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Laboratory Testing and Analysis of Clay Soil Stabilization Using Waste Marble Powder

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Abstract: Soil stabilization is a critical step in numerous engineering projects, preventing soil erosion, increasing soil strength, and reducing the risk of subsidence. Due to its inexpensive cost and potential environmental benefits, waste materials, such as waste marble powder (WMP), have been used as additives for soil stabilization in recent years. This study investigates waste marble powder's effects on unconfined compressive strength (UCS) and clayey soil's ultrasonic pulse velocity (UPV) at different water contents and curing times, and artificial neural networks (ANNs) are also used to predict the UCS and UPV values based on three input variables (percentage of waste marble dust, curing time, and moisture content). Geo-engineering experiments (Atterberg limits, compaction characteristics, specific gravity, UCS, and UPV) and analytical methods (ANNs) are used. The study results indicate that the soil is high-plasticity clay (CH) using the Unified Soil Classification System (USCS), and adding waste marble powder (WMP) can significantly improve the UCS and UPV of clay soils, especially at optimal water content, curing times of 28 days, and 60% WMP. It is found that the ANN models accurately predict the UCS and UPV values with high correlation coefficients approaching 1. In addition, this study shows that the optimum water content and curing time for stabilized clay soils depend on the grade and amount of waste marble powder utilized. Overall, the study demonstrates the potential of waste marble dust as a soil stabilization additive and the usefulness of ANNs in predicting UCS and UPV values. This study's results are relevant to engineers and researchers working on soil stabilization projects, such as foundations and backfills. They can contribute to the development of sustainable and cost-effective soil stabilization solutions.

Keywords: clay soil; soil stabilization; waste marble powder (WMP); unconfined compressive strength (UCS); ultrasonic pulse velocity (UPV); artificial neural networks (ANNs)

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1. Introduction

In the past few decades, there has been a growing interest in researching sustainable and cost-effective techniques for improving the mechanical properties of clay soils [1]. Clay soils are widely distributed worldwide, but their poor geotechnical properties, such as low strength and high compressibility, make them unsuitable for civil and mining engineering projects [2,3]. Stabilizing clay soils with waste materials has emerged as a viable method for improving these properties in an economically and environmentally friendly manner [4–7]. However, the durability of stabilization techniques depends on the specific materials and processes used and the application. It is essential to conduct a comprehensive life cycle assessment (LCA) to evaluate the environmental impacts from cradle to grave, e.g., extraction of raw materials, manufacturing, transportation, construction, use, and disposal [8]. LCA provides a holistic perspective on sustainability by analyzing trade-offs between improved soil properties and potential consequences such as carbon emissions or toxicity [9]. With careful LCA, stabilization techniques can be optimized to balance improved effectiveness and minimal environmental impact.

Soil stabilization is an essential aspect of geotechnical engineering, as it involves enhancing the engineering characteristics of the soil to make it appropriate for future construction [10–12]. The development potential of waste marble dust (WMP) as a soil stabilization admixture lies in its ability to increase the stability and strength of the soil. WMP, when combined with soil, can enhance soil geo-engineering characteristics such as ultrasonic pulse velocity (UPV) and unconfined compressive strength (UCS) [13]. Waste marble dust is a by-product of the marble industry that is often dumped in landfills, causing environmental concerns [14]. Nevertheless, recent research has shown it can be effectively reused as a soil stabilizer. The WMP particles occupy the voids in the soil matrix, resulting in improved compaction and reduced settlement. In this way, the chemical composition of marble dust, which contains calcium carbonate, can react with soil particles to form cementitious compounds, thereby increasing the strength of the soil [15,16].

Predicting the mechanical properties of stabilized clay soils remains problematic due to the non-linear relationships between soil properties and stabilization parameters [17,18], despite encouraging results from experimental investigations. All geotechnical engineering designs apply strength analysis to determine the feasibility of engineering techniques, including the design and stability analysis of foundations, backfills, retaining walls, slopes, and embankments [19–22]. It can be used to monitor the effectiveness of soil stabilization, determine the optimum percentage of stabilizer, and evaluate the significance of factors that influence the strength of stabilized soil [23,24].

The purpose of this paper was to determine the applicability of artificial neural networks (ANNs) as a reliable and effective tool for predicting the geo-engineering properties, such as ultrasonic pulse velocity (UPV) and unconfined compressive strength (UCS), of clay soils stabilized with WMP at different water contents and curing days via numerous models of laboratory tests and analyses.

Artificial neural networks (ANNs) are computational models inspired by the function and structure of the human brain. They can learn from data and make predictions based on the patterns they have learned [25,26]. The use of artificial neural networks (ANNs) to predict mechanical properties of stabilized soils, such as ultrasonic pulse velocity (UPV) and unconfined compressive strength (UCS), has gained popularity in recent years. However, the majority of existing studies have focused on ANN modeling of soil stabilization with lime or cement [27–31]. Despite the proven effectiveness of waste marble powder (WMP) as a sustainable soil stabilizer [8–11], few studies have investigated the potential of ANNs to model clay soil stabilization using WMP.

Burlakovs et al. [32,33] recently conducted extensive research on sustainable soil stabilization techniques, especially for contaminated soils. However, it is still necessary to investigate sophisticated computational techniques such as ANNs for modeling stabilized soil properties. This study attempts to fill this gap in the literature by developing novel ANN models to predict the UPV and UCS of clay soils stabilized with WMP. Unlike previous studies, this research utilizes a comprehensive laboratory experimental program that includes clay soil, WMP percentages, curing times, and moisture contents. The developed ANN models are optimized using this experimental data through rigorous training, validation, and testing. A significant innovation is the comparison of the performance of the ANN model with that of existing empirical models. This allows quantifying the enhancement in prediction accuracy obtained using ANNs over conventional models.

Furthermore, this is the first study to systematically evaluate the effect of individual input parameters (curing time, WMP%, and moisture content) on the ANN-predicted UPV and UCS values through sensitivity analyses. The results shed new light on the complex relationships between soil stabilization inputs and mechanical outputs. This work will facilitate the more effective design and optimization of clay soil stabilization with WMP in engineering practices by enhancing the current understanding in this area. In general, this study demonstrates the viability of using ANNs as a sophisticated modeling tool for the mechanical properties of WMP-stabilized soils.

2. Materials and Method

Soil strength is often evaluated in the laboratory using unconfined compressive strength (UCS) and ultrasonic pulse velocity (UPV). One hundred eighty cylindrical specimens were tested, with 90 specimens used for UPV testing and 90 for UCS testing. These tests were conducted on treated and untreated soil samples at three compaction water contents. Of the 180 samples, approximately 64 samples were resampled and retested. This was performed because of suspected errors in some UPV and UCS values. Specifically, 32 samples were resampled and retested for UPV testing, and 32 were resampled and retested for UCS testing. Three different molding water contents (20, 22.5, and 24.5%) and six different percentages of marble powder (by weight of dry soil) (ranging from 0 to 75%) were used in the UCS and UPV tests performed on the clay and marble powder mixture. Each case was tested at different curing times ranging from zero to twenty-eight days, recognizing that a substance composed of soil and marble powder has the characteristics of a structured geomaterial due to interparticle bonds. The ANNs program was then integrated to estimate the strength of samples using UCS and UPV results, and these results are a valuable approach in geotechnical engineering. The process of the specimens is presented in Table 1.

Table 1. A view of the experimental plan.

Experimental Class		Symbol	Tests	Specimen Dimension		Soil Class	w (%)	Curing Period (Days)	ET (°C)
Natural Soil (%)	Marble Dust (%)			D (mm)	H (mm)				
100	0	X1	PP, UCS	38	76	CH	20, 22.5, 24.5	0, 3, 7, 14, 28	~20–28
85	15	X2	UCS, UPV						
70	30	X3							
55	45	X4							
40	60	X5							
25	75	X6							

Keys: PP = physical properties, UCS = unconfined compressive strength, UPV = ultrasonic pulse velocity, D = diameter, H = height, w = water contents, ET = experimental temperature.

2.1. Soil

Jingdezhen, Jiangxi Province, China, provided the natural soil used in the study. Basic geo-engineering experiments were conducted to determine the soil's physical parameters listed in Table 2. The natural soils were classified as high-plasticity clay (CH) soils in the Unified Soil Classification System. Figure 1 also shows the grain size distribution.

Table 2. The geo-engineering properties of the natural soil.

