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Optimizing properties of clayey soil using lime and waste marble powder: a sustainable approach for engineering applications

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Several studies have explored the potential of waste marble powder (WMP) and lime (LM) as solutions for issues associated with clayey soils. While WMP enhances mechanical properties and addresses environmental concerns, LM effectively improves soil characteristics. This research investigates the efficacy of LM and WMP, both individually and in combination, in addressing challenges specific to clayey soils in Bouzaroura El Bouni, Algeria. These soils typically exhibit low load-bearing capacity, poor permeability, and erosion susceptibility. LM demonstrates promise in enhancing soil properties, while WMP not only addresses environmental concerns but also enhances mechanical characteristics, providing a dual benefit. The study utilizes a three-variable experiment employing Response Surface Methodology (RSM) Box-Behnken Design, with variations in clay content (88%–100%), LM treatment (1.5%–9%), and WMP inclusion (1.5%–9%). Statistical analysis, including ANOVA, reveals significant patterns with p-values <5%. Functional relationships between input variables (clay, LM, and WMP) and output variables (cohesion, friction angle, and unconfined compressive strength) are expressed through high determination coefficients (R^2 = 99.84%, 77.83%, and 96.78%, respectively). Numerical optimization identifies optimal mixtures with desirability close to one (0.899–0.908), indicating successful achievement of the objective with 88% clay content, 3% LM, and 6% WMP. This study provides valuable insights into optimizing clay soil behavior for environmental sustainability and engineering applications, emphasizing the potential of LM and WMP as strategic additives.

KEYWORDS

clayey soil, geotechnical tests, waste recovery, optimization, box-behnken, artificial intelligence, microstructure

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1 Introduction

The rapid growth of the construction industry has revealed the limitations of traditional geology in addressing construction professionals' requirements. In response, geotechnics has emerged as a discipline focusing on problematic soil behavior. Frequently, soil mechanical and structural properties are found to be insufficient according to minimum design and construction standards. This situation often requires stabilization to enhance the required properties (Onyelowe et al., 2021). Numerous studies have investigated the use of various additives, including cement, lime (Firoozi et al., 2017), sodium hydroxide, fly ash geopolymeric binders, ashes, and cementitious binders, to stabilize clayey soils for assessing their effectiveness as soil stabilizers. Soil stabilization typically falls into two categories: mechanical stabilization and chemical stabilization (Ahmed et al., 2021). These processes aim to improve engineering properties such as soil strength, durability, stiffness, and reduce plasticity, swelling, and shrinkage. The application of soil stabilization techniques offers several advantages for treated soils (Firoozi et al., 2017). Many studies have been conducted on the impact of cement on the mechanical behavior of soil (Crawford et al., 2019; Boutahir Born Bencheikh et al., 2021). The incorporation of cement enhances the mechanical characteristics of soil, as indicated by scholarly investigations (Jayasinghe and Kamaladasa, 2007) Ordinary Portland Cement (OPC) stands as the quintessential binding agent within the realm of stabilization and solidification, owing to its remarkable efficacy, affordability, widespread availability, and unwavering reliability (Wang et al., 2019a) Among hydraulic binders employed for stabilization purposes, OPC reigns supreme as the primary stabilizing agent. A sufficient amount of cement increases saturated strength as well as both the long-term and short-term resistance to water erosion. The intricate interplay between the cement concentration, packing density, moisture content, curing conditions, mineralogy, and physical qualities of the sand make it difficult to determine the unconfined compressive strength of cemented soil (Kaniraj and Havanagi, 1999; Subramanian et al., 2020), both provided examples of this. Mani Axel and colleagues elucidated the optimal cement dosage and durability index for quantifying the impact of water absorption on the strength of cement-stabilized loess (Axel et al., 2023), Lime stabilization stands as an established technique for enhancing the characteristics of clayey soil, mitigating its inherent deficiencies including low strength, pronounced compressibility, and substantial volumetric variations, among others, thereby rendering it more conducive for construction purposes. This method not only offers economic benefits by reducing expenses but also alleviates the strain on finite resources, thus curtailing the environmental impact associated with geotechnical engineering endeavors. Geotechnical projects, such as pavement constructions and engineered fills, have markedly profited from the augmented engineering attributes exhibited by densely compacted lime-stabilized clayey soils (Jayasinghe and Kamaladasa, 2007; Garzón et al., 2016; Frank et al., 2022) investigated the effect of 3, 4, and 7% of lime on the swelling of Phyllite clay and reported that 3% of lime is a sufficient dosage in stabilizing Phyllite clay, where the swelling was reduced (Cheshomi et al., 2017). highlights the potential of flyash as a valuable additive to improve the engineering properties of claysoils, particularly in the context of sulfate-bearing clays with lime stabilization. The results of (Okeke et al., 2021) indicate that the minimal reduction in soil strength corresponds to its optimal stabilization with lime. The addition of Pouzzolanic waste to a soil mixture enhances its technical properties and accelerates the process by promoting pozzolanic reactions. Pouzzolanic waste, characterized by a high siliceous content, forms cementitious products upon hydration with water and calcium hydroxide, leading to improved strength and durability (Amakye et al., 2021). in their study reveal the possibility of using waste materials like cement and lime replacement in road construction due to their cementitious properties, engineering properties and characteristics of these waste which as similar to cement and lime (Erdoğan et al., 2012). have employed waste marble powder within the brick industry, an endeavor of notable significance in the recycling of such waste material for brick production, thereby yielding substantial contributions to both economic and ecological spheres (El-Mahllawy et al., 2018). in their study concerning the Feasibility of utilizing marble cutting waste in sustainable building practices, elucidated that the optimal proportion of marble sludge waste stands at 15% when substituting hydrated lime in the fabrication of stabilized clay bricks.

