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Original Article

Industrial Waste Importance on Sustainable Ground Enrichment: A Comparative Analysis of Marble Dust and Synthetic Fibers in the Black Cotton Soil using Machine-Learning Support

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Abstract *- This paper explores the use of industrial waste as a sustainable development in enhancing black cotton soil that can be used in foundations. Waste marble dust and synthetic polyester fibers are used as stabilizing agents, and their performance is measured using the compaction test, the California bearing ratio test, the unconfined compressive strength test, and the model footing load-settlement test. Another machine-learning model is developed on the basis of Random Forest regression that helps predict bearing performance on the basis of laboratory parameters. The findings indicate that maximum dry density and bearing capacity increased significantly with marble dust inclusion, with optimum performance observed at 30% replacement. Synthetic fibers increase ductility, minimize cracking, and maximize post-peak load response, but strength increases are relatively less. The predictive model shows a high level of agreement with the trend of the experiments and indicates the variables that have the strongest effect on bearing behavior. The originality of this piece is in the fact that it combines the valorization of waste and comprehensible machine-learning assistance in a single comparative framework. The paper shows that the integration of materials, which are environment-friendly and data-driven tools, can form a viable avenue to sustainable and streamlined ground-improvement practices.*

Keywords *- Black cotton soil, Bearing capacity, Machine Learning, Marble dust, Synthetic fibers.*

1. Introduction

Black cotton soil has been considered to be among the most problematic expansive soils that are experienced in geotechnical engineering, especially in tropical and semi-arid regions. The seasonal changes in moisture content cause swell-shrink characteristics that are pronounced in the soil, making it experience serious engineering problems like differential settlement, foundation distress, pavement cracking, and failure of the serviceability of lightly loaded structures over the long term [1-3]. The extreme plasticity, low shear resistance, and sensitivity to moisture of these soils result in the need to stabilize or improve the soils through interventions like ground improvement before they can be used in infrastructure projects. The conventional methods of soil stabilization are usually based on cementitious additives, including lime and Portland cement. Inasmuch as these techniques are as good as they are in strengthening and decreasing plasticity, they are becoming more and more limited in their application due to economic and environmental factors. Stabilizers made out of cement require a lot of energy, which is related to significant carbon emissions and does not correspond to the modern sustainability goals in the sphere of construction activities [4, 5]. Therefore, in recent times, there have been research activities towards finding alternative stabilizers that are technically viable and environmentally responsible. At the same time, the increased rate of industrialization has resulted in huge amounts of waste by-products that also need long-term waste disposal solutions. Marble dust, a fine particulate waste generated during marble cutting and polishing activities, is a major environmental issue because of dust pollution, land degradation, and landfill overburden [6, 7].

Geotechnically, the marble dust has physicochemical properties that can enhance the behavior of soil by the effects of packing the particles, altering the plasticity, and strengthening [8-10]. Similar studies have shown that discrete synthetic fibers, including polyester or polypropylene fibers, might be used to promote ductility, crack resistance, and post-peak deformation behavior of fine-grained soils by providing tensile reinforcements [11-19]. Although the field of waste-based soil stabilization has continued to enlarge, there are still some holes. To begin with, the stabilization of marble dust and fiber reinforcement is mainly considered independently, and little systematization of comparison was conducted under the same soil conditions and testing systems [13, 14]. Second, most previous research focuses on the laboratory index property but does not pay enough attention to structural-scale performance properties, including footing load-settlement response, which directly regulates the foundation design and serviceability [20-22]. Third, despite the recent development of machine-learning strategies as geotechnical modeling methods, their combination with the experimental studies concerning the stabilization remains underdeveloped [23-27]. Specifically, the possibility of data-driven tools to find governing variables and help to optimize mix design has not been explored in full. Considering these shortcomings, the current research engages in cohesive comparative research on the use of marble dust and synthetic polyester fibers in the stabilization of black cotton soil.

The experimental program assesses the behavior of compaction, the strength properties, the California Bearing Ratio (CBR), and the model footing load-settlement response. Moreover, a Random Forest regression model is trained to enable the interaction of soil properties with variables of stabilizers (nonlinear) and, as a result, give predictive information about bearing performance. The originality of the study is in three main points: (i) the combination of the comparison of actual mechanisms of particulate and discrete reinforcement in one experimental setting, (ii) the identification with structural-scale footing behavior and standard laboratory indices, and (iii) the synthesis of explainable machine-learning tools to assist the engineering decision-making. With this experimental and data-driven solution approach, it is hoped that the study will make a contribution to sustainable ground-improvement strategies that reconcile mechanical performance with environmental responsibility. This is research with novelty, as the combined assessment of the particulate stabilization and discrete fiber reinforcement is presented in the framework of a single experiment, with the structural-scale footing response and machine-learning-enhanced interpretation.

2. Literature Review

Black cotton soil is well known to be an expansive soil with low shear strength, high compressibility, and high swell-shrink cycles with seasonal changes of moisture. Such properties tend to cause pavement cracking, foundation heaving, and low long-term performance in lightly loaded structures [1-3]. In turn, there has been an interest by researchers in the stabilization methods that enhance the mechanical behavior and minimize impact on the environment and lifecycle cost [4, 5].

2.1. Stabilization of Wastes with Marble Dust

During cutting and polishing, marble dust is produced in large quantities, and it leads to dust pollution, clogging of drainage paths, and land degradation due to uncontrolled dumping of the dust [6-7]. Marble dust interacts effectively with fine-grained soils since it is mainly composed of calcium carbonate, and this enhances better packing of particles, reduces plasticity, and alters soil fabric [8-10].

Some of the studies have indicated that the maximum dry density, California Bearing Ratio, and unconfined compressive strength have been increased with the addition of marble dust at optimum dosage [11, 12]. However, too much replacement of the soil skeleton by marble dust can break the continuity of the soil skeletons and also lessen the efficiency of interactions between particles. This underscores the need to optimize dosage and prepare an equal mix [13].

2.2. Strengthening and Enhancing Ductility

Polyester and polypropylene are synthetic fibers that have been successfully applied as discrete reinforcements in the soil systems [14]. Fiber inclusion, as opposed to chemical stabilizers, does not cause cementation; tensile resistance is mobilized by bridging micro-cracks and greater resistance to deformation as applied loads take effect [15, 16].

Experimental research has demonstrated better ductility, less crack propagation, and a better post-peak loading capacity of expansive soils with fiber reinforcement [17, 18]. However, performance is sensitive to fiber content, aspect ratio, and uniformity of mixes, and thus the variation in performance across reported datasets, making it difficult to compare studies on a case-by-case basis [19].