Geo-Engineering Characteristics of the Clay Soil		Amount
Specific Gravity, %		2.73
Atterberg Limits	Liquid Limit, %	62.2
	Plastic Limit, %	29.6
	Plasticity Index, %	32.6
Finer Component	% Passed No. 200 Mesh, %	71.6
USCS Classification	CH	-
Compaction Parameter	Optimum Moisture Content, %	22.5
	Maximum Dry Density, Mg/m^3	1.60

Table 2. *Cont.*

Geo-Engineering Characteristics of the Clay Soil	Amount
UCS, kN/m^2	245
UPV, m/s	223
Initial Void Ratio (e_o)	0.665
Color	Dark Beige
pH	5.51
Dominant Soil Mineral	Kaolinite

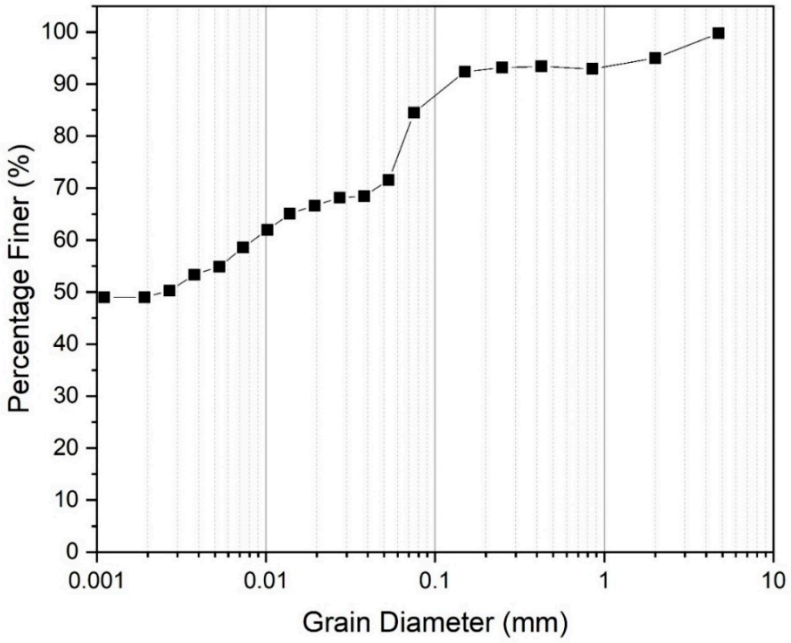


Figure 1. Grain size distribution of the studied soil.

2.2. Waste Marble Powder (WMP)

The marble powder for this experiment came from the city of Yunfu in Guangdong Province, China. It was sourced from the city's industrial waste—the production of marble results in the generation of WMP comprising approximately 96% calcium carbonate as its major chemical component. The minerals and constituents of WMP are listed in Table 3.

Table 3. Chemical composition of the WMP.

Composition	CaO	SiO_2	P_2O_5	Fe_2O_3	Al_2O_3	MnO	Na_2O	K_2O	MgO	LOI	Total
Values (%)	56.33	0.28	0.01	0.37	0.07	0.01	0.06	0.02	0.65	42.27	100.07

2.3. Specimen Preparation

Both the natural soil and marble powders were oven-heated at 105 ± 5 °C for 24 h. The samples were allowed to dry to make them cooler. The wet tamping method was employed, and the different compaction water content was slowly added to mixed specimens. The modified and unmodified soil samples were wrapped in plastic bags for a few hours to ensure water dispersion. Before conducting the experiments, the water content of the samples was checked again. Modified and unmodified soil samples were compacted in three layers to 38 mm diameter and 76 mm height. Three layers were used during compaction to ensure uniformity and consistency. Compacting the soil into three layers can identify and correct any variations or inconsistencies in compaction [34]. This contributes

to a more consistent and reliable compaction result. The specimens were quickly wrapped in plastic and placed in humidity cabinets after compaction to maintain water content as in Figure 2.

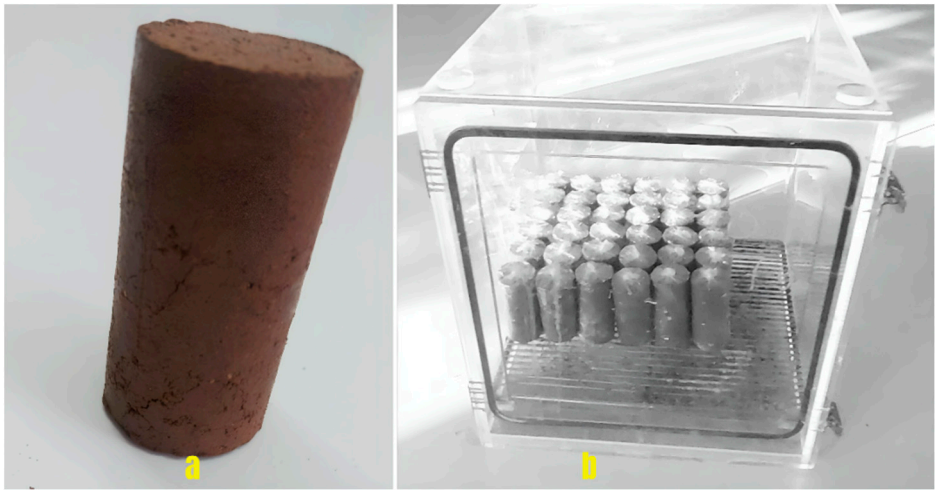


Figure 2. The process of the specimens; (**a**) cylindrical sample and (**b**) samples curing.

2.4. UCS Test

The unconfined compressive strength (UCS) test was performed under ASTM D2166 [35]. Cylindrical specimens were prepared and placed in a compression machine without lateral restraint. Specimens were continuously compressed at a strain rate of 0.076% per minute until fractured, as seen in Figure 3. The test routinely recorded load and deformation measurements to generate load–deformation curves. These curves were used to determine the maximum load, which was then divided by the original cross-sectional area of the specimen to determine the UCS key parameters, such as specimen dimensions, curing procedures, press specifications, and data acquisition details, which were established to ensure the test method could be replicated accurately.

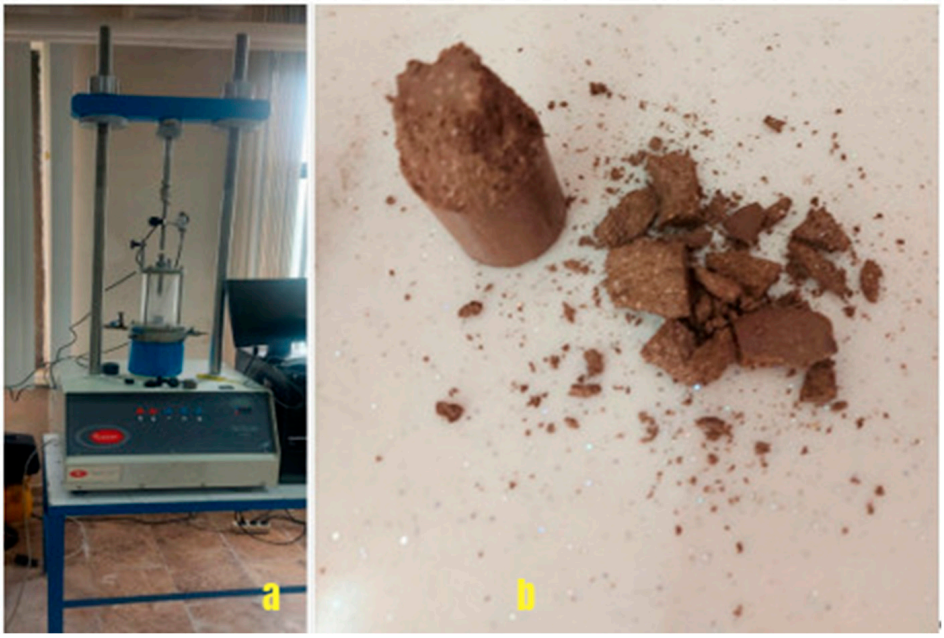


Figure 3. The UCS test process; (**a**) the triaxial machine, (**b**) the sample after testing.

2.5. UPV Test

The ultrasonic pulse velocity test (UPVT) by ASTM C597-16 standards was performed to evaluate the stabilized soil samples' quality and structural integrity [36]. Cylindrical samples were secured between the transmitter and receiver transducers of an ultrasonic pulse velocity instrument. The transmitter transmitted 54 Hz ultrasonic vibrations through the sample, which were detected by the receiver. The instrument recorded the pulse transit time to within 0.1 microseconds. The UPV was calculated by measuring the distance between the transducers. Higher velocities represent denser, more robust soils. Previous research has found that ultrasonic wave frequencies in the 40–80 Hz range effectively evaluate stabilized soils [37].

This test was designed to establish a correlation between UPV and UCS. Critical parameters such as sample dimensions, transducer contact, wave frequency, and data acquisition were controlled to ensure test repeatability.