The utilization of Design of Experiment (DOE) stands as a ubiquitous method within engineering research, wherein a statistical framework is employed to orchestrate experimental trials aimed at constructing a mathematical model. This methodology empowers researchers or practitioners to refine and forecast prospective outcomes contingent upon various parameter configurations. Furthermore, Response Surface Methodology (RSM) emerges as another statistical tool employed for the purpose of modeling and scrutinizing scenarios characterized by the influence of multiple variables upon a given response. The overarching objective of RSM lies in the optimization of the overall response. Moreover, RSM facilitates a reduction in the requisite number of experimental iterations necessary to procure statistically reliable outcomes, thus mitigating the need for redundant experimentation across diverse factors.

Forecasting the mechanical attributes of stabilized clay soils persists as a challenge, primarily attributed to the intricate, non-linear interplay between soil characteristics and the parameters governing stabilization, as evidenced by studies in the field, notwithstanding promising outcomes derived from empirical analyses. Geotechnical engineering endeavors involve the meticulous application of strength analysis to ascertain the viability of various engineering methodologies. This includes the meticulous design and stability assessment of essential structures such as foundations, backfills, retaining walls, slopes, and embankments. Such analysis serves a pivotal role in gauging the efficacy of soil stabilization methods, identifying the optimal proportions of stabilizing agents, and assessing the impact of diverse factors influencing the strength of stabilized soil. Numerous investigations have embraced Response Surface Methodology (RSM) as a tool to orchestrate experiments, construct models, and refine variables with precision and efficacy.

(Umar et al., 2023) investigated the impact of waste marble powder (WMP) on unconfined compressive strength (UCS) and ultrasonic pulse velocity (UPV) in clayey soil. Artificial neural networks (ANNs) were used to predict UCS and UPV based on three input variables. The study, employing geo-engineering experiments and analytical methods, classified the soil as high-plasticity clay (CH) with the Unified Soil Classification System (USCS). Addition of WMP significantly improved UCS and UPV, especially at optimal water content, 28 days curing, and 60% WMP. ANN models accurately predicted values, showcasing their utility in soil stabilization projects, making the results pertinent for engineers and researchers.

In 2023, Kennedy and colleagues introduced three AI-based models, employing Gaussian Processes (GP), Artificial Neural Networks (ANN), and Evolutionary Polynomial Regression (EPR), to forecast the unconfined compressive strengths (UCS) of expansive soil blended with lime and bagasse ash. These models utilized mix contents (BA and Lm), consistency limits (LL, PL, and SL), and compaction parameters (MDD and OMC) as inputs.

This study aims to investigate recent developments, challenges, and opportunities associated with soil stabilization using waste marble powder (WMP) and lime (LM). The objective is to induce positive alterations in the geotechnical properties of treated clay. This is achieved through an optimal blend of 3% LM and 6% WMP, yielding superior outcomes. The treated clay exhibited notable enhancements: a 5.8% increase in dry density, a 38.4% boost in compression strength, a 21.55% improvement in shear characteristics, including a 187% increase in cohesion and a 198.8% rise in the compressibility coefficient. Moreover, there was a nearly 55.5% reduction in swelling. Furthermore, significant increases were observed in magnesia (up by 86%) and calcium (up by 303%), contributing to the efficacy and environmental sustainability of geotechnical engineering. Experimental design methodologies, including Response Surface Methodology (RSM), are employed to optimize parameters for treating clay soil with varying dosages of LM and WMP. A Box-Behnken design explores the interrelationships and effects of different dosages (1.5%–9% by dry weight) on cohesion, internal friction angle, and unconfined compressive strength. The study develops a second-order polynomial model through statistical analyses, assessing its goodness of fit using tools such as analysis of variance (ANOVA), coefficient of determination (R^2), adjusted and predicted.

2 Materials and methods

2.1 Clay soil

The clay soil sample utilized in this study was obtained from Bouzaroura El Bouni, the north-eastern region of Algeria in Supplementary Figure S1, it is geotechnical properties were evaluated according to French standards as shown in Table 1; and in Supplementary Figure S2 was illustrated the grain-size curve of the utilized clay. Based on the analysis of its gradation and plasticity characteristics, the clay soil was classified the clay soil was classified as CL following the methodology outlined by (Bekkouche and Boukhatem, 2016; Bekkouche Rehab et al., 2022; Menadi et al., 2023).

