthermore, the same authors [18] demonstrated, using life cycle analysis, that increasing the replacement of cement with zeolite improved the mixtures' environmental performance, including energy consumption and greenhouse gas emissions. Shirmohammadi et al. [19], demonstrated that a lime-zeolite mixture improves the mechanical strength and durability of silty clay under freeze-thaw cycles. The performance of the soil-stabilising binder mixture was improved by replacing up to 30% of the lime with zeolite. Sheikh et al. [20] found that replacing cement with 30% zeolite increased the strain at failure of treated soil by 50%.

It was also demonstrated that the increase in strength ranged from 2.6% to 28.8% for samples containing 40% and 30% zeolite, respectively, and that the compressive strength and strain at failure improved after 28 days of cure.

Calcined lime from eggshells has also been used to stabilise soil. Tonini et al. [21] found that eggshell quicklime is more effective than industrial calcium lime in reducing the swelling of expansive soils. It also has a lower environmental impact than industrial calcium lime, even after accounting for transportation emissions [21]. In another study, Hamza et al. [22], discovered that eggshell quicklime improves the mechanical properties of highly plastic clay (unconfined compressive strength, CBR index, shear strength, and rigidity modulus E50). This binder reduced the clay's compressibility and swelling potential. Saldanha et al. [23] demonstrated that eggshell quicklime improves the performance of stabilised soils while reducing environmental impact. The authors recommended using eggshell quicklime as a more sustainable alternative to traditional lime for soil stabilisation.

Marls are relatively soft materials with low strength and a high swelling potential when exposed to water, limiting their use as backfill in earthworks. These soils are widely distributed around the world and can be found in a variety of countries and regions. They are sedimentary rocks composed of a mixture of carbonates and clay minerals [24]. Their mechanical behavior is complex and varies according to their lithology, state, and degree of cracking and modification. Homogeneous and indurated marls are similar to hard rocks, whereas soft marls behave more like clays [25]. These marls pose a significant challenge to their use as backfill materials in earthworks for transportation infrastructure (roads, railways). Their stabilisation is required to improve their mechanical and durability properties while maintaining a low cost and minimal environmental impact.

To address this issue, this study will assess the mechanical behaviour of local clayey marl with an unconventional stabilising binder made from eggshell quicklime (EQL) and zeolite (ZEO). The scientific approach is based on experimental methods that include unconfined compression tests, CBR tests, and rectilinear shear tests on various samples of treated marl at varying dosages and curing times. The goal is to make the marl a usable material suitable for road construction by giving the treated soil properties similar to granular borrow material. The goal of reusing marl treated with eggshell quicklime (EQL) and zeolite (ZEO) is to reduce the economic cost and environmental impact of earthworks, providing a viable alternative to traditional stabilisers like cement and lime.

2 Materials and method

2.1 Soil sample

The tested marl is from the Aïn Tine area in the wilaya of Mila, North-East Algeria. After sampling a volume of about 1.5 m³, the soil was dried in the open air at room temperature. The coarse fraction of the marl was then removed through dry sieving using a 20 mm sieve. The physical and geotechnical properties of natural marl, such as particle size, Atterberg limits, maximum dry density, optimum water content, immediate bearing index, free swelling potential, and pH, were determined using ASTM D422 [26], ASTM D4318 [27], ASTM D698 [28], ASTM D4546 [29], and ASTM D1293 [30], respectively. The properties are summarized in Table 1, and the granulometric curve is shown in Figure 1. The marl is classified as low-plastic clay "CL" by the Unified Soil Classification System [31] (ASTM D5287). Figure 2 shows the Standard Proctor and IBI curves of natural marl determined in accordance to ASTM D698 [28].

Table 1: Properties of natural marl.

Designation	Values
Dmax [mm]	6.3
Fraction < 0.08 mm [%]	83
Methylene blue value	3
Liquid limit [%]	40.2
Plastic limit [%]	17.1
Plasticity index Ip [%]	23.1
Optimum water content OMC [%]	15
Maximum dry unit weight MDD [kN/m^3]	19.3
IBI	3.2
pH	8
Free swelling index (%)	0.7