2.6. ANNs Analysis

In recent decades, ANNs have been used to forecast complex systems' operations. In geotechnical engineering, neural networks have been used to predict the strength of various earth materials, especially stabilized soils.

2.6.1. Data Used by the Network

Laboratory experiments on stabilized and unstabilized soils provided the information used to train and validate the artificial neural network (ANN). The primary objective of this study was to investigate the effect of water content, curing time, and percentage of WMP on UCS/UPV. These factors were selected as inputs for the artificial neural network (ANN) model based on their observed importance in influencing the experimental results. This finding is consistent with other research that has also identified these variables as significant factors influencing the strength and stability of stabilized soils [12]. Previous studies have included additional factors, e.g., compaction energy, soil plasticity, additive fineness, and others in modeling stabilized soils [30]. However, the additional parameters were omitted in this study because the primary objective was to closely examine the effects of mix design and the curing process.

By limiting the inputs, it was possible to reduce the complexity of the model while maintaining a high level of accuracy. Correlation coefficients for both UCS and UPV predictions were found to be approaching 1. This finding is consistent with a previous study [25], which showed that using a smaller number of highly influential inputs can yield strong artificial neural network (ANN) models for stabilized soils. However, it is worth noting that the inclusion of factors such as clay mineralogy, organic content, temperature, and other relevant parameters may have the ability to improve the accuracy of model predictions, as shown in previous studies [16]. The existing model provides a robust basic framework; however, the incorporation of additional input parameters represents a promising avenue for further development.

2.6.2. Development of a Neural Network

The Matlab R2019a module was used to construct an ANN with an input layer, two hidden layers, and an output layer. The input layer accepts three variables: water content, curing time, and percentage of waste marble powder. These data pass through two hidden layers, the first containing four units and the second containing three units (as seen in the flowchart mechanism of the neural network in Figure 4).

These hidden layers process inputs by applying weights and biases before passing them to the next stage. The final transformation takes place at the output layer, where the results are interpreted into UCS and UPV values; each has its own dedicated unit within this final processing stage.

During training, the neural network optimizes the connection weights and biases between different stages, thereby minimizing the discrepancy (actual versus expected results).

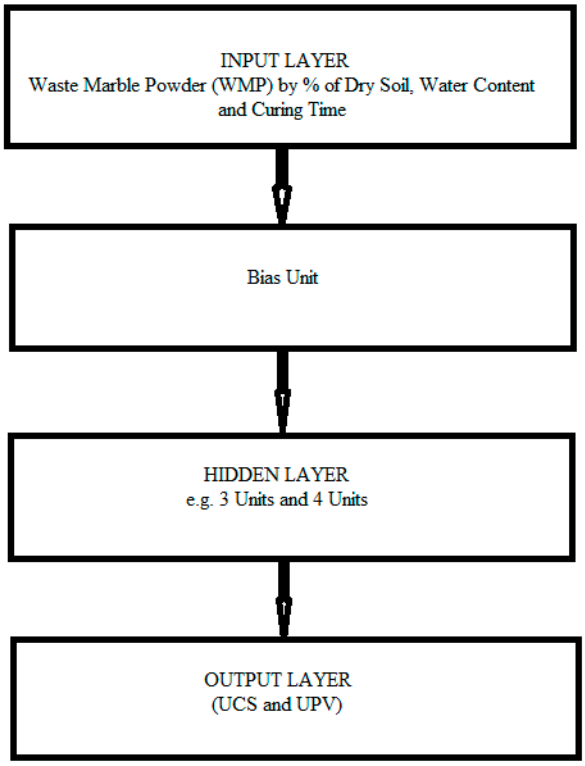


Figure 4. The flowchart mechanism of the neural network.

2.6.3. Sensitivity Analysis

After training, a sensitivity analysis can be performed to determine how changes in each input parameter affect the network's predictions. If we observe substantial fluctuations in a model's performance in response to a change in a particular variable, this may indicate that the factor is more sensitive. Conversely, minimal variance observed under similar conditions may indicate a lower relative importance for the feature in question.

For instance, if changes in water content result in significant adjustments in the predicted UCS/UPV values, the system is extremely sensitive to this parameter. Similarly, the effects of curing time and excess marble powder percentage on strength measurements can be quantified using the same method, allowing us to identify critical factors affecting the overall predictive capabilities of the model.

This type of comprehensive evaluation not only facilitates understanding the relationship between specific variables and results but also informs future strategies for improving the accuracy and reliability of artificial neural networks used in geotechnical engineering.

3. Results and Discussion

3.1. The Physical Behavior of Stabilized and Unstabilized Soils

3.1.1. Specific Gravity

In Figure 5, we observe how variations in soil clay content can be used as a proxy for the physical behavior of soils amended with varying amounts of marble powder. When the percentage of marble powder added to the clay soil increases to 45% (X4), the specific gravity increases from 2.73 to 2.83. However, when the percentage of marble powder is increased beyond 45%, there is no difference. The results of this study are consistent with those of Ref. [38]. The initial increase in specific gravity results from the increased density of the soil mélange caused by the addition of marble powder. Marble powder is denser than clay soil, and when combined with soil, it fills voids and reduces the amount of air in the soil. As such, it causes an increase in the overall density of the soil, increasing its specific gravity [39]. Nevertheless, the specific gravity remains unchanged after the addition of a certain percentage of marble powder. This phenomenon is due to the saturation limit of the

soil, beyond which the addition of marble powder has no appreciable effect on the specific gravity [40].

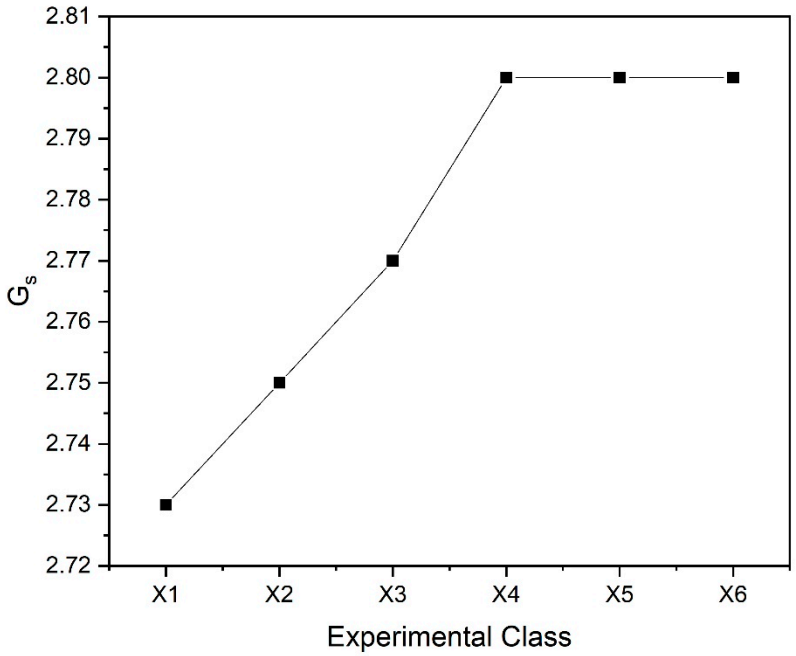


Figure 5. The amended and unamended soil sample's specific gravity characteristics.

3.1.2. Atterberg Limits

Changes in the Atterberg limits (liquid and plastic limits) reflect the plastic behavior of the natural soil and soil modified with different concentrations of marble powder, as shown in Figure 6.

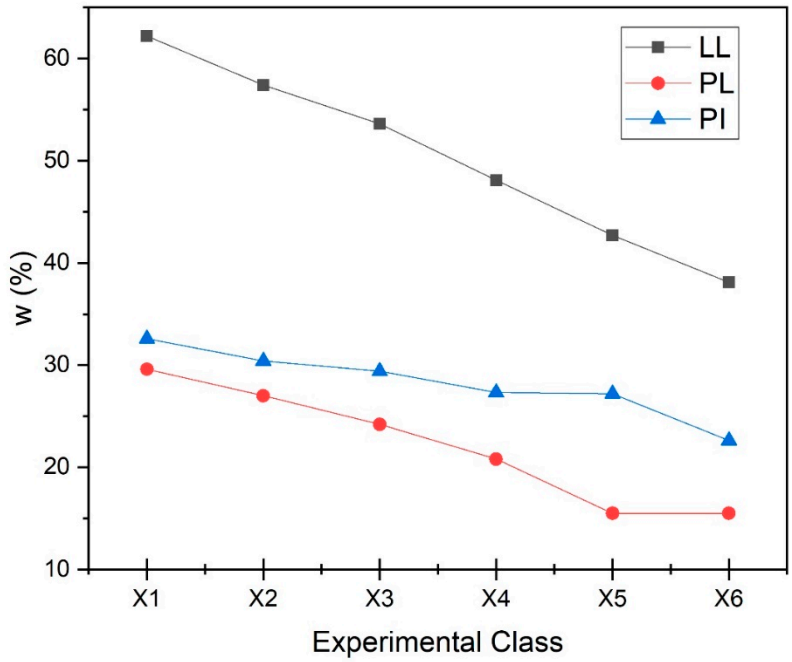


Figure 6. The amended and unamended soil sample's Atterberg limits characteristics.