Supplementary Figure S2 illustrates the grain-size curve of the utilized clay. According to the United Soil Classification System, this clay is categorized class E. The effective sizes (D_{10}, D_{30}, and D_{60}) are 0.001, 0.002, and 0.018, respectively, with a uniformity coefficient (Cu) of 18 and a coefficient of curvature (Cc) of 0.22.

2.2 Lime

The limestone utilized exhibits characteristics outlined in Table 2, detailing its physical and chemical properties. It primarily consists of calcite (CaCO3), constituting 100% of its composition, rendering it a highly malleable calcic fatty lime. Variations in the levels of other components, such as MgO and free CaO, are crucial for its chemical and reactive attributes. Its density ranges from 0.8 g/cm3 to 1.2 g/cm3, impacting its handling and application. With sieve pass rates of 90% and 50% for 200 µm and 80 µm respectively, the lime demonstrates a relatively fine particle size distribution. It contains between 50% and 80% free CaO, driving its chemical reactivity, and may also include 6%–8% magnesium oxide (MgO), further enhancing its reactivity.

2.3 Waste marble powder (WMP)

WMP was retrieved during the process of cutting marble at construction sites. Following the drying of the marble waste, fluorescence spectrometry was conducted to analyze the main parameters describing the physical and chemical properties of the WMP sample used in this study. The results are presented in Table 3.

2.4 Laboratory investigations and mix designs

The geotechnical properties of clay soils and their mixtures with lime (LM) and waste marble powder (WMP) were assessed using established protocols under ambient temperature conditions (22–31°C). The clay soil underwent drying before being manually mixed with LM and WMP at varying percentages until achieving a homogeneous color. Sixteen repetitions involved increasing doses of LM and WMP in clay soil, followed by fixed doses for specific gravity, compaction, direct shear, compression strength, oedometric, and EDX microstructure tests. Significant enhancements in the clay soil properties were observed, confirming the positive impact of LM and WMP. The study involved 16 repetitions of increasing the doses of LM and WMP in clay soil, the doses of LM (1.5%, 3%, 4.5%, 6%, 7.5%, and 9%, respectively) initially, followed by 6 increasing levels of WMP doses (1.5%, 3%, 4.5%, 6%, 7.5%, and 9%, respectively) secondly. Finally, fixed doses were applied with LM at 3% and WMP at doses of 3%, 6%, and 9%, respectively. With pulverized clay, LM, and WMP mixed manually.

2.5 Design of the experiment using the RSM method (box behnken design–BBD)

Response Surface Methodology (RSM) statistical analysis method is very efficient prediction for assessing independent variables influence on responses within limited number of tests as described in the results by (Khor et al., 2016; Boumaaza and BelaadAhmed, 2022; Boutahir et al., 2023). This method is mainly applied if many input variables are influencing the output (response). Their goal is to increase the number of experimental points to create a quadratic model that describes the

TABLE 1 Clayey soil properties.

Soil properties	Unit	Values	Standard
Methylene blue VBS	-	4	NF P94-068 (1998)
Water content W	%	19.70	NF EN ISO 17892-1. (2014)
Plasticity index Ip	%	25	NF EN ISO 17892-12. (2018)
Maximum dry density MDD	-	1.73	NF EN ISO 17892-1. (2014)
Optimum moisture content OMC	%	16	
Internal friction angle φ_{uu}	°	29	NF EN ISO 17892-10. (2018)
Cohesion C_{uu}	KN/m^2	39.3	
IPI Immediate bearing index	-	5.14	
Compressibility coefficient Cc	-	0.09	
Swelling coefficient Cs	-	0.02	
Unconfined Compressive Strength UCS	KN/m^2	125	

TABLE 2 Physical and chemical properties of lime.

lime properties	Unit	Values
Calcite CaCO3	-	100%
Quartz	-	-
Ferricoxide Fe2O3	-	-
Density G	-	0.8–1.2
Plasticity index Ip	%	24
Sievepassers-by 200µ	%	>90
Sievepassers-by 80µ	%	>50
Global free CaO content	-	80%–50%
Content in Magnesium oxideMgO	-	8%–6%
Free water content W	-	2%

TABLE 3 Physical and chemical properties of the (WMP).

WMP properties	Unit	Values
Apparent density	—	2.72
Porosity	%	1.67
Calcite CaCO3	%	98.76
Insoluble	—	<1
MagnesiumoxideMgO	%	0.26
calcium Oxyde CaO	%	55.30
FerricoxideFe2O3	%	<0.05
AluminiumAl 3	%	0.22
Siliciumdioxyde SiO2	%	0.13
PolycarbonatesPC	%	43.78
HydrochloricacidHCl	%	<1

objective function. Practical experience shows that the quadratic function is sufficiently accurate to characterize the objective functions in optimization problems with narrow bounded regions between the experimental levels (Khor et al., 2016; Boumaaza and BelaadiAhmed, 2022).