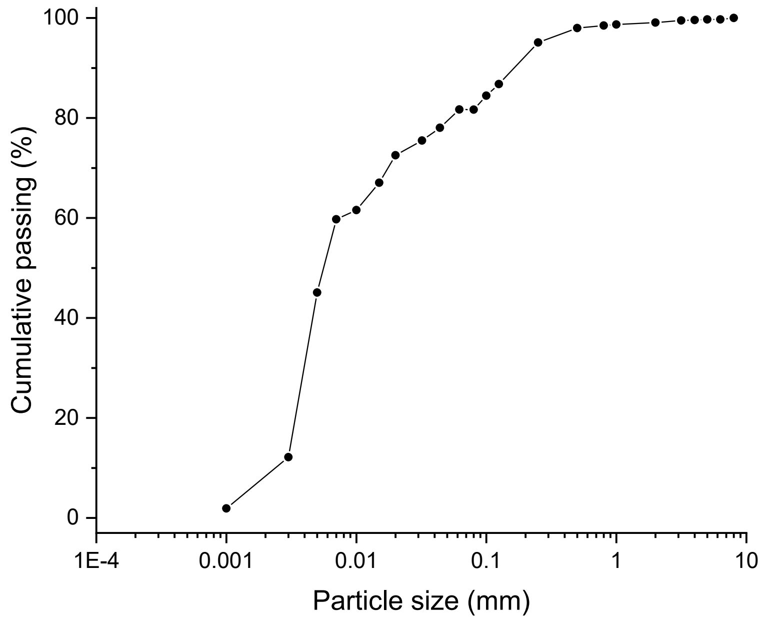


Fig. 1: Granulometric curve of natural marl.

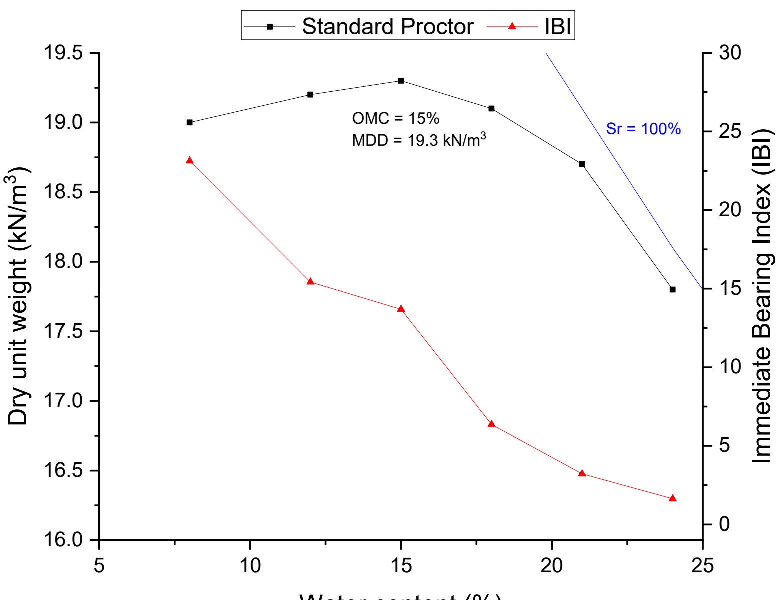


Fig. 2: Proctor and IBI curves of natural marl.

2.2 Additives

The additives used in this study are eggshell quicklime and zeolite. Brown eggshells are collected from bakeries. After washing with running water to remove organic matter from the shell wall, air drying was carried out for 48 h at room temperature. The shell is then calcined in an oven at 900 °C for 2 h to complete the transformation of calcium carbonates into calcium oxides [11]. After cooling, the shell lime is ground with the Micro Deval machine's ball mill, which contains small steel balls. The grinding resulted in a fine white powder with a uniform particle size of 80 µm.

The zeolite used was sourced from the Tuf deposit at Tinebdar, Wilaya de Béjaïa. This deposit is situated on the left (west) bank of the Remila wadi in the Algerian Tell Mountains [32]. It is known for its zeolite-rich sedimentary deposits. This zeolite is mostly of the mordenite type, which is a common crystalline structure in natural zeolites [33]. The raw material extracted is crushed stones. To obtain fine zeolite powder with a particle size of less than 80 µm, the stones are ground in a Los Angeles machine and sieved to separate fine and coarse particles.

Table 2 summarizes the chemical properties of eggshell quicklime and zeolite as determined using XRF. It reveals that the eggshell, after calcination, contains approximately 92% CaO. This high concentration of calcium oxide suggests that it can react with zeolite, which contains approximately 66% SiO_2, to form a cementitious material. The exothermic reaction between calcium oxide (CaO) and silica (SiO2) yields calcium silicate [34]. Calcium silicate is the primary component of cementitious materials, providing strength and durability.

Table 2: Chemical properties of eggshell quicklime (EQL) and zeolite (ZEO).

Chemical compounds	EQL [%]	ZEO [%]
CaO	94.82	2.04
SiO2	0.14	62.10
Al2O3	0.09	18.08
Fe2O3	0.03	1.20
MgO	2.45	1.53
K2O	0.05	4.02
SO3	0.30	0.03
Na2O	1.57	7.59
TiO2	/	0.47
Others	0.55	1.68

2.3 Experiments

Three mechanical performance tests were carried out on marl samples treated with different binder stabiliser dosages and eggshell quicklime/zeolite proportions (EQL-ZEO). First, unconfined compression tests (UCS) were performed on cylindrical specimens (H=15 cm and Ø=7.5 cm) of natural marl (0%) and treated with five dosages of binder (2%, 4%, 6%, 8% and 10%) and six proportions of EQL-ZEO (100-0, 90-10, 80-20, 70-30, 60-40, 50-50, 40-60) to determine the optimal composition of the combined EQL-ZEO binder. All mixtures had a dry density of 18 kN/m3 and a water content of 21%. This water content falls within the water state required for binder hydration. After static compaction, the cylindrical specimens were sealed and stored at 20±2°C until the time of the UCS tests (short and long term) (Figure 3). The latter were made in accordance with ASTM D2166 [35].