2.3. Strategies of Combined Stabilization

Hybrid stabilization methods are trying to combine the effects of densification offered by marble dust with the ductility offered by fibers. It is reported that strength and deformation control show synergistic results on the occasion of the joint use of the two materials [20, 21]. However, the bulk of the literature still largely depends on laboratory index testing, and few studies are conducted on structural-scale measurements like the footing load-settlement behavior, which is needed to design a foundation structure and determine its serviceability [22].

2.4. Geotechnical Engineering: Machine-Learning Applications

Recently, machine-learning tools have become relevant to complement experimental geotechnical studies. Random Forest, Gradient Boosting, and Neural Network algorithms have been tested to make predictions of compaction properties, strength indices, and bearing capacity based on small datasets [23-25]. Such models are useful where the interactions between soil properties, additives, and testing conditions are nonlinear. Although they perform well, the majority of the applications have not been integrated with the stabilization programs, and they are rarely utilized in making decisions that are aimed at optimizing the mixes [26, 27].

2.5. Summary of Gaps

Based on the literature review, the following gaps can be identified:

1. The dust in marble and fiber reinforcement is often studied separately, and there is little concomitant comparison under the same testing conditions [13];
2. Not many studies measure both laboratory strength indices and footing load-settlement response at the same time;
3. The combination of machine-learning prediction and experimental stabilization is not yet very common, and
4. Waste valorization does not always have sustainability benefits that are considered alongside engineering performance [21].

In that regard, the current study undertakes an integrated comparative study of marble-dust and synthetic-fiber stabilization of black cotton soil and includes a Random Forest model as the support tool of predictive evaluation and determination of the optimal dosage.

2.6. Environmentally Friendly Ground Improvement with Industrial by-Products

The latest developments in sustainable geotechnical engineering focus on the valorization of industrial by-products as a substitute for the traditional cementitious stabilizers. Pozzolanic or filler pozzolana, like fly ash, Ground Granulated Blast Furnace Slag (GGBS), silica fume, and rice husk ash, have shown significant increases in the strength, stiffness, and durability of problematic soils. An example is fly ash stabilization, which has been reported to decrease plasticity and increase bearing resistance as a result of the particle packing effect and secondary cementitious reactions [21]. In the same way, slag-based stabilization is not only beneficial to the development of long-term strength and low compressibility, but also results in lower embodied carbon than the Portland cement systems. Agricultural by-products such as rice husk ash have also been noted to enhance compaction property as well as shear strength via silica-driven reactions and modulation of microstructure. All these studies point to one common fact: that waste-based stabilizers have the potential to provide similarly good engineering attributes like conventional additives and improve environmental aspects of disposal and carbon emissions. Mineralogical composition, compatibility of such materials with soil additives, and particle gradation are, however, of paramount importance in the effectiveness of such materials. Marble dust is non-chemically reactive as compared to pozzolanic ashes; however, it acts by densification and modifying plasticity, and thus exemplifies a different stabilization mechanism, which has to be evaluated separately.

2.7. Mechanistic Role of Calcium-Rich Waste Materials

There is a growing interest in the use of calcium-dominant industrial wastes in the process of soil improvement due to the capacity to alter soil fabric and physicochemical interactions. Marble dust, mostly constituted of calcium carbonate ($CaCO_3$), is not similar to lime and cement, but rather it alters the particle organization, distribution of the void, and inter-particle friction. This is unlike pozzolanic wastes like fly ash or slag, where marble dust is the dominant factor that influences mechanical modification and densification and particle packing process mechanisms, but not cementation. Research has indicated that fine calcium-based fillers have the potential to cause decreased liquid limit, plasticity index, and swellability of expansive soils by disrupting diffuse double-layers and forming dense packing [8]. The mechanism of mechanical stabilization, such as the packing and densification effects of particles, but not chemical cementation, is mostly responsible for the observed improvements in the maximum dry density and the bearing characteristics. Notably, the functionality of calcium-rich fillers is characterized by a threshold behavior. Although a certain optimum dosage has been observed, excess fines can interfere with the continuity of the soil skeleton, causing loss of strength and stiffness. This effect provokes the need to optimize the dosage and support comparative studies with low and high replacement levels. These results support experimental designs to include the measurement of peak performance limits, and not hypothetically increase with an experiment.

2.8. Performance of the Structural Scale

Although laboratory index tests still play a central role in the stabilization of soil assessment, recent literature emphasizes the significance of the structural scale in the assessment of realistic engineering interpretation. The bearing capacity and settlement response to footing loads are two combined expressions of stiffness, strength, and compressibility. Some researchers have shown that similar UCS or CBR value stabilized soils can also behave very differently in terms of load-settlement behavior because they can have dissimilar deformation characteristics and different failure modes [20, 22]. Examples that can be found in fiber-reinforced systems can have moderate maximum strength increases and major increases in ductility and shape-holding properties. Nevertheless, in spite of this appreciation, several stabilization research works solely use small-scale measures of strength, which restrict direct generalization to foundation design. The model footing tests assist in giving a more realistic test of serviceability and ultimate performance, especially with expansive soils where control of settlement is a criterion of serviceability. The relative scarcity of such structural-scale studies in waste-based stabilization literature indicates that there is a methodological gap that should be filled in by future studies.

2.9. Predictive Geotechnical Modeling Machine Learning

The use of Machine Learning (ML) models in geotechnical engineering has grown at an increasing pace because of the ability to describe nonlinear correlations between soil parameters. Random Forest (RF) ensemble learning algorithms have been shown to be very effective in predicting the characteristics of compaction, strength indices, and bearing behavior [23-27]. RF models, in contrast to the traditional regression methods, create multiple decision trees based on stochastic sampling, thus improving generalization and decreasing model variance. The ML methods are particularly beneficial in stabilization research in which the relationships between moisture content, density, and proportions of the additives are nonlinear by nature. Previous studies have been able to use RF and hybrid ML to predict California Bearing Ratio, resilient modulus, and shear strength with high accuracy measures [25, 26]. However, a lot of the ML-based studies are conducted without experimental stabilization software, and therefore, the models do not have a mechanistic explanation or a material of interest. Combining ML and laboratory-controlled data offers a way of both predictive modeling and variable-importance analysis, which allows determining engineering parameters that govern the system.

2.10. Interpretability of Models and Engineering Relatability

In addition to the predictive accuracy, in the recent discussion on the topic of ML-assisted geotechnics, interpretability and physical consistency are stressed. The relative impact of soil descriptors and testing variables has been analyzed using feature-importance analysis, permutation sensitivity, and SHAP (Shapley Additive Explanation) [26, 27]. This kind of interpretability facility is critical to engineering adoption because entirely data-driven forecasting whose mechanistic plausibility is not established may erode practical trust. In the scenario of soil stabilization, interpretable ML frameworks may inform on whether the properties of performance changes are ruled by density effects, additive contents, or strength indices. This is the ability to close the gap between both experimental observation and predictive analytics that promote rational mix-design optimization as opposed to empirical trial-and-error solutions. Therefore, the joint application of laboratory testing and interpretable ML is a new area of research that has considerable practical consequences.