The investigation centers on the interplay of cohesion (c), internal friction angle (phi), and unconfined compressive strength (UCS) as pivotal factors influencing the geotechnical attributes of clayey soils subject to treatment with lime (LM) and waste marble powder (WMP). Employing Design-Expert® software (version 13), the research delves into elucidating the impacts of these variables on the outcomes across sixteen meticulously crafted experiments devised using the Box-Behnken design methodology. The utilization of a quadratic function is discerned to be sufficiently precise in delineating the objective functions within optimization quandaries characterized by constrained regions between experimental tiers. The determination of the experimental design's size was guided by Eq. 1 (Khor et al., 2016).

$$N = 2K(k - 1) + C_0 \tag{1}$$

TABLE 4 Range of variation of the parameters to be optimized.

Input parameters	Unit	Coded	Levels of variation	
			Minimum value	Maximum value
Clay soil (Clay)	%	A	88	100
Lime (LM)	%	B	0	9
Waste marble powder (WMP)	%	C	0	9

The inquiry encompasses K parameters under investigation alongside Co repetitions of experimental steps. Each analysis involved the execution of a comprehensive set of 16 experiments, incorporating 4 central replicates. Following the model selection, the equation representing the model and its associated coefficients were ascertained employing the quadratic equation (Eq. (2)) as referenced (Khor et al., 2016).

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X^2 + \sum_{i \le j}^{k} \sum_{j}^{k} \beta_{ij} X_i X_j \tag{2}$$

Where, β_0, β_i, β_{ii}, and β_{ij} are constant, linear, quadratic, and interaction coefficients of regression, respectively. Furthermore, Xi and Xj represent encoded independent variables, with k denoting the quantity of variables involved. A statistical examination was conducted to assess the precision and sufficiency of the model through ANOVA, yielding probability values falling within the range of Prob [F] < 0.05. Subsequently, the model's predictability and adequacy underwent scrutiny employing metrics such as the coefficient of determination in linear regression (R^2), precision adequacy, lack-of-fit criteria, adjusted determination coefficient (Adj-R^2), and residual analysis (Khor et al., 2016).

The Box-Behnken Design (BBD), utilizing triadic gradations for every variable, offers an efficient quadratic coefficient arrangement, necessitating fewer iterations compared to alternative methodologies within Response Surface Methodology (RSM). The study focuses on clay soil, lime (LM) additive, and waste marble powder (WMP) additive, assigning each a high (+1) and low code (−1). The BBD-based levels and ranges for each input are outlined in Table 4.

Design Expert (v.13) is used for the experimental plan and graphical analyses. Following the BBD with three factors and two levels, 16 experimental configurations are conducted, involving various levels of testing variables such as the substitution of clay soil, LM, and WMP (ranging from 0% to 9%). Mixture proportions and responses (cohesion (C), angle of internal friction (φ), and unconfined compressive Strength (UCS) are presented in Table 5.

3 Results and discussions

3.1 Effect of LM and WMP on the compaction properties of clay soil

The histogram illustrated in Supplementary Figure S3 depicting the variation of dry density as a function of different percentages of LM, WMP, and LM + WMP reveals a decrease in dry density of approximately 3% for LM. LM can reduce the value of the dry weight of clayey soil samples (Ankush et al., 2020; HuuLoc and Le, 2021). There is an increase of about 5% for marble. Regrouping by adding LM causes the compaction behavior to be much more influenced by friction than electric forces, reflecting the behavior of clay soils (Elmahallawy and Rashed, 2012; Alishiri et al., 2023). Compaction tends to result in lower dry density due to the rearrangement of grains without filling all voids. Similar results were demonstrated by (Saxena, 2017; Wang et al., 2019a; Anand et al., 2021; Malathi et al., 2021; Axel et al., 2023). We can say that WMP positively affects the soil more than LM, and the combination of 3% LM and 6% WMP results in an increase in dry density of approximately 5.8% compared to natural clayey soil. Similar findings were reported by (Dumpa et al., 2014) who found an improvement in the mechanical properties of marine clay treated with 3% lime and 1% cement.

3.2 Effect of LM and WMP on the unconfined compressive strength properties of clay soil

The unconfined compressive strength of the clay soil by compressive test conducted on cylindrical samples was evaluated before and after treatment, the corresponding results for all samples are illustrated in Supplementary Figure S4.

According to the depicted graph, the unconfined compressive strength (UCS) reaches its zenith at 9% of LM, exhibiting an impressive 84% surge in comparison to the inherent strength of natural clay. At a concentration of 6% of WMP, there is a notable increment of approximately 32% in UCS. It is discernible that as more LM or WMP is introduced, the compressive strength experiences augmentation. Particularly, the inclusion of WMP enhances the soil's resistance (Axel et al., 2023). Scholars have elucidated that this bolstering of strength stems from protracted pozzolanic reactions occurring between silica and aluminum elements within the soil, facilitated by the presence of calcium and water. This phenomenon is widely acknowledged as pivotal in fortifying the soil with LM (Anand et al., 2021). Conversely, WMP, often regarded as chemically inert due to the absence of Ca2+ dissociation under normal temperatures, inhibits the progression of strength through pozzolanic reactions (Anand et al., 2021). Nevertheless, the inherent strength of WMP surpasses that of clay (Anand et al., 2021). In the formulation of LM-WMP blends within clay soil, it has been observed that the optimal pressure resistance occurs at a ratio of (3% LM + 6% WMP), resulting in a notable increase in unconfined compression strength by 38.4% when compared to untreated clay. This enhancement

TABLE 5 Experimental results (input variables and output variables).