Following the results of the UCS tests, CBR and shear tests were performed on the optimal EQL-ZEO proportions obtained in the first phase. CBR tests (IBI value) without the loading ring and rectilinear shear at the Casagrande box are carried out in accordance with ASTM D1883 [36] and D3080 standards [37], respectively, for all binder dosages (2%, 4%, 6%, 8%, and 10%). It should be noted that the rectilinear shear tests are of the drained consolidated (CD) type and are performed on specimens of soil-binder mixtures reconstituted by static compaction at the same dry density and water content as the UCS tests, namely 18 kN/m^3 and 21%, respectively. The specimens measure 2 cm high and 6×6 cm in section (Figure 3). Table 3 summarizes all of the combinations and curing times for each test. To ensure measurement consistency, the tests were repeated twice for all binder contents.

Fig. 3: Photo of specimens prepared for UCS and shear tests.

Table 3: Mixing combinations, dosages, EQL-ZEO proportions and curing times for all experiments.

Tests	Combination	Dosage [%]	Proportion		Cure time [day]
			EQL [%]	ZEO [%]	
UCS	SOIL	-	-	-	-
	SOIL+EQL	2, 4, 6, 8, 10	100	0	7-28-56
	SOIL+EQL+ZEO	2, 4, 6, 8, 10	90	10	7-28-56
	SOIL+EQL+ZEO	2, 4, 6, 8, 10	80	20	28
	SOIL+EQL+ZEO	2, 4, 6, 8, 10	70	30	7-28-56
	SOIL+EQL+ZEO	2, 4, 6, 8, 10	60	40	28
	SOIL+EQL+ZEO	2, 4, 6, 8, 10	50	50	28
	SOIL+EQL+ZEO	2, 4, 6, 8, 10	40	60	28
CBR (IBI)	SOIL	-	-	-	-
	SOIL+EQL	2, 4, 6, 8, 10	100	0	7
	SOIL+EQL+ZEO	2, 4, 6, 8, 10	90	10	7
	SOIL+EQL+ZEO	2, 4, 6, 8, 10	70	30	7
Direct shear test	SOIL	-	-	-	-
	SOIL+EQL	2, 4, 6, 8, 10	100	0	7-28
	SOIL+EQL+ZEO	2, 4, 6, 8, 10	90	10	7-28
	SOIL+EQL+ZEO	2, 4, 6, 8, 10	70	30	7-28

3 Results and discussion
3.1 Unconfined compressive strength
3.1.1 UCS at 28 days

Figure 4 shows the results of unconfined compression tests after 28 days of curing for different dosages (2%, 4%, 6%, 8%, and 10%) and proportions of EQL-ZEO (100-0, 90-10, 80-20, 70-30, 60-40, 50-50, and 40-60). The results show that increasing the binder dosage increases UCS for all EQL-ZEO proportions, with the exception of the 6% and 10% dosages at the 80-20 and 60-40 proportions and the same dosages at the 50-50 and 40-60 proportions. The strength increases ratios compared to the initial UCS value (natural marl) range between 4 and 8 times for low and medium dosages (2%, 4%, and 6%) and 7 to 11 times for high dosages (8% and 10%). These ratios demonstrate that the treatment has a positive effect on both mechanical performance and the binder's reactivity with soil particles, allowing the formation of new cementitious bonds and, as a result, a stronger and more resilient internal structure.

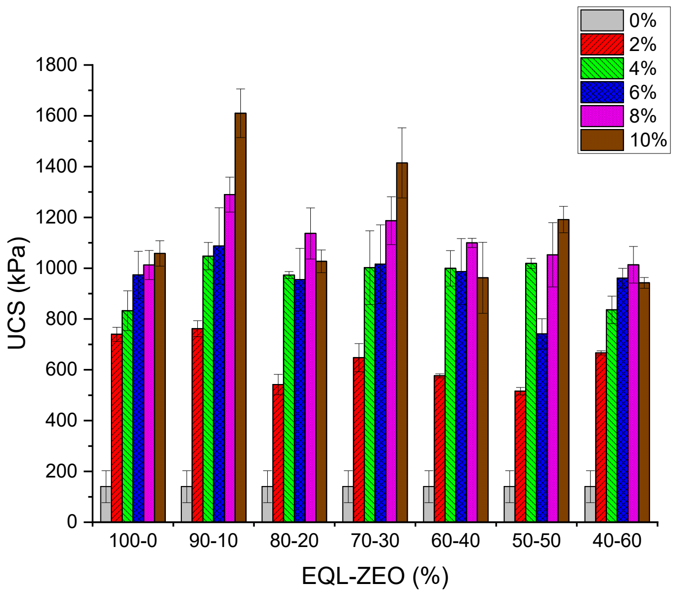


Fig. 4: UCS evolution with different EQL-ZEO dosages and proportions.