3. Methodology

3.1. Materials

The soil of the current research was black cotton soil that was gathered at Kovilpatti, Tamil Nadu, in India. The disrupted samples were dried by air, ground, and sieved through a 4.75 mm IS sieve before testing. The soil was visually known to be a highly plastic clay that is characteristic of expansive black cotton soils. Essential indexing characteristics, such as liquid limit, plastic limit, and specific gravity, were identified on the basis of IS 2720 standards in order to define classification and engineering properties. A local marble-processing industry was used to get marble dust. The content was mostly comprised of fine particles of calcium carbonate. Simple physical attributes like specific gravity and particle attributes were established to determine suitability in modifying the soil. The elements of synthetic polyester reinforcement functioned as discrete elements and were incorporated randomly in the soil matrix. The fibers had the same geometry and were chosen according to their tensile resistance and durability properties. The most important properties that determined the efficiency of reinforcement were the nominal length, the diameter, and the aspect ratio. Marble dust and synthetic fibers were chosen to illustrate two radically different stabilization mechanisms, that is, particulate densification and discrete tensile reinforcement, to allow a comparative assessment of competing improvement strategies.

3.2. Mix Proportions and Sample Preparation.

The replacement levels of the marble dust of 10, 20, 30, and 40 percent were adopted according to the proportioning of each weight to the overall weight of the soil mass that was dried. Fiber levels of 0.5, 1.0, and 1.5 were chosen according to the common values in the studies on soil reinforcement. The proportions of soil and additives needed were measured in terms of dry weight. This was dry mixed to make sure that the marble dust was evenly distributed, and then water was added gradually up to the desired moisture level. The addition of fibers was done with care so as not to cluster and to get randomly dispersed. The mixtures prepared were weighed and closed, and the mixtures equilibrated with moisture before compaction and strength testing.

3.3. Laboratory Testing Program

Laboratory tests were done to determine the compaction, strength, and bearing properties of non-treated and stabilized soil mixes. Standard Proctor tests were used to determine the compaction characteristics in compliance with IS 2720 (Part 7) / IS 2720 (Part 8). Unconfined Compressive Strength (UCS) tests were conducted according to the standards of the IS 2720 (Part 10). The tests of California Bearing Ratio (CBR) were performed under the conditions of IS 2720 (Part 16), both in the soaked and unsoaked conditions. All experimental tests have been done in several trials to get repeatability, and average values were used to interpret. All the experimental outcomes are a mean of repeated experiments, and variation was also measured by standard deviation to make sure that the measurements are consistent.

3.4. Test Procedure of Model Footing

There were model footing tests in order to model structural-scale bearing behavior. The experimentation was conducted in a stiff test tank, whereby there was sufficient clearance on the boundaries of the tank to reduce edge effects. The optimum moisture content and maximum dry density conditions of the soil were prepared on the soil beds. The square model footing was centrally located on the prepared soil surface, and the vertical loads were added gradually. Loadings of equal size were noted until a failure or too much deformation of the material occurred at the settlement. Monotonic vertical compression with the loading was applied, and dial gauges were used to record the settlements at every loading step and capture the vertical movement.

3.5. Development of the Machine Learning Models

The regression model used was a random forest regression to predict the performance of the bearing using the experimental parameters. Marble dust content, fiber content, maximum dry density, UCS, and CBR values were used as input variables. The ultimate bearing capacity of model footing tests was the target output variable. The data was split into training and testing sets to determine predictive ability, and the performance of the model was measured by statistical measures like the coefficient of determination (R^2) and error measures. The cross-validation was used to choose hyperparameters aiming at balancing the bias-variance behavior and enhancing the model generalization. To make sure that overfitting was minimized, the training and testing errors were compared.

3.6. Model Transparency of Machine Learning

One data-driven predictive model of Random Forest Regression was applied to predict bearing performance to supplement the investigation that was conducted experimentally. Random Forest was chosen because it is strong in nonlinear relationships, does not overfit, and can be applied to relatively small experimental data, which is often the case in geotechnical research [23-27]. The input feature set was that of experimentally quantifiable parameters, and it included marble dust content, fiber content, Maximum Dry Density (MDD), Unconfined Compressive Strength (UCS), and California Bearing Ratio (CBR). The choice of these variables was because they are directly physically relevant to the strength, stiffness, and load-deformation behavior. The final bearing capacity was determined as the target output variable, which was the result of model footing tests. Before the model training, the dataset was filtered in terms of consistency and completeness. No data augmentation was done artificially, and only values that were observed by experiment were used.

The data was also subdivided into training and testing subsets in order to test predictive generalization. This division is necessary in order that the model's performance be an indication of true predictive ability, as opposed to the recall of training samples. Construction of the model was carried out by constructing several decision trees through bootstrap aggregation. All the trees were trained on randomly selected predictors, thus minimizing variance and enhancing the stability of the model. The number of trees and the depth of trees were selected by trial and error based on prediction error. The robustness of the model was evaluated by evaluating the performance measures of the training and testing to ensure that overfitting had been reduced. The accuracy of the prediction was measured using statistical indicators, such as the coefficient of determination (R^2) and the error. These measures give a clear analysis of concordance between the anticipated and experimental answers. The similarity of the predicted and observed values is evidence that the model was able to represent the nonlinear interactions of the soil properties and the stabilizer variables. In order to increase the interpretability, variable-importance analysis was conducted to determine the most significant predictors that control bearing performance. This type of analysis is especially useful in geotechnical applications because it offers a mechanistic understanding of the factors that predominate the system behavior, instead of viewing the model as a numerical tool. In general, the implemented machine-learning framework is a decision-support mechanism that can be used to complement experimental observations, as well as predict performance in the investigated parameter space.

3.7. Statistical and Error Analysis

In order to ascertain the reliability and repeatability of the results of the experiment, every laboratory test was done in several trials with the same testing conditions. The given values of the Maximum Dry Density (MDD), Optimum Moisture Content (OMC), Unconfined Compressive Strength (UCS), California Bearing Ratio (CBR), and model footing parameters are the average of the repeated measurements. The standard statistical measures of variability, such as standard deviation and coefficient of variation, were used to evaluate the variability of the experimental data. These measures have a quantitative evaluation of spreading and measure consistency. The resulting differences in the repeated tests were identified as being within reasonable limits that are normally related to geotechnical laboratory tests. The dispersion is relatively low, which proves that the selected sample preparation and test procedures led to stable and repeatable results.