Exp. N°	Experiment codes	Input variables			Output variables		
		Clay (%)	LM (%)	WMP (%)	C (KN/m^2)	φ (°)	UCS (kN/m^2)
1	Clay0/0	100	0	0	29	28.3	125
2	ClayLM98,5/1.5	98.5	1.5	0	40	30.65	133
3	ClayLM97/3	97	3	0	51	31.95	133
4	ClayLM95,5/4.5	95.5	4.5	0	57	32.2	145
5	ClayLM94/6	94	6	0	60	32.9	176
6	ClayLM92,5/7.5	92.5	7.5	0	62	31.7	194
7	ClayLM91/9	91	9	0	62	30.1	230
8	ClayWMP98,5/1.5	98.5	0	1.5	48	30.7	155
9	ClayWMP97/3	97	0	3	60	31.5	166
10	ClayWMP95,5/4.5	95.5	0	4.5	65	30	165
11	ClayWMP94/6	94	0	6	60	31	165
12	ClayWMP92,5/7.5	92.5	0	7.5	45	32	150
13	ClayWMP91/9	91	0	9	22	34.7	140
14	ClayLMWMP94/3/3	94	3	3	87	34.2	160
15	ClayLMWMP91/3/6	91	3	6	89	34.4	160
16	ClayLMWMP88/3/9	88	3	9	55	33.3	150

in soil strength, ranging from 3% to 9% WMP, is attributed to several factors, including improved gradation, heightened compactness of the soil matrix due to reduced porosity, and augmented inter-particle bonding facilitated by the incorporation of WMP within the soil matrix. These findings align with previous research (Saxena, 2017). Furthermore, considering WMP dust as a waste byproduct, its utilization for soil stabilization represents an environmentally conscientious approach, offering a sustainable solution for enhancing soil properties.

3.3 Effect of LM and WMP on mechanical shear characteristics of clay soil

Understanding the shear strength of the soil is crucial and essential for solving stability problems of geotechnical structures such as foundations, roads and embankments. The rectilinear shear test is the most commonly used in soil mechanics to evaluate the fundamental shear strength properties, cohesion (C) and the internal friction angle (φ).

From Supplementary Figures S5, S6, we observe a notable increase in the friction angle and cohesion, rising from 28.3° for untreated clay to 32.9° for 6% LM and 34.7° for 9% WMP. Upon the addition of LM or WMP, the soil responds, with cohesion (at 3% LM + 6% WMP) experiencing a 187% increase compared to natural soil, and the internal friction angle increasing by 21.55%. This suggests that the introduction of clay particles with the additives consistently forms robust cementitious bonds (Umar et al., 2023). This phenomenon is attributed to the low density of LM and WMP, along with the rearrangement and new texture resulting from their incorporation into the soil matrix. Moreover, it leads to the creation of a more uneven shear surface compared to untreated samples.

The infusion of lime and marble into the soil substrate alters the configuration of soil particles, resulting in a more compact and resilient framework. These cooperative physical and mechanical processes play a pivotal role in mitigating swelling tendencies and enhancing the geotechnical characteristics of the examined soil. Prior investigations have elucidated that the incorporation of LM into soil stabilization blends has the potential to augment both the friction angle and cohesion value of the soil, as opposed to soil devoid of additives (Umar et al., 2023). This enhancement in soil properties is attributed to LM's capacity to diminish the soil plasticity index while concurrently fortifying interparticle bonds, thereby imbuing the soil with heightened rigidity and stability. The unconfined compressive strength increased with increasing curing time and percentages of LM and WMP. Furthermore, marble dust accelerates the early strength of soil at shorter curing periods (Umar et al., 2023).

3.4 Effect of LM and WMP on compressibility properties of clay soil

The aim of this experiment is to examine the consolidation behavior of clay soil samples under incremental vertical loads. This is done while enabling vertical drainage and confining the samples within a rigid enclosure. Supplementary Figure S7 illustrates how the compressibility characteristics (Cc and Cs) of clay are influenced by different percentages of LM and WMP content.

The findings from the oedometric test reveal a discernible reduction in both the swelling index and compressibility index as the waste marble powder (WMP) rate escalates, all while maintaining a constant 3% proportion of the lime (LM). The graph in Supplementary Figure S7 shows us that with (3% LM) the compressibility coefficient decrease by 76% and the swelling decreases by almost 78%. For (6% WMP), an increase in Cc of 11.36%, and a decrease in Cs of 5.7%. For (3% LM +6%WMP) there is an decrease of 67% for the Cc and a decrease of 55.5% for the Cs and the swelling is reduced to half, so the mixture at (3% LM + 6% WMP) gives the best parameters, the coefficient of compressibility reaches abetter value, and the bloating is halved, thus of great deformation of the grains of the soil and compression of the air, similar results found by (Dumpa et al., 2014; Anand et al., 2021; Zubair et al., 2023).