The findings also indicate that the proportions 90-10 and 70-30 produced the highest UCS across all binder assays. These two proportions exhibit a constant increase in resistance with increasing dosage, indicating mechanical stability in the treated marl. These findings appear to be consistent with those of Kordnaeij et al. [38], who determined that 30% zeolite was the optimal amount for maximizing the unconfined compressive strength of cement-stabilised sand. In another study, Mola-Abasi et al. [39] demonstrated that the compressive strength of the soil-cement-zeolite mixture was optimal with 30% cement replacement by zeolite because the amounts of SiO2 and AlO3 are close to CaO, allowing the pozzolanic reaction to contribute to the treated soil's compressive strength. According to the same study, the UCS improves by 68% at the optimal zeolite concentration of 30%. In contrast, for the proportions 80-20, 60-40, and 40-60, the UCS increases as the dosage increases (2%, 4%, 6%, and 8%) before dropping to 10%. The proportion 50-50 results in a decrease in UCS at a 6% dosage.

3.1.2 Short and long-term UCS

The three soil-binder mixtures with the proportions EQL-ZEO 100-0, 90-10, and 70-30 were tested for short (7 days) and long-term (56 days). The compressive strengths (UCS) are shown in Figure 5. The results show that UCS gradually increases with curing time for all dosages (2%, 4%, 6%, 8%, and 10%). Between 7 and 28 days of curing, the increase in UCS for the low dosage of 2% and the high dosage of 10% exceeds 90% for all three EQL-ZEO proportions. This increase in UCS is greater for mixtures containing zeolite (90-10, 70-30) than for eggshell quicklime alone (100-0). For the other dosages (4%, 6%, and 8%), the increases in UCS do not exceed 15% when treated with eggshell quicklime alone (100-0), whereas this percentage increase reaches 56% and 68% when zeolite is added to eggshell quicklime at 90-10 and 70-30, respectively. These findings are consistent with those of Mola-Abasi et al. [17], who found that pozzolanic reactions between zeolite, calcium, and silica in the soil contributed to increased strength, particularly at 30% zeolite replacement.

Furthermore, Shirmohammadi et al. [19] found that a mixture of 5% lime and 15% zeolite significantly increased soil strength during freeze-thaw conditions. The results showed that the soil's compressive strength increased by about 40% compared to the untreated sample, demonstrating the efficacy of zeolite addition. This increase is due to the formation of hydrated bonds between the soil and the eggshell quicklime-zeolite composite binder. Indeed, zeolite is classified as a pozzolan due to its pozzolanic reactivity when reacting with eggshell quicklime, which is primarily composed of calcium hydroxide ($Ca(OH)_2$) and dissolves in water to form calcium ions (Ca^{2+}) and hydroxide ions (OH-) (Saldanha et al. 2021). The latter (hydroxide ions) react with the aluminum (Al_2O_3) and silicon (SiO_2) ions in the zeolite to form CSH and CAH gels, which then form a strong and long-lasting soil-binder matrix [39].

This result demonstrates that the combination of these two materials (eggshell quicklime and zeolite) appears to have a synergistic effect, increasing the strength of the final material when compared to using eggshell quicklime alone. Between 28 and 56 days (long term), the percentage increase in UCS for the low dosage of 2% and the high dosage of 10% is significant for all three EQL-ZEO proportions. The 2% and 10% dosages have an average of about 17% and 22%, respectively, which demonstrates how sensitive these two dosages are to the combined effect of the quick shell lime-zeolite proportion. For the other three dosages (4%, 6%, and 8%), regardless of the EQL-ZEO proportion, the percentage increase in UCS is nearly zero, and resistances remain stable over time (56 days).