Liquid limit: Stabilizing the clay with marble dust waste significantly improved the engineering properties of the soil, as evidenced by a decrease in the liquid limit from 62.2% to 31.8%. This research is supported by the previous literature [40,41]. The reduction in the liquid limit is due to the infilling action of the marble powder, which reduces the void

ratio and increases the density of the soil [39]. The infilling action of the marble powder refers to the process by which the powder particles fill the voids between the soil particles. This infilling reduces the void ratio—the ratio of voids to soil volume. Lower void ratios indicate less void space between soil particles. Because the particles are packed closer together, the soil density increases. Density reduces the soil's liquid limit [42]. The liquid limit is the moisture content at which soil becomes plastic. Denser soil resists deformation and requires more moisture to become plastic. Because of the marble powder infill, the liquid limit decreases as soil density increases [43].

The marble powder also contributes to the formation of a cementitious material that binds the soil particles together, thereby increasing the stiffness and shearing strength of the soil [40]. In furtherance, the pozzolanic reaction between the marble particles and the soil produces stable compounds that increase the durability and resistance of the soil to weathering [44].

Plastic limit: The plastic limit of clay declined from 29.6 to 15.5 as the marble powder content increased up to 60% (X5) but did not change as the marble powder content increased at 60% and 75%. This result is consistent with that of the [45] investigation, which found that the plastic limit of clay soil decreases up to 60% marble powder content and stays constant. As such, this is intriguing and can be explained by the fact that the marble powder particles occupy the spaces between the clay particles, reducing their plasticity. Importantly, this specific mechanism by which marble powder reduces plasticity may vary depending on the clay and marble powder's composition and properties. Marble powder could affect the lower plastic limit, which is the moisture content at which clay becomes too dry and loses its plasticity. Without additional information or context, it is difficult to determine the exact cause of the decreased plasticity in this particular case.

More so, this would lead to a decrease in the plastic limit of the clay soil [40]. The clay particles may become coated with marble powder particles at higher marble powder concentrations, resulting in a more stable and less malleable soil mass [46].

Plasticity index: The plasticity index, which is the mathematical difference that exists between the plastic limit and the liquid limit, reduces as the marble powder content of the soil rises (Figure 7). When WMP is added to clay, the plasticity index drops drastically from 32.6% in clay soil to 22.6%. These results are in agreement with those of Ref. [40]. The inclusion of WMP, which acts as a pozzolanic material, may explain why the plasticity index dropped. The geo-engineering properties of soil can be enhanced by adding pozzolanic minerals, which are known to react with calcium hydroxide in the presence of water to form cementitious compounds. As a result of the WMP reducing the soil's ability to hold water, the plasticity index may have lowered [45].

3.2. Compacted Behavior

The compaction test procedure was performed according to the ASTM D698 standard [47], and the results are graphically presented in Figure 7 by showing the variation of maximum dry density (MDD) and optimum moisture content (OMC) for untreated soils and soils treated with different amounts of WMP by weight of dry soil.

3.2.1. MDD

The use of WMP to stabilize clay resulted in an increase in MDD values from 1.65 to 2.31 Mg/m^3 at 60% marble powder and no change at 75% marble powder. As such, this suggests that clay strengthening and compaction can be achieved using WMP. While some researchers, such as Jain et al., have found that MDD values increase with marble dust content, others, such as Singh and Jain, have found that they reduce [41]. Some researchers have suggested that differences in the physical and chemical properties of the WMP and clay used in the various tests may be responsible for the conflicting results.

The increasing trend in MDD values observed when clay is stabilized with WMP in this study can be attributed to several factors: First, marble powder (WMP) is known to have a higher specific gravity than clay. This suggests that the addition of WMP to clay

increases the overall density of the mix, resulting in higher MDD values [48]. Second, WMP particles' angularity is greater than clay particles. This angularity improves particle interlocking, resulting in increased compaction and higher MDD values [49]. In addition, WMP contains fine particles that can fill the spaces between clay particles, resulting in a denser and more compact mix [43,50].

It is crucial to note that the mineralogy, particle size distribution, and chemical composition of the WMP and clay used in the study can also influence the observed trend. These properties can vary between different sources of WMP and clay, resulting in different results between studies.

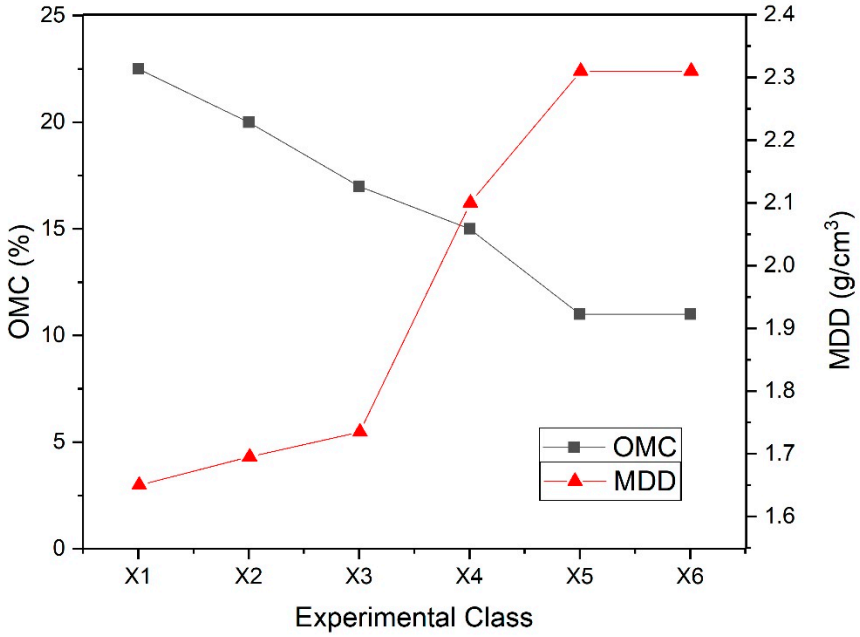


Figure 7. The amended and unamended soil sample's compaction characteristics.

3.2.2. OMC

The clay stabilized with WMP results indicates that the OMC values are reduced from 22.5% at 0% marble powder to 11% at 60 and 75% marble powder. For this reason, it is suggested that waste marble powder can effectively reduce the OMC of clay, which may have notable implications for soil stabilization and engineering applications. Compared with [40], the results are consistent with previous studies that have shown the effectiveness of waste marble powder in reducing the OMC of clay. As such, it can be attributed to the high specific surface area and pozzolanic activity of the waste marble powder, which enhances the microstructure and strength of the clay.

3.3. The Mechanical Behavior of Stabilized and Unstabilized Soil

3.3.1. The Impacts of Water Content on the UCS

It is intriguing to observe that soil type, additive type, water content, and curing time all substantially determine the maximum UCS of treated and untreated soil samples. The UCS of unmodified and modified clay samples as a function of water content and curing time is shown in Figure 8. The results show that as the WMP increases, the UCS of X1, X2, X3, X4, and X5 increase and then decrease slightly at X6, while the maximum UCS was obtained at 28 days of curing and with the addition of X5 marble powder, with the UCS values at dry moisture content (DMC), optimum moisture content (OMC), and wet moisture content (WMC) paths of 472 kN/m^2, 661 kN/m^2, and 540 kN/m^2, respectively.