The dissemination of lime (LM) and waste marble powder (WMP) possesses the capacity to alter the composition and consistency of soil. Moreover, the introduction of LM and WMP within the soil matrix engenders interstices, thereby diminishing the operative contact area between LM, WMP, and the clay constituents.

For the variation of the Californien bearing ratio, Supplementary Figure S8, variation depending on percentage of additions in the soil the graph of mixture (Clay +3% LM+6%WMP) indicates that increased the load index of this clay up to 296% almost 300% compared to the soil without additive, a better results than lime or marble alone. Also Abdelkader et al., found that CBR improved by 203.5%, with a growing percentage of granite waste up to 20%, where the swelling was reduced (Abdelkader et al., 2022; Zubair et al., 2023).

3.5 Effect of LM and WMP on microstructural and chemical analysis

While reviewing all geotechnical tests, the mixture of (3% LM+ 6% WMP) incorporated into the clayey soil yielded excellent results, showing improvements in all characteristic parameters of the tests. To further investigate these results, a microstructural analysis is highly recommended to gain insights and clarification. In order to clarify the mechanism of changes in soil behavior treated with (3% LM +6% WMP) micro-analyses were performed on samples taken from the fractured part of the tested sample. The utilization of the Phenom Pure desktop scanning electron microscope facilitated the examination of microstructural alterations within the treated samples. SEM analysis was conducted on a diminutive representative specimen. The mineralogical constitution of the Clay-LM-WMP mixtures was assessed via X-ray diffraction (XRD), as depicted in Supplementary Figures S9, S10.

The chemical composition of clay presented Supplementary Figures S11, S12 in reveals silica (Si) and aluminum (Al) as the primary elements, accompanied by small quantities of magnesium (Mg) and calcium (Ca). For the Clay-LM-WMP mixture, in addition to SiO2 and Al2O3, there may be CaO and MgO (Mao et al., 2004).

We can observe that for the soil mixed with (3% LM + 6% WMP), at the atomic scale, magnesia increased by 86%, and calcium increased by 303% compared to natural soil. This significant increase stands out in comparison to other atoms where slight variations are observed. This confirms that the mixture acquired pozzolanic properties, thereby enhancing its mechanical characteristics. The X-ray diffraction (XRD) analysis reveals that the main chemical elements present are O, Si, Al, Ca, Mg, and Fe. However, the sample with the addition shows a higher quantity of Ca compared to the natural sample, while the content of Si and Al is lower than that of the natural soil. (Mao et al., 2004), found that generally, MgO and CaO can be introduced into clay formulations to enhance their properties, such as mechanical strength, thermal stability, and chemical resistance.

4 Statistical analysis and response surface methodology (RSM) modeling

Response surface regression is employed to scrutinize the correlation between a given response and an array of quantitative experimental variables or factors. The regression analysis was performed for each response, employing coded units, and subsequently amalgamated within Tables 6–8 (khor et al., 2016; Boumaaza and BelaadiAhmed, 2022).

4.1 Designing a mathematical model

This study followed the Box-Behnken design (BBD) experimental approach to investigate the impact of three factors: the percentage of clay (A), the percentage of LM (B), and the percentage of WMP (C) on the cohesion (C), angle of internal friction (φ), and unconfined compressive strength (UCS) of clay-LM-WMP mixtures. The effects of these factors were predicted using a response surface methodology (RSM) model. The quadratic equations utilized to represent individual responses such as cohesion, angle of internal friction, and compressive strength were determined to be the most appropriate, as ascertained through analyses of their correlation coefficients, predicted R^2, and adjusted R^2 values, which are elaborated upon in Tables 6–8.

According to the results of the analysis of variance (ANOVA) for the cohesion response presented in Table 6, the quadratic model demonstrates excellent performance with a coefficient of determination $R^2 = 99.84\%$ and an adj-$R^2 = 99.76\%$. These values indicate that the model explains 99.83% of the variance in the dependent variable. The contribution of 99.83% to cohesion suggests that the main independent variable explaining this variance is cohesion.

For the second response, concerning the internal friction angle, applying the same principle of ANOVA statistical analysis as presented in Table 7, The quadratic model demonstrates outstanding performance with a coefficient of determination $R^2 = 77.88\%$ and

TABLE 6 ANOVA results of the quadratic response surface model for cohesion for clay-LM-WMP mixtures.

Source	SS	Df	MS	F-value	*p*-value	Contribution%	Remarks
Model	4595.55	5	919.11	1233.44	<0.0001	99.83	Significant
A-Clay	1361.95	1	1361.95	1827.73	<0.0001	29.58	
B-LM	6.41	1	6.41	8.60	0.0150	0.14	
AB	193.38	1	193.38	259.51	<0.0001	4.20	
AC	3179.33	1	3179.33	4266.66	<0.0001	69.06	
BC	3024.29	1	3024.29	4058.58	<0.0001	65.70	
Residual	7.45	10	0.7452				
Cor Total	4603.00	15					
SD = 0.8632				R^2 = 99.84% R^2 adjusted = 99.76%			

TABLE 7 ANOVA results of the quadratic response surface model for Angle of internal friction for clay-LM-WMP mixtures.