Uncertainty in measurement can be due to the existence of slight heterogeneity in the mix of soils, the distribution of moisture, specimen preparation, loading plates, seating, and sensitivity of instruments. Efforts were made to reduce such uncertainties by keeping the compaction energy, moisture conditioning, and loading rate constant, and by using a calibrated measurement apparatus. Specifically, great care was taken to ensure that the fiber does not cluster or separate during mixing, as this may affect strength and deformation behavior. In the model footing tests, the possible sources of experimental error are boundary effects, local density variation, and the precision of settlement measurements. The following effects were countered by the proper tank size in reference to the size of the footing, standardized procedures in bed preparation, and systematic application of loads. At the machine-learning stage, predictive error was measured by statistical performance measures, such as the coefficient of determination (R^2), Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and Mean Absolute Percentage Error (MAPE). Errors in the training and testing were compared to assess the generalization of the model and ensure that overfitting was reduced. The stability of the indicators of errors shows that the Random Forest model is strong in the predictive evaluation within the range of the investigated parameter. All in all, the statistical analysis with the uncertainty analysis justifies the validity and repeatability of the experimental results.

4. Results and Discussion

In the section on the impact of black cotton soil on the engineering behavior of the marble dust, synthetic polyester fibers are given, after which the performance of the machine-learning model is presented. Discussion of results is done in relation to compaction properties, strength parameters, and footing load-settlement behaviour.

4.1. Compaction Behaviour

Table 1 gives the compaction properties of untreated and stabilized soil mixes. The findings indicate that as the content of marble dust increases gradually until a maximum point, it then slightly decreases. This is because the presence of such fine marble particles fills voids in surfaces and leads to improved densification of the soil and enhanced packing of particles in the soil matrix. The highest value of dry density can be achieved at 30 percent marble-dust replacement, and this means that the optimal need for rearrangement of particles can be achieved. In addition to the optimal content, the addition of fines can also interfere with the continuity of the soil skeleton and the ability to pack the particles, which will slightly decrease the dry density.

Table 1. Compaction properties of untreated and stabilized soil mixes

Mix ID	Marble Dust (%)	Fiber (%)	MDD (g/cc)	OMC (%)
BC-0	0	0	1.65	18.5
MD-10	10	0	1.72	17.9
MD-20	20	0	1.79	17.1
MD-30	30	0	1.84	16.3
MD-40	40	0	1.82	16.7
F-0.5	0	0.5	1.69	18.9
F-1.0	0	1.0	1.71	19.2
F-1.5	0	1.5	1.70	19.6

Figure 1 shows the variation of maximum dry density with the various mix compositions and agrees with the discrete peak at 30 percent marble dust. On the contrary, *fiber*-reinforced mixes have relatively small variations in density; the presence of discrete fibers disturbs the soil fabric and needs more moisture to be mixed properly, leading to slightly increased optimum moisture levels. The observations suggest that the primary effect of marble dust on densification is positive, whereas fibers have a minimal effect on compaction but will be more important in deformation behaviour in further tests.

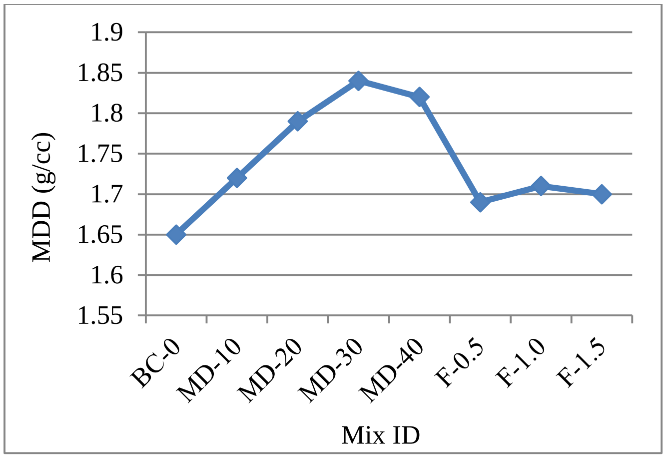

Fig. 1 Fluctuation of stabilization mix with maximum dry density

4.2. Unconfined Compressive Strength (UCS)

The results of the unconfined compressive strength of the untreated and stabilized mixes are outlined in Table 2. It is obvious that the strength increases clearly with the marbling dust until the optimum dosage of 30 percent. This action is mostly explained by the fact that the particles are better packed and that friction among them increases due to the addition of small marble dust particles. The obtained effect of strengthening is controlled by densification and fabric change effects, and not by chemical cementation. Beyond the optimum dosage, inclusion of excess marble dust disturbs particle positioning and undermines inter-particle interaction mechanisms, leading to a small strength reduction.

Table 2. Unconfined compressive strength

Mix ID	UCS (kPa)
BC-0	105
MD-10	145
MD-20	185
MD-30	230
MD-40	210
F-0.5	160
F-1.0	175
F-1.5	168

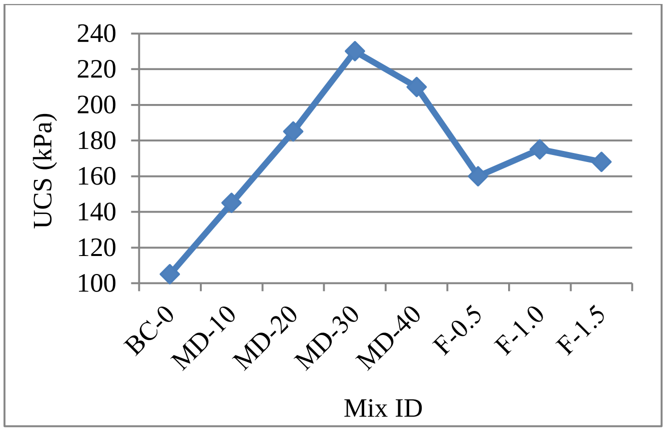

Fig. 2 Stabilization mix variation of unconfined compressive strength

Figure 2 depicts the trends of the strengths of the different mixes, indicating that the strength is significantly high when the percentage of marble dust is 30. Fiber-reinforced soils, in comparison to dust-stabilized soils, do not show significant peak strength increments, but they do have significantly different failure behaviors. Fiber-reinforced specimens exhibit gradual softening of the peak load instead of brittle fracture, and thus they have better toughness and ability to bridge cracks. This is helpful in field loading conditions when the stresses and resistance against progressive cracking must be redistributed. Generally, the UCS behavior confirms that the behavior of marble dust is mainly credited with the enhancement of the strength, whereas fibers have more significance in altering the failure mode and enhancing post-peak behavior as opposed to maximizing peak strength.

4.3. California Bearing Ratio

The results of the penetration tests in the form of the California Bearing Ratio are given in Table 3. The findings reveal that the marble-dust stabilization brings about significant CBR enhancement, and the highest value achieved is at 30 percent replacement. This increment is mainly because of the enhanced interlock of the particles and less plasticity, which facilitates effective distribution of stress during penetration. Inclusion of excess marble dust causes changes in particle arrangement and diminishes the inter-particle interaction mechanisms and, to some extent, decreases bearing resistance. There is also a greater increase in CBR in fiber-reinforced mixes than in the untreated soil, but the increase is lower than that of marble dust.