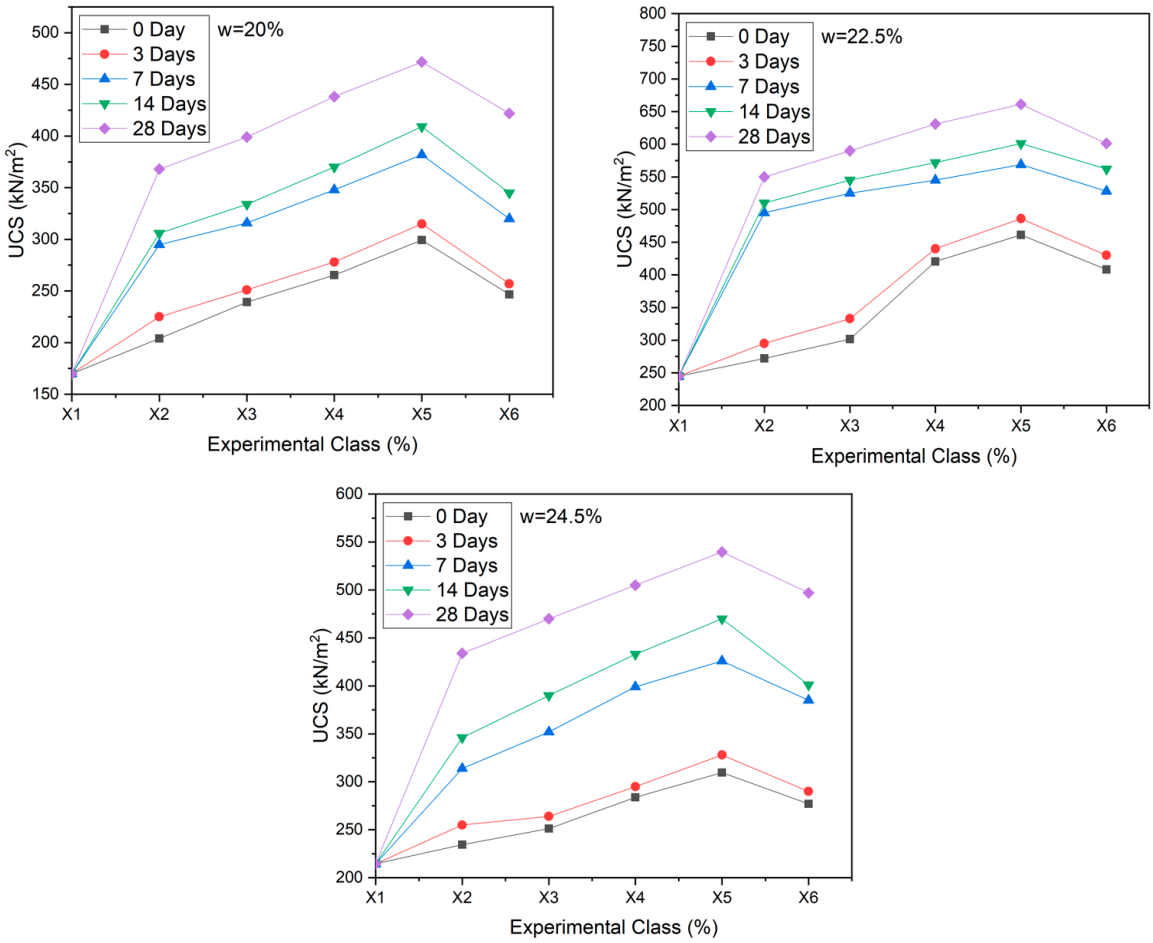


Figure 8. Depiction of the maximum UCS of amended and unamended clays influenced by water content and curing time.

This study's systematic optimization of WMP dosage, moisture content, and curing time provides new insights into maximizing UCS. In particular, the peak UCS at optimal moisture content is consistent with compaction theory. Yin et al. and Driss et al. reported identical results [1] in contrast to Umar's and Orakolu Firat's studies, which found that following a 7-day curing period of fine-grained soil stabilized with WMP, the increment in UCS is greater for samples compacted with DMC than those compacted with OMC and WMC [47], where the peak UCS occurred at lower moisture contents. Furthermore, in contrast, Umar et al. [43] observed that the UCS of CH soil stabilized with bentonite and bagasse ash rises with increasing water content up to a certain point and that the strength is higher for WMC than for DMC and OMC. This demonstrates the distinct reactivity and stabilizing effect of the strengthening agent and the soil.

In addition, this study established a novel correlation between UCS results and ultrasonic pulse velocity measurements to characterize strength enhancement comprehensively. Compared to previous research, the integrated experimental-modeling methodology that combines UCS, UPV, and ANN simulations provides a more comprehensive approach.

The three compaction paths detailed the above pattern: Path I, or the dry path of optimum, has pores of a bigger size, some of which cannot be entirely filled and bonded with the admixture due to larger pores. Moreover, the amount of water consumed is enough for performing chemical reactions due to the fact that it contains low water content [51]. On the other hand, Path II, or the optimum path, shows that higher water content can help with strength development by allowing for more efficient reactions between the marble powder and clay particles. The cation exchange process also substantially alters soil texture and structure, which can ultimately impact the porosity and volume capacity of

the soil particles [52]. Finally, Path III, or the wet path of optimum, involves increasing the moisture content beyond the OMC. This increase in moisture content leads to a decrease in electrolyte concentration, increasing the expansion of the dispersed twofold layer and the distance between clay particles and alumina–silicate unit layers. This reduction in internal friction and cohesiveness is due to water entry into the pores [43]. As more water is added, the continual capillary moisture reduces suction, which lessens strength when moisture exceeds an optimal value. The dispersed structure becomes more homogeneous when added water decreases the UCS [53].

The function of marble in modifying the Soil Water Retention Curve (SWRC) of the samples is to increase the soil's water-holding capacity. As a porous material, marble dust can absorb and retain water, increasing the available water content of the soil [54].

The addition of marble and the resulting increase in strength is not directly related to the change in soil stress. The addition of marble primarily affects the soil's ability to retain water, which may indirectly affect the strength of the soil. The increased capacity for water retention may increase the soil's resistance to shear stress and its overall resilience [39,55,56].

However, adding marble does not directly affect the change in suction stress, which refers to the matric suction or negative pore water pressure in the soil. Suction stress is primarily determined by soil texture, pore size distribution, and the presence of air-filled pores. While the addition of marble may indirectly affect these factors by altering their water retention properties, its effect on suction stress is not the primary mechanism by which the addition of marble improves the strength of a material [57].

3.3.2. The Impact of Curing Time on the UCS

During the curing process, water reacts with the clay and WMP particles to form a solid matrix through the hydration reaction. This reaction continues over time, causing the sample material to increase in strength. The more time the hydration reaction proceeds, the greater the UCS [58]. A curing period of 28 days is generally considered standard for determining the UCS of stabilized soils [59,60]. However, the specific curing time required for optimum strength depends on a number of variables, and there is a maximum gain in strength after a certain point [61,62]. The strength of clay soils can be enhanced by mixing in marble powder. How much strength increases depends on how much marble powder is added and how long the combination cures. This study cured the treated and untreated samples for 0, 3, 7, 14, and 28 days.

When WMP is added to clayey soils, microscopic particles cluster together to form a crystalline structure that fills the gaps between the sample material particles. This solid structure improves soil strength and reduces soil plasticity, which improves workability and gradation [63].

Additionally, the increased soil matrix compactness resulting from a reduction in porosity can contribute to the overall improvement of the soil's properties [64,65]. Furthermore, at the end of the process, chemical compounds resulting from inter-reactions between marble dust, soil alumina, and soil silica had increased the strength of the soil. Over time, as the curing process takes place, these reaction products solidify and become more integrated into the soil matrix. This solidification further improves the soil's stability and resistance to erosion [39]. In addition, this soil stabilization method has the added benefit of preventing soil liquefaction during seismic events. Soil liquefaction is a phenomenon in which saturated soil loses its strength and behaves like a liquid during an earthquake or other seismic activity. By increasing the soil's strength and stability, using marble dust, soil alumina, and soil silica can help reduce the risk of soil liquefaction in areas prone to seismic events [66–68]. Recycling marble powder for soil stabilization is an environmentally friendly way to increase soil strength and stability while reducing waste.

3.3.3. The Impact of WMP on the UCS

Research on WMP-stabilized clay shows that the compressive strength improves as more powder is added, up to a concentration of X5 (60%). However, a slight decrease in

compressive strength was observed at X6 (75%). With this in mind, it was determined that a 60% marble powder amendment provides the strongest soil amendment. In one study by Gurbuz [44], clayey soils were stabilized with marble powder, and the maximum UCS value was obtained at a lower dose level of 5%. Another study by Jain [39] found that the highest UCS was achieved in samples treated with 20% waste marble powder. In yet another experiment by Yorulmaz et al., a 50% dose of WMP achieved the highest strength in stabilizing soil with fine [69]. Therefore, these and related studies indicate that the continuous addition of WMP raises the UCS of soil with fine up to a specific dose.

It should be noted that the effectiveness of marble powder as a stabilizing agent may vary based on several factors. These factors include the type of clayey soil being stabilized and the type and quality of waste marble powder used. Other factors that may affect the stabilization process include the regional origin of the marble powder, its impurity levels, vein density, and color. Therefore, it is essential to carefully consider these variables when determining the optimal dosage of marble powder needed to achieve the desired stabilization results [70].