Source	SS	Df	MS	F-value	*p*-value	Contribution%	Remarks
Model	35.98	5	7.20	7.02	<0,0001	77.83	Significant
A-Clay	0.4037	1	0.4037	0.3940	0.5443	0.87	
B-LM	0.6446	1	0.6446	0.6291	0.4461	1.39	
AB	15.94	1	15.94	15.56	0.0028	34.48	
AC	0.4965	1	0.4965	0.4846	0.5022	1.07	
BC	3.05	1	3.05	2.98	0.1152	6.60	
Residual	10.25	10	1.02				
Cor Total	46.23	15					
SD = 1.01				R^2 = 77.83% R^2 adjusted = 66.75%			

an adj-R^2 = 66.75%. These values indicate that the model explains 77.83% of the variance in the dependent variable.

Finally; the ANOVA statistical analysis for the compressive strength response, as shown in Table 8, reveals that the quadratic model exhibits exceptional performance, boasting a coefficient of determination R^2 = 96.78% and an adj-R^2 = 95.18%. The substantial contribution of 96.78% to unconfined compressive strength implies that the dominant independent variable elucidating this variability is the compressive strength itself. Additionally, quadratic models were found to be unsuitable for all responses due to their exceedingly low correlation coefficients. To evaluate the significance and interrelation of the variables in each individual response model, an analysis of variance (ANOVA) was conducted (refer to Table 3). In the context of the Box-Behnken design (BBD), the model fitting process involves iterative steps to attain a precise model for the response. Initially, a quadratic model (Eqs 3–5)) is employed to estimate the dependence between variables and responses using experimental data. Subsequently, the model is refined by eliminating irrelevant terms based on statistical analysis.

The outcomes of the ANOVA analysis indicate that the equations proficiently encapsulate the correlation between the independent variables and the corresponding responses. Moreover, the discussion includes the correlation coefficients and *p*-values associated with the obtained model.

$$C = +80.58 - 42.48A + 1.36B + 16.10QB + 52.62AC + 60.07BC \quad (3)$$

$$\varphi = +33,16 - 0,7313A + 0,4305B + 4,62AB + 0,6576AC + 1,91BC \quad (4)$$

$$Rc = +164,75 - 31,89A + 3,81B + -46,12AB + 36,85AC5,26BC \quad (5)$$

The F-values for the cohesion (c), angle of internal friction (φ), and unconfined compressive strength (UCS) models were 1233.44,

TABLE 8 ANOVA results of the quadratic response surface model for compressive strength for clay-LM-WMP mixtures.

Source	SS	Df	MS	F-value	*p*-value	Contribution%	Remarks
Model	9601.36	5	1920.27	60.18	<0.0001	96.78	Significant
A-Clay	767.80	1	767.80	24.06	0.0006	7.74	
B-LM	50.59	1	50.59	1.59	0,2366	0.51	
AB	1586.80	1	1586.80	49.73	<0.0001	15.99	
AC	1558.84	1	1558.84	48.85	<0.0001	15.71	
BC	23.22	1	23.22	0.7278	0.4136	0.23	
Residual	319.08	10	31.91				
Cor Total	9920.44	15					
SD = 5.65				R^2 = 96.78% R^2 adjusted = 95.18%			

7.02, and 60.18, respectively, indicating the significant importance of these models according to ANOVA analysis. Furthermore, the *p*-values (<0.0001) were well below 0.05, confirming the significance of the model terms. In the case of unconfined compressive strength (UCS), terms A, AB, and AC were identified as significant, while for cohesion (c), terms A, B, AB, AC, and BC were considered important. AB emerged as a significant term for the angle of internal friction in the current models.

The variance between the predicted R^2 and the adjusted R^2 values Presented in the three Tables 6–8 for the three responses, remained consistently below 0.2 for all models. The accuracy values, serving as indicators of good accuracy and evaluating signal-to-noise ratios, were 125.750, 8.662, and 29.213 for cohesion(c), angle of internal friction (φ), and unconfined compressive strength (UCS), respectively. All of these values exceeded the threshold of 4, suggesting a strong signal and endorsing the application of these models for exploring the conceptual domain.

4.2 Primary factors and response surface plots for mixture

In the Response Surface Methodology, After the statistical analysis study of ANOVA, it is crucial to assess the adequacy and accuracy of the quadratic models applied to clay soil treated with LM and WMP by employing diagnostic graphs against experimental values. Supplementary Figures S13–S15 illustrating the precision and relevance of the models through plotting. The distribution of experimental data was evaluated using the normal probability approach, a commonly employed method to assess data distribution through a normal probability plot. Supplementary Figures S13–S15 clearly demonstrate that the data is distributed approximately normally, as evidenced by the visualization of the plotted data forming a straight line.

Analyzing the interplay among influential factors involves the use of three-dimensional (3D) contour graphs, as shown in Supplementary Figures S16–S18, and response surface plots, as shown in Supplementary Figures S19–S21. These tools facilitate the visualization of the response surface. Additionally, they assist in constraining the ranges of variation for response values and identifying desirable operating conditions.