Table 3. California Bearing Ratio

Mix ID	CBR (%)
BC-0	3.0
MD-10	5.6
MD-20	7.8
MD-30	9.5
MD-40	8.7
F-0.5	5.1
F-1.0	6.3
F-1.5	5.8

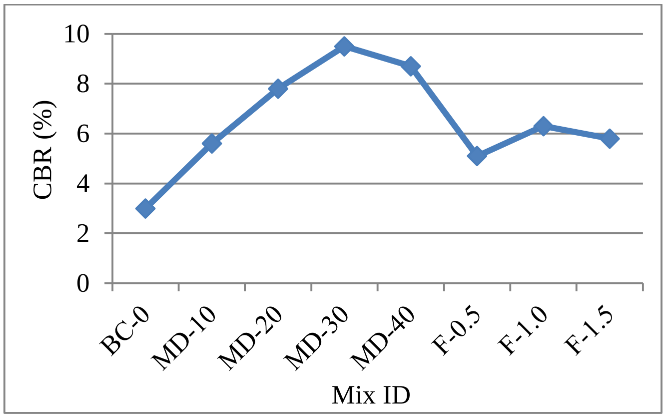

Fig. 3 The dependence of California Bearing Ratio on stabilization mix

Figure 3, showing the variation of CBR with mix composition, clearly reveals the sharp peak at the optimum level of the dosage of marble dust and the comparative stability of the behavior with the fibers. These results also indicate that the marble dust mainly increases the stiffness and resistance to loading, whereas the fibers have secondary strengthening effects.

4.3.1. Comparison of Soaked and Unsoaked CBR

Table 4 presents a comparison between soaked and unsoaked CBR conditions. Reduction in CBR under soaked conditions was observed in all mixes, but the marble-dust-stabilized soils had significantly higher soaked CBR values than the untreated soil because their structure is firmer and less sensitive to water. Fiber-reinforced mixes also have a more soaked behavior on natural soil, implying that the fibers hold back a deformation even in the presence of moisture.

Table 4. Comparison of soaked and unsoaked CBR

Mix ID	Unsoaked CBR (%)	Soaked CBR (%)
BC-0	3.0	1.8
MD-10	5.6	3.4
MD-20	7.8	4.9
MD-30	9.5	6.2
MD-40	8.7	5.7
F-0.5	5.1	3.2
F-1.0	6.3	4.1
F-1.5	5.8	3.7

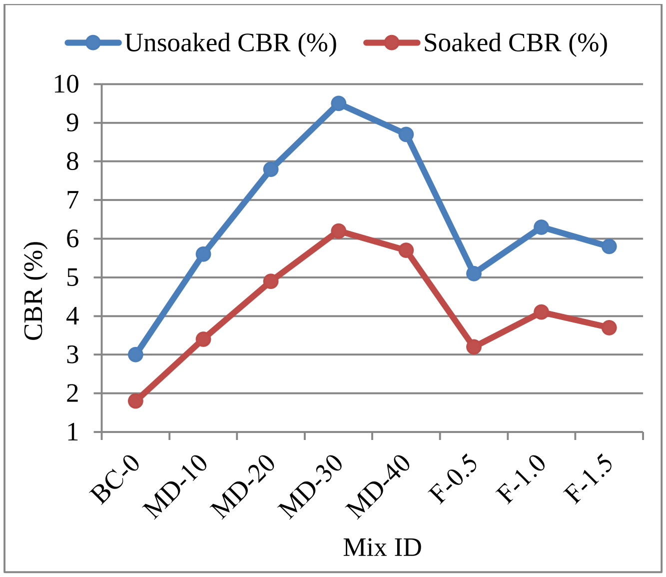

Fig. 4 Soaked and unsoaked CBR values comparison of various mixes

The relationship of the soaked and unsoaked form is indicated by Figure 4 and indicates that the CBR loss rate is slower in stabilized soil compared to untreated soil. Overall, the findings support the observed trend that marble dust is more effective in enhancing bearing resistance, whereas fiber reinforcement primarily contributes to deformation control and stability under adverse moisture conditions.

4.4. Response to Model Footing Load-Settlement

The load-settlement behavior extracted from the model footing tests contributes to understanding the field behavior of the stabilized soil. The main parameters obtained during the tests, ultimate bearing capacity and settlement at failure, are summarized in Table 5. The black cotton soil is untreated and therefore has been tested to have a high rate of settlement at a comparatively low level of load, and therefore, this confirms that the soil is low in stiffness and has a high compressibility.

The soils stabilized by marble dust exhibit a significant increase in load-carrying capacity. The ultimate bearing capacity is increased in the footing that is supported on the mix with 30 percent marble dust, with significantly lower settlement. This behavior is primarily attributed to improved soil structure densification and enhanced inter-particle friction resulting from the inclusion of fine marble particles. When the replacement levels are further than the optimum, the bearing capacity reduces slightly, as the formation of other weaker skeletons of particles occurs.

Table 5. Model footing results

Mix ID	Ultimate Bearing (kN)	Settlement at Failure (mm)
BC-0	22	18.5
MD-20	32	14.2
MD-30	41	10.6
MD-40	37	12.1
F-0.5	29	13.8
F-1.0	31	12.9
F-1.5	30	13.3

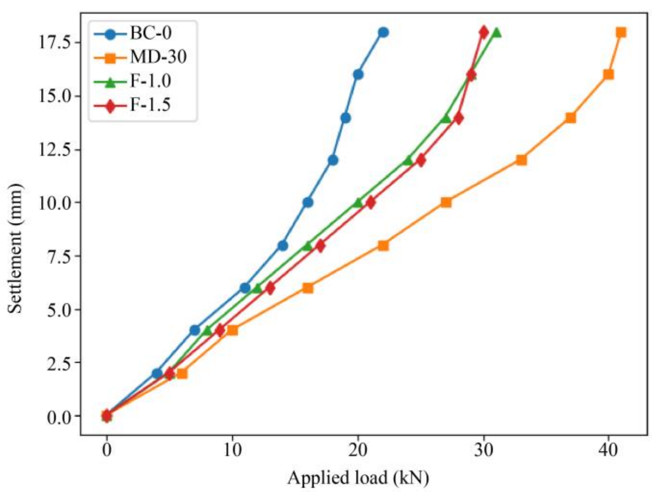

Fig. 5 Load-settlement behaviour of model footing in untreated and stabilized soil

The load-settlement curves presented in Figure 5 demonstrate the opposite nature of dust-stabilized and fiber-reinforced systems. Although the initial stiffness and the load-settlement curves of marble dust are higher and steeper, the fiber-reinforced soils are more ductile. The fibers serve as tensile bridges and thus spread surface loads and prevent sudden shear failure. Consequently, the settlement development occurs more gradually, and fiber-reinforced specimens are able to maintain load even when yielding has begun. These observations imply that the bearing capacity is mainly increased with densification by the marble dust and deformation control and post-peak stability by fibers. Design-wise, the stabilization of marble dust is favorable in situations where the maximum bearing resistance is needed, and the fiber reinforcement is especially useful in those situations when the serviceability and control of cracks are of utmost importance.