The use of WMP as an additive in clay soil has been found to have both positive and negative effects on the properties of the soil. The addition of marble dust reduces the soil's clay content and increases the additive's proportion. A minor pozzolanic reaction occurs when water is present, forming a stable calcium silicate hydrate. This reaction enhances the soil's unconfined compressive strength (UCS) and gains significant strength. This finding is consistent with the results of a similar study conducted by Sabat et al. [71]. However, when marble dust is used to substitute clay soil at a certain point, the cohesiveness and density of the mixtures decrease [72]. As such, it can lead to a decline in soil strength when the percentage of marble dust exceeds 60 percent, as observed in this study. Therefore, using marble dust as an additive in clay soil must be carefully controlled to ensure that the desired properties are achieved without compromising the strength or cohesiveness of the soil [73]. It is essential to conduct thorough testing and analysis to establish the most effective and efficient use of marble powder in specific soil stabilization applications. Still, adding WMP can increase fine-grained soils' strength and stability.

3.3.4. UPV Impacts

The results of UPV tests performed on stabilized and unstabilized samples using different combinations of WMP and water contents during the curing period are presented in Figure 9. The results show that as the WMP increases, the UCS of X1, X2, X3, X4, and X5 increase and then decrease slightly at X6, while the maximum UPV was obtained at 28 days of curing and with the addition of X5 marble powder, with calculated DMC values of 412 m/s, OMC values of 849 m/s, and WMC values of 561 m/s. Additionally, the results showed that the UPV rose to its maximum value at the OMC. After that, the UPV fell as the moisture content rose. The results also showed that the UPV rose to its maximum value at the OMC. After that, the UPV fell as the moisture content rose. The UPV enhancement directly correlates with the measured gains in density and strength, validating UPV testing to characterize soil stabilization effectiveness.

Importantly, the UPV values were lower than that observed in experiments using additives other than fly ash and lime [74]. This reveals the uniquely low performance of WMP, attributed to its fine particle size and chemical reactivity.

Umar and Orakolu Firat vindicate the results of this study [47] by examining marble powder for soil improvement after seven days of curing. This work systematically optimized WMP dosage, moisture content, and curing time to maximize UPV. The broader analysis of factors influencing UPV adds novel insights.

Moreover, this is the first known study to combine UPV measurements with advanced artificial neural network modeling to predict the optimal stabilization process. The validated model provides engineers with a new design tool for WMP-modified soil mixtures.

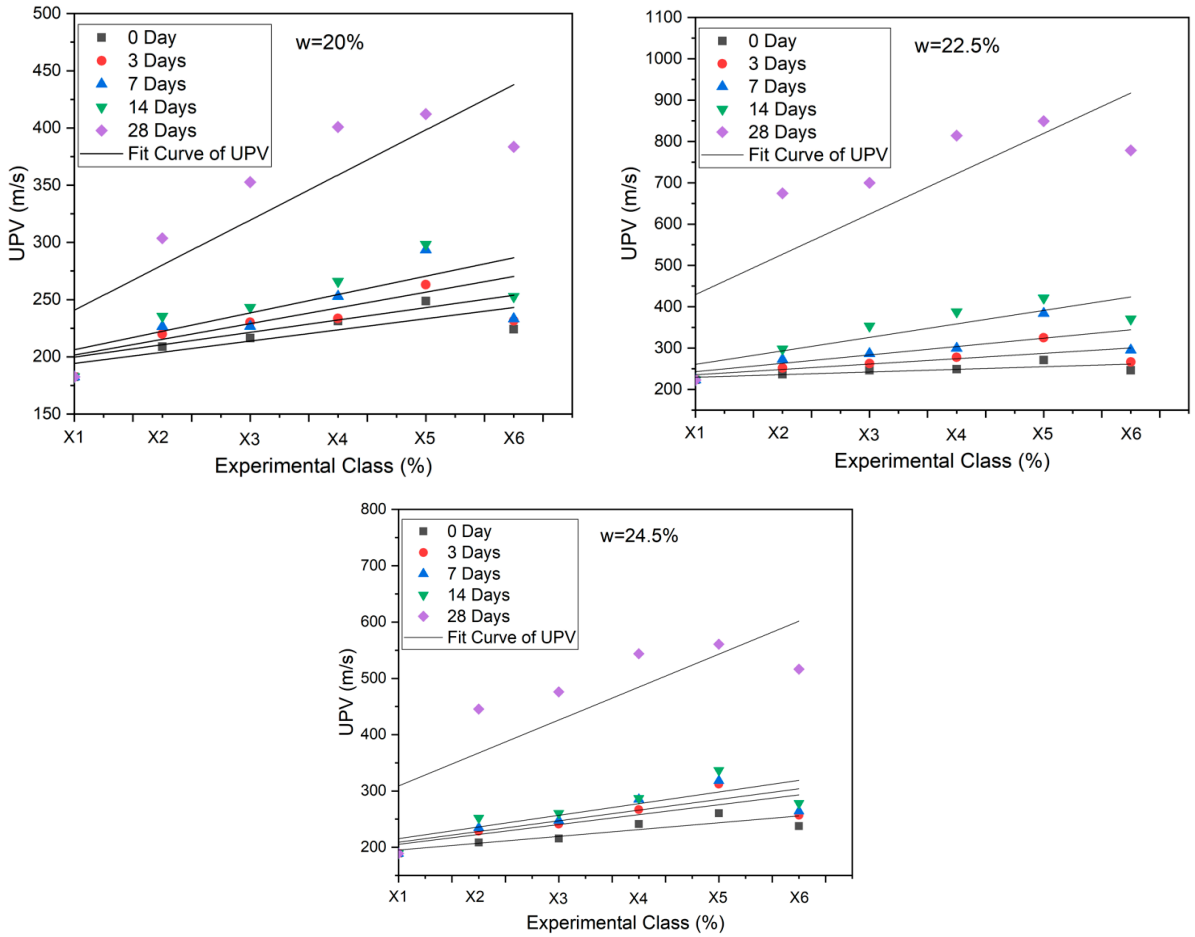


Figure 9. Depicts the UPV of amended and unamended clays influenced by water content and curing time.

3.4. Developing Artificial Neural Networks

3.4.1. Pearson Correlation Matrix

A useful statistical tool is the Pearson correlation matrix, which provides information about the direction and strength of a linear relationship between two variables. It can take values between −1 and 1, where −1 indicates a completely negative correlation, 0 indicates no correlation at all, and 1 indicates a completely positive correlation.

3.4.2. ANN Generated UCS

This research indicates that using an artificial neural network (ANN) framework consistently predicts untreated and marble powder-stabilized clay soils' unconfined compressive strength (UCS). This prediction is achieved by considering the percentage of waste material, moisture content, and curing time as input variables, as seen in Table 4. The predicted unconfined compressive strength (UCS) values exhibited a robust positive Pearson correlation with the empirical results, with coefficients close to 1. The results of this study corroborate those of Mohammadi et al., who found that the predicted UCS values of the ANN model were highly correlated with their input parameters [75].

Furthermore, this study represents the first application of artificial neural network (ANN) modeling in soil stabilization using marble powder waste. The results demonstrate that artificial neural networks (ANN) can accurately incorporate the various physicochemical effects of the marble powder additive to mimic unconfined compressive strength (UCS).

Previous studies have used artificial neural networks (ANN) in soil stabilization [75]. However, this research introduces a novel approach by integrating the ANN model with experimental optimization techniques to analyze the components that affect the unconfined compressive strength (UCS). This facilitates the improved prediction of the optimal quanti-

ties of marble powder to be added to achieve the desired engineering targets of unconfined compressive strength (UCS).

Using an integrated modeling-experimental methodology and validating an artificial neural network (ANN) approach to simulate the significant unconfined compressive strength (UCS) improvements achieved by marble powder stabilization provide a unique tool for designing and optimizing these environmentally friendly soil combinations.

Table 4. Pearson correlation matrix between the input data and the UCS values predicted by the ANN model.

	w (%)	WMP (%)	CT	UCS
w (%)	1			
WMP (%)	0.442476	1		
CT	0.100023	0.350106	1	
UCS	1	0.442476	0.100023	1

Keys: WMP = waste marble powder, CT = curing time, w = water contents, UCS = unconfined compressive strength.

3.4.3. ANN-Generated UPV

In the case of the UPV (ultrasonic pulse velocity) of stabilized and unstabilized soil samples developed by an artificial neural network, the Pearson correlation matrix can be used to examine the relationship between the input parameters and the UPV values predicted by the ANN model. Table 5 shows the Pearson correlation matrix between the input data and the values of the UPV predicted by the ANN model. The strong Pearson correlation observed between the predicted and experimental ultimate compressive strength demonstrates the ability of artificial neural networks (ANN) to accurately capture the distinct physicochemical interactions caused by the presence of marble powder.