To understand how the investigated factors interact with the response and their interrelationships, dependent variables can be expressed as a function of two independent variables, as shown in Supplementary Figure S15, assuming other variables are held at fixed levels. Supplementary Figures S19–S21 present the 3D response surface plots, illustrating the interaction between input parameters: percentage of Clay (A), percentage of LM, and percentage of WMP within the designed space, based on the previously mentioned regression equations. These insights can be applied to responses, validating the results of the ANOVA analysis.

4.3 Primary impacts of mixtures involving clay-LM-WMP

It is difficult to achieve maximum values for several replies at once. As a result, optimization methods are used to optimize several answers at once. Compromise optimization was carried out in this study for three input variables and three responses: WMP, LM, and clay. The dependent variables are the angle of internal friction (φ), cohesion (C), and unconfined compressive strength (UCS). The best combinations of the three parameters that maximize the three response values were found using the Box-Behnken design (BBD). The Design-Expert 13 software's process optimization features were used in this study.

The multi-objective optimization, aiming for the highest possible values for the three-geotechnical characteristics, has yielded multiple solutions, with the first solution, with the highest desirability (0.908), involves incorporating two waste materials (LM and WMP), substituting LM with a quantity of 3% and WMP with 6% of the dry clay soil weight. This combination yields maximum values for all three geotechnical characteristics (φ, c, UCS).

5 Conclusion

The study delves into the myriad challenges associated with clayey soils, encompassing constraints such as limited bearing capacity, subpar permeability, and susceptibility to erosion. Through an in-depth examination, the investigation delves into the efficacy of incorporating additives, notably Waste Marble Powder (WMP) and lime (LM), to ameliorate the characteristics of fine soils. The findings underscore substantial technical, environmental, and economic advantages, underscoring the effectiveness of these additives in bolstering soil properties.

The principal technical merits of this investigation are underscored by the markedly augmented mechanical attributes of the treated clay. An optimal amalgamation of 3% LM and 6% WMP yielded the most favorable blend, showcasing superior outcomes across all administered evaluations in contrast to untreated clay. In terms of compaction characteristics, a noteworthy escalation in dry density of approximately 5.8% was recorded, coupled with a conspicuous 38.4% augmentation in compressive strength. Concerning shear properties, a substantial enhancement of around 21.55% in the friction angle and a remarkable 187% upsurge in cohesion were observed. Similarly, the compressibility traits of the clay exhibited a parallel trend, with the compressibility coefficient escalating by 198.8% and swelling diminishing by nearly 55.5%. Through microstructural and chemical scrutiny at the atomic level, magnesia demonstrated an 86% augmentation, while calcium exhibited a remarkable surge of 303%. This considerable amplification sets it apart from the marginal fluctuations detected in other atomic constituents.

Of noteworthy significance is the identification of an optimal amalgamation comprising 6% of waste marble powder (WMP) and 3% of lime (LM), exhibiting pronounced efficacy in reinforcing stabilized soil strata. By pinpointing precise proportions of LM and WMP pivotal to overall enhancement, the study elucidates pathways for practical implementation aimed at ameliorating problematic soil conditions. The incorporation of lime and marble powder serves to sustain soil stability through the facilitation of Pozzolanic reactions, augmentation of overall density (where the additives act as filler materials), and mitigation of soil mixture void ratio. These interventions not only offer technical advantages but also hold considerable environmental promise, including the potential reduction of carbon emissions or pollutant discharge, particularly given the abundant availability of discarded marble powder. Similarly, the prospect of more judicious utilization of natural resources, diminished reliance on non-renewable materials, and curtailment of waste generation and its attendant pollution emerges as plausible outcomes.

However, it is important to note that the performance of lime and marble powder waste to stabilize the soil can vary depending on different elements such as the composition of the soil, the dosage and the curing conditions. It is essential to carry out further research and field experiments to improve the application parameters and evaluate the long-term results.

Employing the Box-Behnken response surface methodology as a sophisticated optimization strategy, the study streamlines testing procedures and experimental iterations. This methodological approach not only yields readily interpretable outcomes but also unveils intricate interrelations among various factors. Furthermore, it lays the groundwork for the development of predictive models, which are meticulously evaluated for adaptability, significance, and coefficient validity through rigorous analyses of variance and model diagnostics.

By optimizing critical parameters such as cohesion, angle of internal friction, and compressive strength, the Box-Behnken methodology yields simulation results exhibiting a negligible deviation of within 5%. This substantiates a robust correlation and underscores the rationality and feasibility of the optimization endeavor.

The findings and deductions derived from this investigation hold validity solely within the context of Bouzaroura El Bouni clay and necessitate substantiation when applied to other clay varieties.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

Author contributions

GB: Conceptualization, Formal Analysis, Investigation, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. MeB: Conceptualization, Formal Analysis, Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. MoB: Conceptualization, Formal Analysis, Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. SA: Conceptualization, Formal Analysis, Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. MS: Funding acquisition, Investigation, Resources, Software, Supervision, Visualization, Writing–original draft, Writing–review and editing. HN: Formal Analysis, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmats.2024.1392875/full#supplementary-material

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