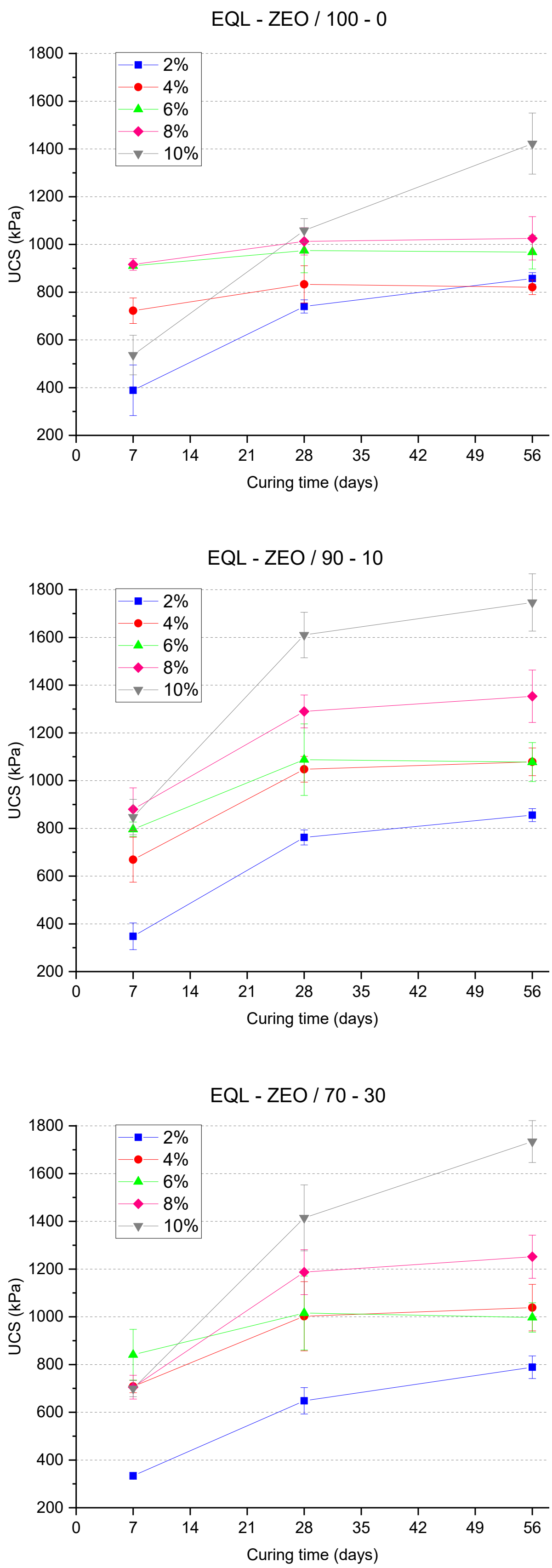


Fig. 5: Unconfined compressive strength as a function of curing time for different EQL-ZEO proportions.

3.2 Effect of treatment on bearing capacity

The results of the Immediate Bearing Index (IBI) after 7 days of curing for different dosages and EQL-ZEO proportions are shown in Figure 6. The Immediate Bearing Index (IBI) results show that IBI increases with dosage increases ranging from 2% to 8%, followed by a decrease to 10% for all quick shell-zeolite proportions. This result demonstrates the treatment's positive effect for dosages less than 8%; however, at 10% and under the negative effect of binder overdose, the balance of interactions between the marl particles and the binder leads to a weakening of the mixture. The treated marl's bearing capacity exceeds 20 after 7 days of curing, and this is only for a 2% binder dosage. The maximum IBI value exceeded 50 for an 8% dosage at a 90-10 EQL-ZEO ratio. For the same binder dosage, the results show that the addition of zeolite to the shell has little influence at 2%. For the other dosages (4%, 6%, 8%, and 10%), the addition of zeolite has a positive effect, with the best results obtained at proportions of 90-10 and 70-30. This finding indicates that zeolite improves the treatment efficiency of eggshell quicklime marl.

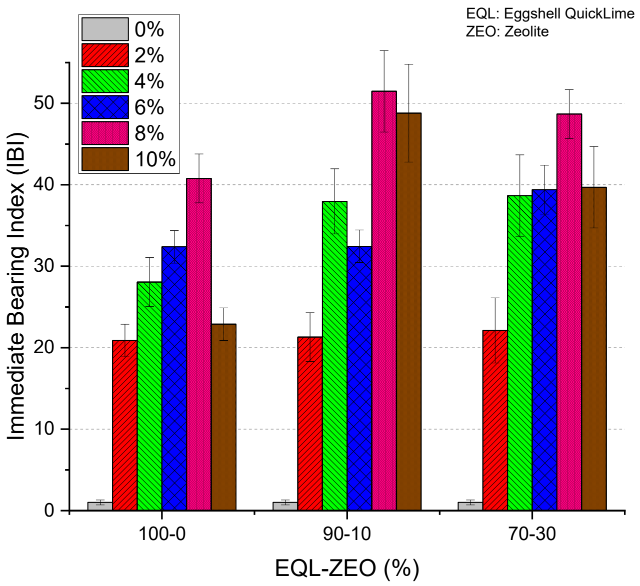


Fig. 6: Evolution of IBI with different EQL-ZEO proportions for different binder dosages.