4.5. Advanced Machine Learning Methods and Interpretability

The use of Machine Learning (ML) techniques has become more popular in geotechnical engineering because it is capable of modeling nonlinear relationships that are too complicated to be represented by simple linear or nonlinear methods. Random Forest (RF) regression was selected to be used as a predictive model in the current research due to its strength, ability to avoid overfitting, and appropriateness to the relatively small experimental data set [23-27]. In contrast to single-model algorithms, the ensemble algorithm, like RF, builds many decision trees via stochastic sampling, which enhances generalization and the stability of predictions. Despite many ML algorithms, such as Artificial Neural Networks (ANN), Support Vector Machines (SVM), and Gradient Boosting algorithms being used in the prediction of soil-related properties, RF models have clear benefits on experimental geotechnical data. Such strengths include low assumptions on data distribution, automatic support of variable interactions, and low noise sensitivity. The reasons why RF was selected in the current study are further supported by the nonlinear interaction between compaction properties, strength indices, and proportions of additives. In addition to predictive accuracy, ML model interpretability is a key requirement for engineering decision-making. Predictions that are made using black boxes may not be practically useful. Thus, model interpretability methods were used to assess the relative significance of input variables that control the performance of bearings. A quantitative approach is also given by variable-importance analysis, which can be used to identify the most important engineering parameters because it can be used to determine the contribution of each predictor to the model output. The review showed that parameters of density and strength indices had the greatest effect on predicted bearing capacity. This finding is in agreement with the established geotechnical principles, in which bearing resistance is significantly related to compaction state and stiffness properties. Additive proportions, such as the marble dust and fiber content, showed secondary effects, indicating that they mostly affected the properties by altering the density and strength. The insights of interpretability add additional value to the practicality of the ML integration to connect the observed results of an experiment to the predictive modeling. Instead of being a purely numerical estimator, the RF model is a decision-support tool that can be used to determine which mechanisms are controlling and to support the optimization of a mixture. This method enhances the levels of trust in data-driven predictions and adheres to the laws of soil mechanics.

4.6. The performance of Machine-Learning Models

To forecast the footing bearing performance using the experimental data, a random forest regression model was created. The input variables were marble-dust content, fiber content, maximum dry density, unconfined compressive strength, and CBR values, whereas the output prediction was the bearing response, which was received after the model footing tests. The dataset was split into the training and testing subsets, and the model parameters were optimized by means of iterative tuning.

The experimental responses are found to be well-correlated with the predicted values, which means that the model can ensure that the nonlinear interactions between the soil properties and the stabilizer contents are observed. As revealed in the predicted and observed values given in Figure 6, it is observed that most of the values are clustered near the line of equality; deviations are only minimal. Measurements of errors provide confidence that the model is acceptable in prediction accuracy, implying that engineering decision-making could be supported using the model.

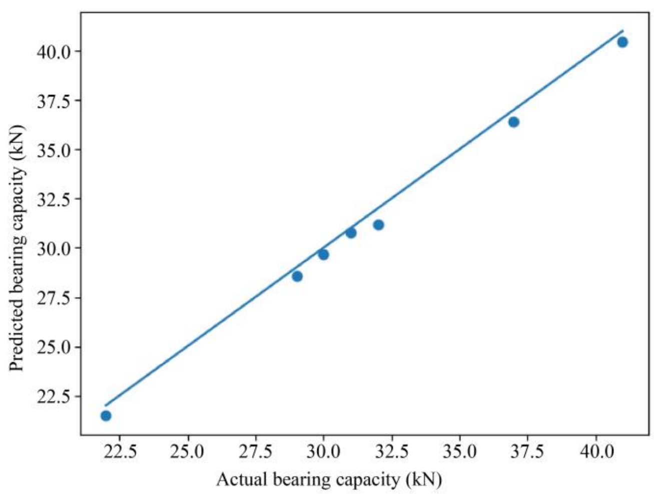

Fig. 6 Comparison between predicted and actual bearing performance acquired by the use of the Random Forest model.

Variable-importance analysis shows that the most significant predictors are maximum dry density and marble-dust content as the second and third, respectively. The observation is in line with the experimental results, in which the marble dust mainly controls the strength and stiffness gains, and fibers are involved in the deformation control.

The findings indicate the potential of machine-learning solutions in the elucidation of governing parameters, and they reduce the need to use laboratory testing on a large scale.

Table 6. Evaluation metrics of machine learning

Metric	Description	Value
R^2	Coefficient of determination (goodness of fit)	0.964
RMSE (kN)	Root Mean Square Error	0.566
MAE (KN)	Mean Absolute Error	0.412
MAPE (%)	Mean Absolute Percentage Error	2.31

The list of model performance indicators in Table 6 verifies an adequate prediction accuracy. The metrics of evaluation prove that the Random Forest model has high predictive accuracy. The R^2 of 0.964 implies that the model explains the variation in bearing capacity of about 96 percent. The values of both RMSE and MAE are below 1 kN, which shows that the average errors of prediction are very small. The fact that the MAPE value is 2.31% validates that the prediction accuracy falls within the acceptable engineering range. All these findings indicate that the model is effective and can be relied on to estimate bearing performance in terms of simple-to-determine soil parameters.

Random Forest functions by building a set of decision trees, each of which is an unbiased sample of a subset of the data set and predictors. The average of individual trees is taken to derive the final prediction and minimize overfitting as well as enhance generalization. The algorithm in the present study was able to effectively represent nonlinear relationships between the mix composition, geotechnical properties, and footing response. Variable-importance analysis also indicated that maximum dry density and marble-dust content were the most influential predictors, and this is in line with the experimental estimates.

In general, the Random Forest model has a high potential to be used as a decision support tool to optimize the process of stabilization and predict the behavior of bearings under various mix combinations. The database can continue to be expanded with more and more experimental studies, which will further improve the robustness and the generalization abilities of the model.

4.7. Overall Interpretation

The interaction of marble dust and synthetic fibers on bearing performance is depicted by the combined effect of the two in Figure 7, whereby the three-dimensional surface depicts the interaction between stabilizer content and footing response. The increasing nature of the trend in the marble-dust axis shows the bearing capacity reaches an optimum level of about 30 percent and starts to remain constant, which proves the necessity of densification and enhanced particle interlocking to be the main strengthening mechanisms [8, 22].