Table 5. Pearson correlation matrix between the input data and the UPV values predicted by the ANN model.

	w (%)	WMP (%)	CT	UPV
w (%)	1			
WMP (%)	0.738375	1		
CT	0.032906	0.01804	1	
UPV	1	0.738375	0.032906	1

Keys: WMP = waste marble powder, CT = curing time, w = water contents, UPV = ultrasonic pulse velocity.

Previous research has explored the utilization of marble powder in concrete to model its ultrasonic pulse velocity (UPV) [47]. However, this study represents the pioneering attempt to employ artificial neural networks (ANN) to simulate UPV in stabilized soil. Additionally, this approach integrates artificial neural network (ANN) modeling with a systematic optimization technique to analyze the effects of curing and composition parameters on ultrasonic pulse velocity (UPV).

The proven artificial neural network (ANN) technique presents a novel predictive tool for customizing soil mixtures stabilized with marble powder. This tool aims to obtain specific ultrasonic pulse velocity (UPV) values associated with desired levels of strength and integrity.

3.5. Validation of Models

Figure 10 shows a robust relationship between the estimated UCS and the observed UCS to further determine the model's accuracy. This indicates the success of the model in predicting the UCS of the samples, an important measure of its overall quality and strength. Additionally, the ultrasonic pulse velocities (UPVs) agree well with the predicted and observed data, as shown in Figure 11. Further, this lends credence to the theory that the model accurately predicts sample strength. The ANN model is quite effective in predicting strengths. Furthermore, it is worth noting that although other research has documented

the substantial accuracy of artificial neural networks (ANN) in predicting unconfined compressive strength (UCS) [72], this particular model is the first instance of its validation specifically for soil stabilization with marble powder waste. The results demonstrate the effectiveness of artificial neural networks (ANNs) in capturing the specific improvements brought about by the additive in question.

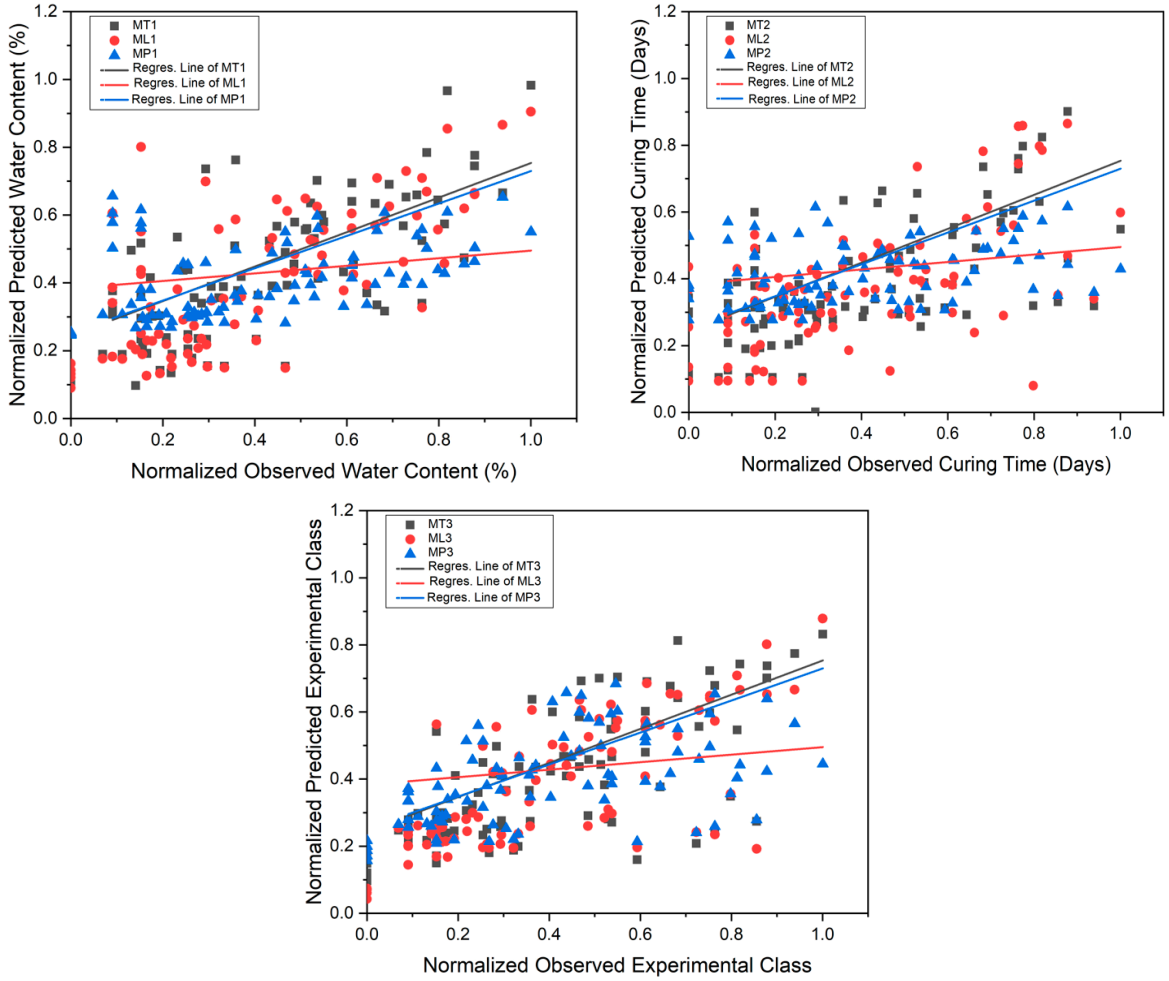


Figure 10. Observed versus predicted values of UCS for water content, curing time, and experimental class (waste marble powder by the percentage of dry soil).

The model's accuracy was evaluated over various variables, including different amounts of marble powder content, curing times, and moisture levels. However, further validation efforts should expand the input parameters' range to include a wider range of clay mineralogy and sample types.

This study showed a strong relationship between the predictions of the artificial neural network (ANN) model and the experimental data for both unconfined compressive strength (UCS) and ultrasonic pulse velocity (UPV), with correlation coefficients (R) close to 1 for both. The observed values exceed the established standards for robust correlation ($R > 0.8$), as well as the criteria outlined by Smith [76] for an exceptionally high level of correlation ($R > 0.9$).

The R-values observed in this study are significantly similar to those of previous artificial neural network (ANN) modeling studies on stabilized soils, where R-value ranges are close to 1 [77]. This observation suggests that the present model more accurately represents the improvements resulting from the use of marble powder stabilization.