3.3 Direct shear strength

3.3.1 Shear characteristics at 7 and 28 days

Figures 7 and 8 show the results of drained consolidated direct shear (CD) tests on treated and natural (untreated) marl at three EQL-ZEO proportions. The figures show how the internal friction angle (φ) and cohesion (C) change with binder content for 7 and 28-day curing times. Overall, the findings indicate that the binder dosage (EQL+ZEO) has a significant effect on the friction angle and cohesion. The results after 7 days (Figure 7) show an increase in the friction angle as the dosage increases. The friction angles for the proportions 90-10 and 70-30 are slightly higher than those for the proportions 100-0 and significantly higher than for natural marble. For example, at 6% dosage, the values for the proportions 90-10, 70-30, and 100-0 are 18°, 14°, and 12° higher than those of natural marl (2°). In terms of cohesion, the dosages of 2% and 4% show an increase, followed by a decrease for the three dosages of 6%, 8%, and 10%, as well as the two proportions (90-10 and 70-30).

For proportion 100-0, cohesion was insensitive to the effect of quick shell lime treatment alone for the first three dosages of 2%, 4%, and 6%, which are equivalent to those of natural marl, but then decreased to 8% and 10%. A combined analysis of the two parameters reveals that φ and C increase together for 2% and 4% dosages, then decrease together for 6% and 8% dosages. However, for the 10% dosage, the increase in φ is offset by a decrease in C. The increase in both parameters φ and C results in marl-binder mixes with greater resistance to particle sliding (φ effect) and solid matrix confinement (cohesion effect), allowing for the formation of a more shear-resistant soil structure. An overdose of binder greater than 6% can have the opposite effect (decrease of φ and C) by weakening the interaction between soil particles (φ) and reducing cohesion, resulting in a less resistant and less confined solid matrix.

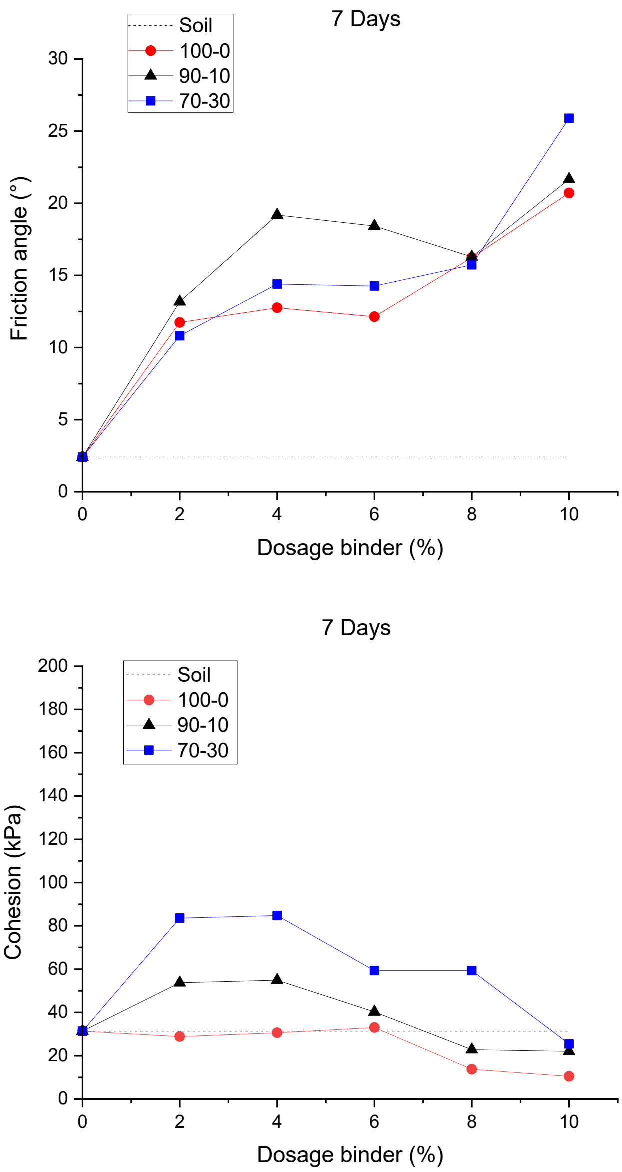
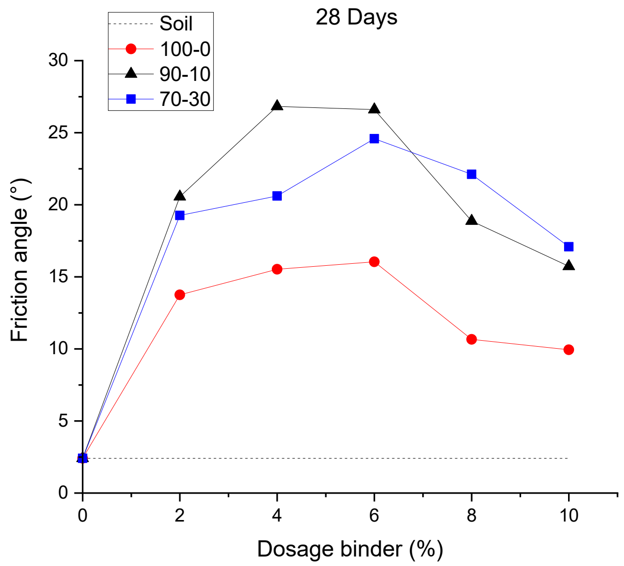


Fig. 7: Evolution of the angle of friction and cohesion as a function of binder dosage for different EQL-ZEO proportions after 7 days of curing.