In the fiber axis direction, the surface is moderately improved, with the curve becoming flat after 1.0 percent. This trend is indicative of decreasing returns with increasing fiber contents, wherein excessive reinforcement interrupts soil packing without any increase in the load resistance [14, 17, 19]. Still, the surface is always elevated in comparison with untreated soils, and it means that fibers still assist in deformation control and residual strength throughout the loading process [16, 18].

The response surface trend indicates complementary behavior between marble dust and fiber reinforcement mechanisms. Stiffness and bearing resistance are mainly controlled by marble dust, which promotes crack-forming resistance by increasing packing and decreasing plasticity, while post-peak ductility and settlement are controlled by fibers bridging emergent cracks [10, 13, 26]. Therefore, it is not the maximization of additive content but the choice of a balanced combination that meets the same requirements of strength, durability, and serviceability that helps achieve the most effective stabilization strategy [5, 20, 28].

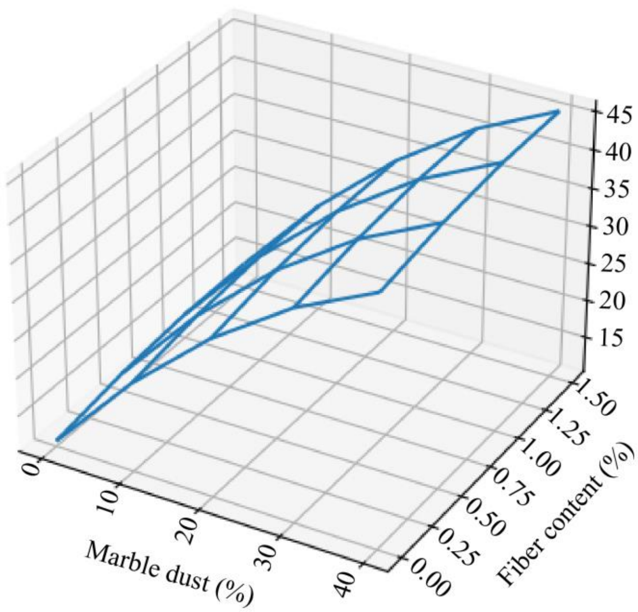

Fig. 7 Three-dimensional interaction between marble-dust content, fiber content, and bearing capacity

4.8. Comparative Benchmarking with Literature

The observed trends are consistent with prior stabilization studies, which reported improved bearing performance due to enhanced densification when fine industrial by-products were incorporated into expansive soils [8, 9, 13, 28]. The experimental findings recorded during the research were compared to the already established results regarding the waste-based stabilization and fiber-reinforced soil systems. This benchmarking is necessary to determine the consistency, reliability, and practical relevance of the improvements that have been measured. The enhancement in Maximum Dry Density (MDD) with the addition of marble dust, which is found in the current study, is in line with trends that have been reported in earlier research that has used fine industrial by-products. And the researchers who have come across it previously have explained the increase in density by the filling of the voids, rearrangement of the particles, and efficiency of packing due to the non-plastic fines [9, 13]. The observed optimum marble dust content above which the density gains are reduced is also consistent with the observed threshold behavior in filler-based stabilization systems. High fines can interfere with the continuity of soil skeletons, causing a peripheral decrease in compaction efficiency, which was also observed in former studies. Patterns of strength enhancement, as indicated by unconfined compressive strength (UCS) outcomes, also show good correlation with the literature. Research on marble dust shows that moderate amounts of replacement with such fillers as calcium are said to enhance strength by densifying and enhancing inter-particle friction instead of chemical cementation [9].

This decrease in UCS at greater replacement levels in the current study is hence mechanically feasible and supports previous experimental measurements on the significance of optimization of dosage rate [13]. These interpretations are further supported by the trends of the California Bearing Ratio (CBR), which were made on marble-dust-stabilized specimens. Earlier studies have established that plasticity decreases and dry density increases tend to be associated with an increase in the penetration resistance [21]. The comparative superiority of marble dust to discrete fiber reinforcement in enhancing CBR values, which is reported in this study, is in line with the fact that bearing resistance is more sensitive to change in stiffness and density than tensile bridging mechanisms. Regarding fiber-reinforced mixes, current findings show a moderate increase in peak strength with a major alteration in failure behavior as well as deformation characteristics. This reaction is similar to those that have been observed in previous experiments of randomly distributed synthetic fibers, whereby an increase in ductility, crack resistance, and retention of post-peak load were observed to be more significant than an increase in peak strength [11, 15-19]. The weak influence of fibers on the compaction parameters also complies with the available existing experimental data that discrete inclusions can cause minor disturbances in the particle packing and enhance the control of the deformation processes.

The observed model footing responses of the current study prove that the main factors affecting the increase in bearing capacity are densification and stiffness enhancement by marble dust, and settlement behavior and ductility by fibers. Similar differences between discrete reinforcements and particulate stabilizers have been mentioned in previous structural-scale studies [20, 22]. This confirms the reading that various stabilization mechanisms control ultimate resistance and control deformation. In terms of machine-learning performance, the great predictive power of the Random Forest model can be correlated to the previous research that has shown the appropriateness of the ensemble learning algorithm to nonlinear geotechnical data [23-27]. It is also consistent with known geotechnical principles that a bearing performance is dependent on the compaction state and stiffness characteristics, as evidenced by the preponderance of density-related variables in the variable-importance analysis. On the whole, the correspondence of experimental tendencies and mechanisms supported in the literature proves that the outcomes are technically plausible and physically consistent. The novelty of the current work is not a particular behavior of materials but rather an integrated relative structure that incorporates waste-based stabilization, fiber reinforcement, structural-scale analysis, and interpretable machine-learning assistance in terms of one approach.

5. Life Cycle Assessment and Sustainability

Life Cycle Assessment (LCA) is commonly known as a methodological approach to assessing the environmental effects of materials, processes, and engineering systems in terms of their service life. When considering sustainability in ground improvement, mechanical performance is not the only factor, but also resource efficiency, valorization of wastes, energy consumption, and associated emissions in stabilizing agents. Traditional soil stabilization procedures often depend on cementitious binders, e.g., lime and Portland cement. Even though these additives are good at improving engineering properties, their manufacturing is linked with considerable energy consumption and greenhouse gases. Cement production processes, which include calcification, also contribute to carbon dioxide emissions in the world economy, and thus, there is a need to consider other stabilizers that have a lesser carbon footprint [5, 21, 29]. The use of marble dust in soil stabilization is a waste valorization approach in accordance with the principles of the circular economy. Marble-processing industries produce considerable amounts of fine particulate residues, which, in most cases, are challenging to dispose of and have environmental impacts, such as dust pollution and land degradation [6, 7]. The recycling of such waste materials in geotechnical applications can lessen the landfill addiction, lessen environmental pollution, and decrease the need to use virgin stabilizing resources.