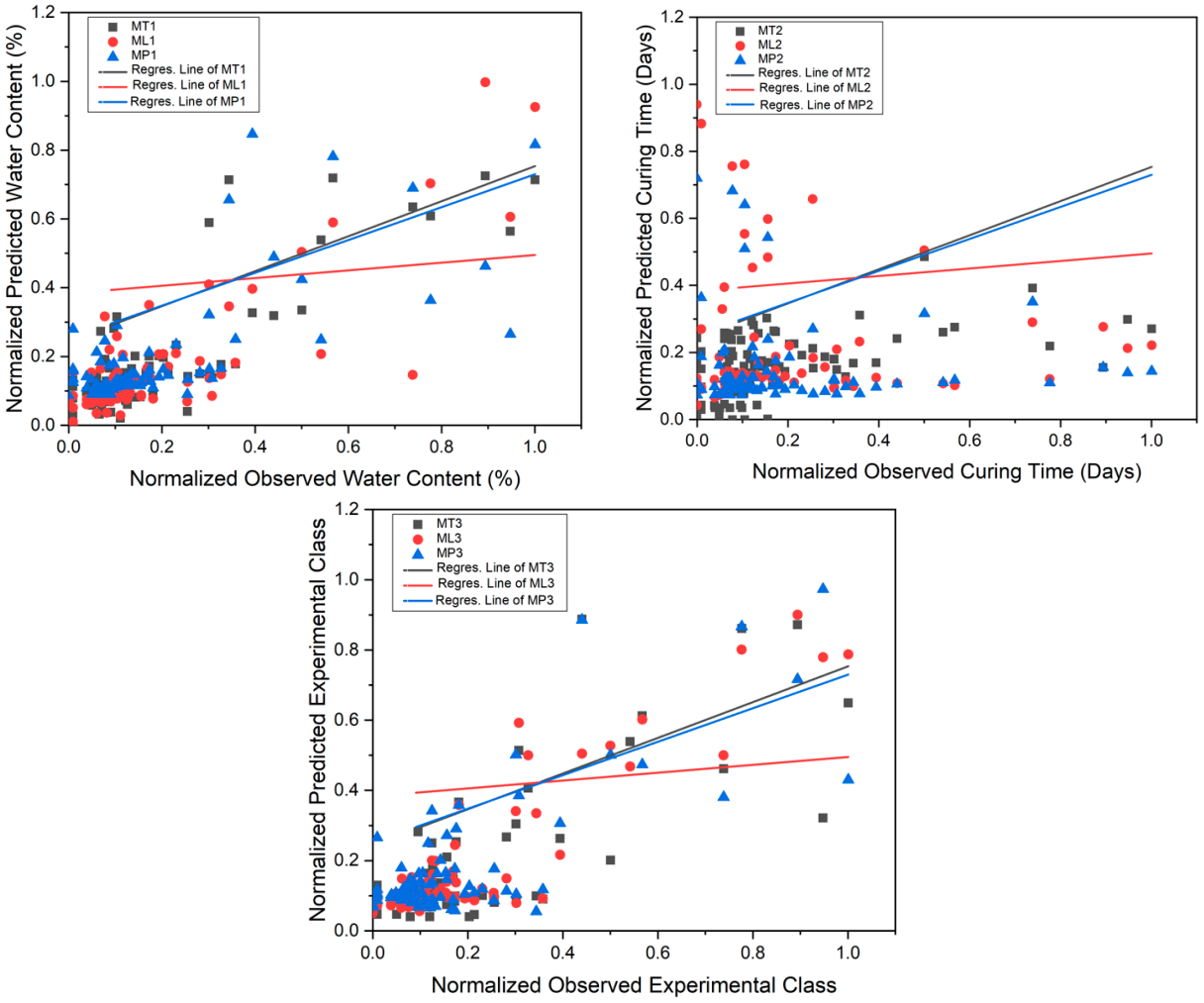


Figure 11. Observed versus predicted values of UPV for water content, curing time, and experimental class (waste marble powder by the percentage of dry soil).

Nevertheless, it is critical to conduct a comprehensive evaluation of model performance by considering additional statistical metrics, such as Root Mean Square Error (RMSE) and R-squared (R^2), as recommended by Cherkassky et al. [78]. Additional experimentation with a wider range of parameter settings would contribute to the generalizability of the model.

The following tables show a comparison of the datasets used in the training and testing phases of UCS (Table 6) and UPV (Table 7). Using MATLAB's neural network transfer functions, we found that water content had a greater effect than either curing time or percent of WMP. It was also found that while TANSIG has a better correlation in training, LOGSIG is superior in the test phase of UCS, and LOGSIG is slightly better in UPV in both phases.

Table 6. The training phase and testing phase of UCS of the ANN model.

Performance Criteria for UCS				
ANN				
Training	**R^2**	**MSE**	**RMSE**	**R**
TANSIG-1	0.904147	0.023242	0.152452	0.817482
TANSIG-2	0.831887	0.061215	0.247416	0.692036

Table 6. *Cont.*

Performance Criteria for UCS				
TANSIG-3	0.798742	0.032909	0.181408	0.637989
PURELIN-1	0.904147	0.023242	0.152452	0.817482
PURELIN-2	0.686603	0.105066	0.324139	0.471424
PURELIN-3	0.754218	0.039194	0.197976	0.568844
LOGSIGM-1	0.846953	0.035995	0.189723	0.71733
LOGSIGM-2	0.82197	0.064475	0.253919	0.675635
LOGSIGM-3	0.814882	0.030541	0.17476	0.664032
Testing				
TANSIG-1	0.601973	0.042325	0.20573	0.362372
TANSIG-2	0.622862	0.069647	0.263908	0.387956
TANSIG-3	0.874912	0.030024	0.173274	0.765472
PURELIN-1	0.54196	0.046882	0.216522	0.293721
PURELIN-2	0.471229	0.088526	0.297533	0.222057
PURELIN-3	0.703579	0.064647	0.254257	0.495023
LOGSIGM-1	0.741733	0.029859	0.172798	0.550168
LOGSIGM-2	0.558	0.078363	0.279934	0.311364
LOGSIGM-3	0.887453	0.027195	0.164908	0.787573

Table 7. The training phase and testing phase of UPV of the ANN model.

Performance Criteria for UPV				
ANN				
Training	**R^2**	**MSE**	**RMSE**	**R**
TANSIG-1	0.86345	0.012736	0.112853	0.745547
TANSIG-2	0	0	0	−1.67406
TANSIG-3	0.741965	0.015311	0.123738	0.550511
PURELIN-1	0.773548	0.020102	0.141781	0.598376
PURELIN-2	0	0	0	−6.6081
PURELIN-3	0.635361	0.020313	0.142522	0.403684
LOGSIGM-1	0.860028	0.013031	0.114154	0.739648
LOGSIGM-2	0	0	0	−10.4289
LOGSIGM-3	0.900973	0.006412	0.080077	0.811752
Testing				
TANSIG-1	0.793585	0.009322	0.096551	0.629777
TANSIG-2	0	0	0	−0.08955
TANSIG-3	0.798659	0.019459	0	0.637856
PURELIN-1	0.408841	0.020971	0.144813	0.167151
PURELIN-2	0	0	0	−0.64634
PURELIN-3	0.723872	0.025578	0.159931	0.52399
LOGSIGM-1	0.412758	0.02089	0.144533	0.170369
LOGSIGM-2	0	0	0	−0.85259
LOGSIGM-3	0.90483	0.009741	0.098697	0.818717

Furthermore, the systematic evaluation of different artificial neural network (ANN) training functions and input parameters provides a unique approach to optimize the model architecture specifically for soil stabilization using marble powder. The use of parametric optimization at this level allows for the development of customized artificial neural network (ANN) models specifically designed for this particular application.

This study significantly enhances the design and predictive capabilities of artificial neural network (ANN) models by accurately and uniquely representing the improvements in UCS and UPV achieved through the use of marble powder as a soil stabilizer. The results of this research contribute to the optimized application of this environmentally friendly soil stabilizer.

4. Conclusions

This study conducted an extensive experimental and modeling investigation on the stabilization of clay soils using marble powder waste. Various tests were conducted to analyze the effects on geotechnical properties such as strength (UCS and UPV). Advanced modeling techniques were also implemented to validate further and optimize the soil stabilization process. The major conclusions arising from this comprehensive study are:

(1) The incorporation of increasing amounts of WMP into clay soil increases specific gravity from 2.73 to 2.83, primarily due to increased soil density, void filling, and reduced air content. Additionally, marble dust waste stabilizer improves clay engineering properties by reducing the liquid limit from 62.2% to 31.8%. It also reduces the plastic limit from 29.6 to 15.5% with increasing WMP content. Marble powder particles occupy spaces between clay particles, reducing the plasticity index from 32.6% to 22.6%.

(2) Marble powder stabilizes clay, increasing maximum dry density (MDD) values from 1.65 to 2.31 Mg/m^3, over 40% at 60% WMP content. WMP also reduces OMC values from 22.5% at 0% marble powder to 11% at 60 and 75% marble powder, making it useful for soil stabilization and engineering applications due to its high specific surface area and pozzolanic activity.

(3) After 28 days of curing, the clay showed an increase in UCS as the maximum UCS of the specimens is attained at X5 (60%), with DMC, OMC, and WMC paths of 472 kN/m^2, 661 kN/m^2, and 540 kN/m^2, respectively. The best strength (661 kN/m^2) is achieved at 22.5 percent OMC, 60 percent WMP, and 28 days of curing. The strength enhancement depends on factors such as WMP quality, clay mineralogy, and curing time. Unconfined compressive strength testing successfully evaluated stabilization effectiveness, whereas, after a 28-day curing test, maximum UPV values were seen in clay soil stabilized with marble powder, with X5 powder providing the maximum boost. We found the UPV to be 412 m/s at DMC, 849 m/s at OMC, and 561 m/s at WMC. This further verified the improved structural integrity of stabilized and unstabilized clay soils. UPV values increased with WMP addition, correlating well with UCS trends. Combined UCS and UPV testing provides comprehensive strength characterization.

(4) This study analyzed the Pearson correlation matrix to determine the relationship between the input parameters and the ANN model's predicted UCS and UPV values. The results showed a positive correlation, indicating the model's effectiveness in predicting the strength of stabilized and unstabilized soil samples. Validation confirmed the model's accuracy in predicting strength, as the correlation coefficients are close to 1. Finally, the long-term performance of soil stabilized with WMP and the consequence of environmental elements, e.g., rainfall and temperature in applications such as foundations and road subgrades, could be the subject of future research.

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