Figure 8 shows the trends in φ and C at 28 days as binder dosage increases, as well as the effect of EQL-ZEO proportions on shear properties. Friction angle (φ), an indicator of shear strength, gradually increases up to 6%, then decreases for 8% and 10% dosages across all EQL-ZEO proportions. The friction angle values for the mixtures with the addition of zeolite (90-10 and 70-30) are higher than those for the treatment with quick shell lime alone, and this holds true across all dosages. In terms of cohesion, the three mixtures (100-0, 90-10, and 70-30) show a slight increase up to an 8% dosage, followed by a significant increase at 10% for the mixtures (90-10 and 70-30), while the mixture 100-0 shows a decrease in cohesion at this dosage. At this high dosage (10%), the results show that the treatment has a positive effect on cohesion but a negative effect on the friction angle, leading us to conclude that binder overdose weakens shear characteristics.



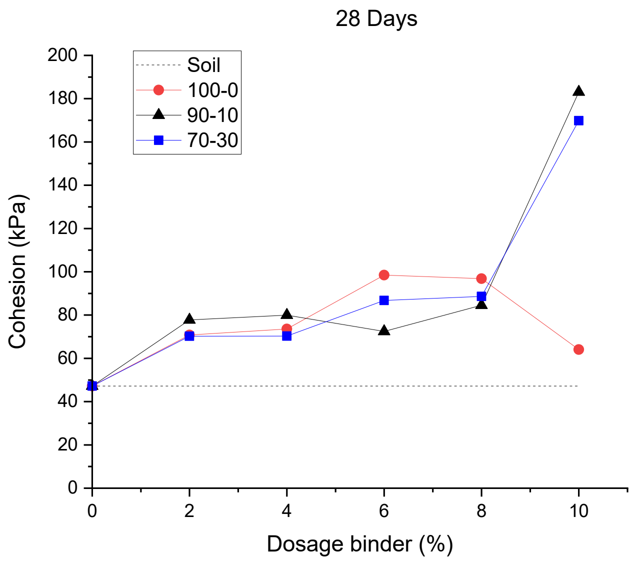


Fig. 8: Evolution of the angle of friction and cohesion as a function of binder dosage for different EQL-ZEO proportions after 28 days of curing.

3.3.2 Evolution of shear characteristics as a function of curing time

Figures 9 and 10 show the evolution of φ and cover curing time (7 and 28 days) for different binder dosages and EQL-ZEO proportions. The analysis of these results reveals some intriguing trends regarding the effect of EQL-ZEO on the shear properties of stabilised marl. Indeed, the friction angle, a key indicator of shear strength, increases with dosage and curing time, with the exception of high dosages (6%, 8%, and 10%) at the 100-0 proportion and a 10% dosage at the 90-10 proportion. The 70-30 proportion yielded the highest friction angle values after 28 days. The cohesion increases significantly between 7 and 28 days for all binder dosages and EQL-ZEO proportions, with the 90-10 and 70-30 mixtures outperforming the 100-0 and natural marl. The 70-30 proportion is distinguished by an ideal balance of friction angle and cohesion, especially at 28 days. These findings lead us to conclude that the addition of the combined EQL-ZEO binder, at moderate dosages and with adequate curing time, can significantly improve the shear properties of stabilised marl, particularly at the 70-30 proportion.