In contrast to cementitious binders, marble dust is mainly stabilized by mechanical means, including the formation of particle packing and densification, thus having the potential to reduce the effect of embodied energy. In the same way, synthetic fiber reinforcement also helps in performance improvement via mechanical interaction instead of chemical reactions. Inclusion of fibers enhances ductility, crack resistance, and deformation without necessitating heating at the application point. Although the manufacturing of synthetic fibers requires industrial use of energy, their low dose requirements and permanency properties could be compensated by the environmental burden when the lifespan of stabilized systems is taken into consideration. Taking a lifecycle approach, the joint utilization of the materials of industrial wastes and individual reinforcements could be associated with numerous sustainability benefits. These are minimization of waste-disposal effects, preservation of natural resources, and possible increase of serviceability in infrastructure due to enhancement of soil behavior. Moreover, the enhanced bearing capacity and settlement could also be an indirect contributor to sustainability due to the lower frequency of maintenance and structural rehabilitation. Admittedly, an extensive quantitative LCA involves in-depth inventory information, emission factors, and system boundaries, which cannot be provided in the current experimental study. However, the functional principle of the stabilization approach is consistent with the idea of sustainable construction practices, which encourage the positive reuse of industrial by-products and reduce the use of energy-consuming conventional binders.

6. Field Validation and Scalability

The experimental research used in this work was carried out under laboratory-controlled conditions in order to separate the influence of marble dust and synthetic fiber reinforcement on the behavior of black cotton soil. Although laboratory testing offers a uniform system of comparative assessment, the interpretation of laboratory testing results into the field of application cannot be done without a close consideration of the effects of scale, the effect of the boundaries, and the variability that relates to construction. In real ground-improvement conditions, the soil deposits are heterogeneous regarding density and distributions of moisture and mineralogical composition. The performance of stabilized soils can thus be affected by the procedures of compaction in the field, mixing efficiency, and environmental exposure conditions. The achievement of homogeneous dispersion of marble dust and synthetic fibers on the field scale may prove more difficult than in specimen preparation of laboratory procedures, especially in fiber-reinforced systems, whereby there are chances of clustering or segregation of fibers, thereby influencing mechanical response.

Bearing capacity and settlement behavior, in particular, are dependent on scale. The model footing tests reproduce the basic load-deformation processes, though the prototype foundations are subject to other stress distributions, confinement, and drainage conditions. Cyclic loading, cycles of wetting and drying of the environs, and long-term creep effects, which cannot be adequately reproduced in short-duration laboratory tests, are also found in field foundations. Therefore, engineering judgment should be used in the extrapolation process of absolute values of bearing resistance and settlement in full-scale systems. In spite of these weaknesses, the trends that are observed are useful in real-world practices. It is deduced that in expansive soils, marble dust can be used as a mechanical stabilizer due to the gradual enhancement of the compaction properties, strength properties, and bearing behavior. Correspondingly, the ductile and deformation-resistant advantages of fiber inclusion imply the possibilities of service load reducing brittle failure and progressive cracking. Constructability-wise, the materials examined in the present research are suitable for the traditional soil-stabilization methods. Marble dust may be added through regular blending and compaction machinery, and synthetic fibers may be added during mixing, subject to proper quality control processes. The fact that it has a relatively low dosage requirement also helps in scaling as long as proper mixing protocols are implemented. Pilot-scale or field-scale validation should be considered in future research to determine the performance in the long run concerning realistic loading and environmental conditions. These investigations can take the form of large-scale plate-load tests, durability tests, and monitoring of volume changes caused by moisture. Field datasets can be further forecasted, and predictive reliability can be enhanced through the integration of field datasets with machine-learning frameworks, which can also be site-specifically calibrated. All in all, despite the fact that the current research is laboratory-based, the conclusions provide a mechanistic framework of how it can be implemented in the field and what some of the major requirements are that should be taken into consideration when it comes to making the implementation scalable and applicable to the field.

7. Conclusion and Recommendations

This paper tested the stabilization of black cotton soil with waste marble dust and synthetic polyester fibers and tested its performance based on stabilization through compaction, strength test, CBR test, footing load-settlement behavior, and machine-learning prediction. According to both the results of the experiment and analytical results, the following conclusions can be made:

The incorporation of marble dust also enhanced the properties of compaction, such as higher maximum dry density and lower optimum moisture contents, to an optimum dosage of 30 percent, beyond which compaction began to slow down a little.

The unconfined compressive strength and CBR values were significantly improved with the same optimum dosage, and this proved that marble dust improves the packing of particles and the shear resistance.

The fiber reinforcement showed moderate strength increases but showed significant enhancement in ductility, crack control, and post-peak behavior, especially in the soaked condition.

Experiments on model footing demonstrated that stabilization of marble dust was the main factor leading to increased bearing capacity, and fibers were the main factor in enhancing settlement control and redistribution of loads.

The Random Forest model demonstrated good predictive accuracy, which validates the fact that the model was able to capture nonlinear interactions among the examples of stabilization variables. The model is a useful estimate of a foundation response decision support tool that is not overly reliant on full-scale testing.

The integrated explanation is the affirmation that the action of marble dust and fiber follows complementary effects. Optimized dosage is the most efficient method of stabilization as opposed to pushing one of the components to the maximum.

Sustainably, the value of marble-processing waste minimizes the levels of disposal, as well as environmental pollution, and improves the performance of the ground at the same time. Synthetic fibers, when properly applied, can provide better serviceability with less resource usage.

7.1. Limitations and Effects of Scale

The findings made during the current research are encouraging; however, some limitations are to be mentioned. The model scale samples and controlled boundary conditions that were used in the laboratory testing program are not fully representative of the stress states and variability in the field. Scale effects can also cause a response in the load-settlement curve, especially in footing tests where confinement, moisture migration, and stress distribution vary at prototype sizes. Moreover, the single soil type was studied, as well as only a few doses of the stabilizers. The Random Forest model was also trained on the same data, and its predictive power can decline when applied to ranges outside the test set. These restrictions mean the work can only be used as engineering judgment and tested on a field scale through validation.

7.2. Recommendations

The field-scale validation is suggested to verify the long-term behavior in case of real loading and climatic conditions. More hybrid combinations should be explored, such as the incorporation of other industrial by-products, to potentially achieve even more performance and sustainability improvement.

Larger data sets ought to be created to train and test machine-learning models to enhance the accuracy of generalization when used in soils and site conditions.

To achieve a practical design, it may be suitable to have as starting guidelines marble dust contents of the order of 30 percent and fiber contents of the order of 0.5 to 1.0 percent, but these will depend upon site-specific calibration.

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