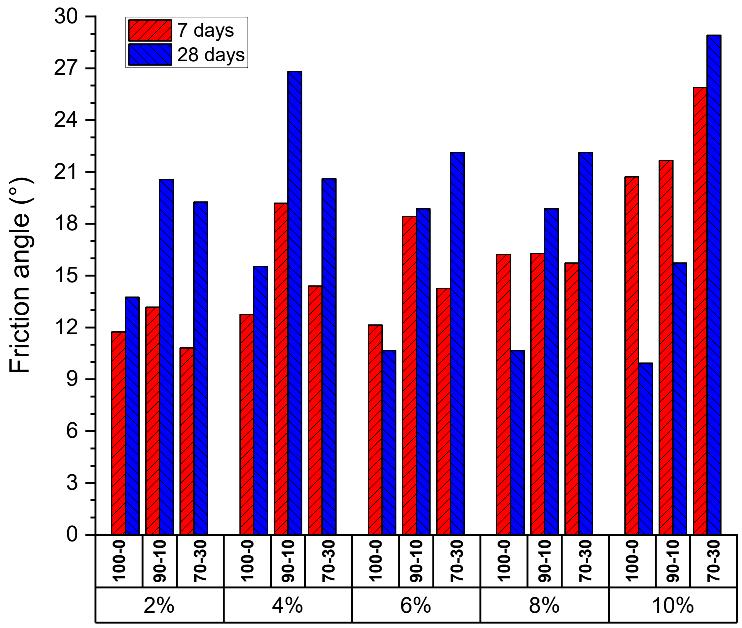


Fig. 9: Evolution of the angle of friction as a function of curing time for different EQL-ZEO dosages and proportions.

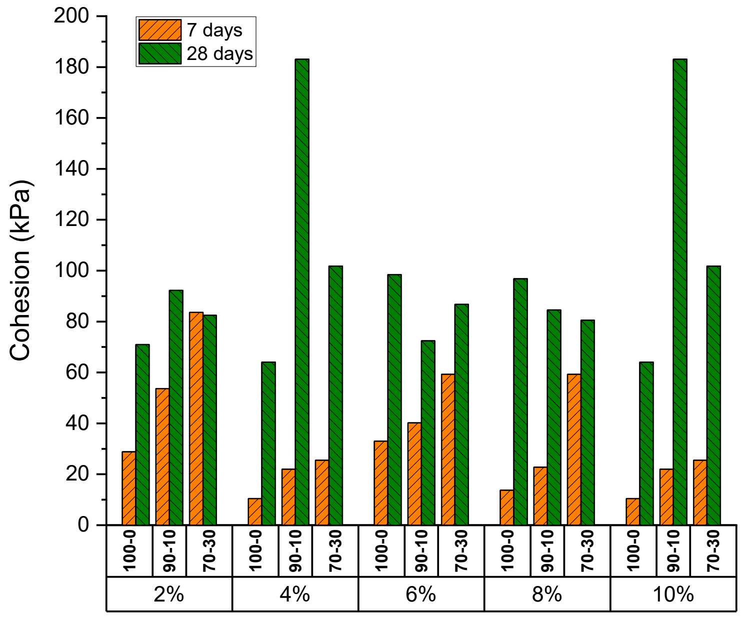


Fig. 10: Evolution of cohesion as a function of hardening time for different EQL-ZEO dosages and proportions.

4 Conclusion

This study examined the mechanical properties of clayey marl treated with a new binder made of eggshell quicklime and zeolite. The results of unconfined compression, CBR (IBI), and shear tests lead us to conclude that adding the new EQL-ZEO treatment binder significantly improves the mechanical properties of the marl, making it suitable for road construction applications (embankment, subgrade). The increase ratios compared to the initial value of unconfined compressive strength (UCS natural marl) are between 4 and 8 times for low and medium dosages (2%, 4%, and 6%) and 7 to 11 times for high dosages (8% and 10%). The proportions 90-10 and 70-30 produced the highest UCS across all binder assays. In fact, the increase in UCS of EQL-ZEO stabilised marl is caused by the formation of hydrated bonds between the soil and the composite binder. Shell lime and zeolite, with their high CaO, silica, and alumina content, strengthen soil particle bonds and promote material solidification. The combined action of shell lime and zeolite outperforms shell lime alone, allowing for higher levels of mechanical performance.

The increase in UCS over the medium and long term is significant for the low (2%) and high (10%) dosages, regardless of the three EQL-ZEO proportions. This increase in UCS is greater for zeolite-containing mixtures (90-10, 70-30) than for the 100-0 mixture. The increases in UCS are less significant at the other dosages (4%, 6%, and 8%), regardless of the EQL-ZEO proportion. In the long run (56 days), there is almost no percentage increase in UCS. After 7 days of curing, the 2% treated marl has a bearing capacity greater than 20. The maximum IBI value was obtained with an 8% dosage at a proportion of 90-10. Overall, the addition of zeolite to the shell has a positive effect, with the best results obtained at proportions of 90-10 and 70-30. In addition, the shear strength of marl stabilised with EQL-ZEO binder is improved in the short and medium term by increasing the values of the shear characteristics (φ and C) as a function of increasing low and medium dosages.

However, this trend is reversed for high dosages. The addition of zeolite appears to increase shear strength. The results show that the addition of quick shell lime and zeolite improves the marl's resistance to mechanical stresses. As a result, the marl will be better able to withstand the loads and mechanical stresses encountered during road construction. The pozzolanic effect of the EQL-ZEO mixture in the presence of water causes the formation of hydrated compounds like calcium silicates and aluminates. These compounds strengthen the cement matrix, increasing the material's resistance to wear, weathering, and aggressive agents, thereby extending its useful life.

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