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Original Article

Stabilization of Expansive Soil with Ceramic Marble Dust Waste Reused Sustainably: Microstructure, Performance, and Mechanism

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Abstract - *The expansive soils have extreme swelling-shrinkage characteristics that undermine the foundations and pavements' serviceability. Simultaneously, ceramic and stone-processing sectors produce high amounts of marble dust, the disposal of which is not planned and is an environmental and land-management problem. This research paper will assess the sustainable re-utilization of ceramic marble dust waste as a microfiller in the stabilization of expansive soil, but to reinforce it further using synthetic polyester fibers. A systematic program that included compaction, shear strength, and California Bearing Ratio (CBR) and model footing tests was undertaken in order to measure density, stiffness, and bearing performance improvements. Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), and X-Ray Diffraction (XRD) of microstructure and minerals provided the means to explain the stabilization mechanism, and finite-element analyses of PLAXIS 2D were employed to confirm the behaviour of load-settlement. The findings indicate that marble dust acts mainly as a calcium-carbonate microfiller, pore structure refiner, and enhances particle packing, and polyester fibers act as tensile bridging of particles and deformation control. The use of new crystalline phases was not observed, which proved the improvement mechanism to be mainly physical but not chemical. The hybrid mixture, which had 30 wt.% marble dust and 1.0 wt.% fiber, gave the best performance, showing high density, strength, and settlement resistance. The numerical predictions were in good agreement with experimental trends. On the whole, the research shows that there is an ecologically friendly avenue of valorizing the waste of ceramic marble dust and enhancing the working of expansive soils based on the principle of microstructural densification and mechanical reinforcement.*

Keywords - *Bearing Capacity, Circular Economy, Compaction Behavior, Expansive Soil, Marble Dust, Microstructural Analysis, Physical Densification Mechanism, PLAXIS 2D, Polyester Fibers, Reuse of Ceramic Waste, SEM, Soil Stabilization, Sustainability, TEM, and X-Ray Diffraction (XRD).*

1. Introduction

Expansive soils are well-known problematic geomaterials in geotechnical engineering because of their high swelling-shrinkage characteristic, high plasticity, and high sensitivity to changes in moisture content.

The inactive nature of such soils is mainly controlled by the occurrence of active clay minerals such as montmorillonite minerals that cause large volumes of volumetric change and loss of the engineering performance under environmental loading conditions [1-3]. The consequence of the same is seen in the form of differential settlement, loss of bearing capacity, and premature pavement and shallow foundations deterioration [3, 4]. The traditional soil stabilization methods usually use chemical fixants like lime and cement; in this case, the fixants get improved through the reaction of pozzolans and cementitiveness bonding [5, 6]. Even though useful, such stabilizers are linked to the embodied energy and carbon emissions, which provide a powerful reason to seek to identify sustainable options relying on industrial effluents and waste products [7-9]. Marble dust is one of the key wastes of the ceramic and stone-processing industries, in which the cutting and polishing processes result in significant amounts of fine $CaCO_3$-laden particulate waste [10-13]. Disposal of marble dust poses chronic environmental challenges such as particulate emissions in the air, slurry management challenges, and contamination of land [9, 14]. Marble dust has become a potential material to be reused in the construction materials sector and soil stabilization because of its fine particle size distribution, which allows it to have a relatively high specific gravity, and is chemically inert at ambient temperatures [10]. In contrast to reactive binders, calcium carbonate-based wastes largely change soil behavior by physical processes such as filling the voids, strengthening particle packing, and refining pore structure instead of mineralogical conversion [11, 15]. Past studies on marble dust stabilization are mostly on macroscopic engineering reactions, which include compaction properties, strength augmentation, and California Bearing Ratio (CBR) augmentation [10]. Although the increments of strength are always mentioned, the mechanisms that control these increments are not fully explained. Specifically, there are few studies on the microstructural development of expansive clay matrices subjected to $CaCO_3$-based fillers that are characterized by multi-scale methods [15, 17]. More advanced experimental instruments used as commonplace in materials science, such as Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), and X-Ray Diffraction (XRD), are relatively underused in the elucidation of stabilization processes of expansive soils [16, 18-20]. This means that the correlation between filler-induced refinements of fabrics, nanoscale platelet rearrangement, and bulk mechanical response needs to be researched further [2, 15]. Nevertheless, the current research on the stabilization of marble dusts hardly combines the multi-scale microstructural evidence with numerical validation.

There is a range of industrial by-products that have been explored to be used in the stabilization of expansive soils, such as fly ash, Ground Granulated Blast Furnace Slag (GGBS), and Rice Husk Ash (RHA) [7, 8, 21]. The primary mechanism of action of these materials is pozzolanic or cementitious reactions that change the mineralogy of soils and result in strength acquisition with time. Although successful, these chemically reactive stabilizers are highly dependent on curing conditions, reaction kinetics, and chemical compatibility.

Conversely, marble dust, which is majorly made of calcium carbonate, is a non-reactive microfiller at ambient temperatures. Its stabilization effect is controlled primarily through particle packing enhancement, void filling, and refinement of pores as opposed to mineralogical transformation. Such a difference enables the minimization of curing dependency and the minimization of variability of reaction-controlled stabilization. Environmentally, microfiller-based stabilization also has a smaller carbon footprint, as the production processes of the binder are not as light-emitting as CO_2.

Besides particulate fillers, fiber reinforcement has also been highly identified as a powerful approach in enhancing ductility, resistance to deformation, and post-peak action of fine-grained soils [22-24]. Synthetic fibers boost soil performance mainly by acting as mechanical restraints, which include tensile bridging, crack suppression, and redistribution of stress [23-25]. The most appealing properties of polyester fibers are that they are chemically stable, corrosion resistant, and do not react with non-reactive soil matrices [22, 26]. Although the positive effects of marble dust stabilization and fiber reinforcement have been reported individually, the few studies that have systematically examined their combined effect in expansive soil systems have not been performed [27].

The other lingering weakness of the studies on stabilization is around the combination of laboratory observations and numerical modelling. Geotechnical analysis has been extensively done using finite-element methods, but limited use has been made to them as validation tools in experimentally observed stabilization mechanisms [28]. To come up with mechanistically consistent interpretations, it is critical to establish a consensus between experimentally observed strength-stiffness increase and numerically simulated load-settlement behavior.

These knowledge gaps are filled in the current study by assessing how waste marble dust in the form of $CaCO_3$-based microfiller can be used to stabilize expansive black cotton soil in the presence of synthetic polyester fiber reinforcement. The focus is on the determination of the controlling improvement mechanisms using the combined framework that includes mechanical testing, Multi-Scale Microstructural characterization (SEM and TEM), Mineralogical Analysis (XRD), and Finite-Element Modeling with the PLAXIS 2D.

The value that this research adds is the combination of the assessment of marble dust stabilization in a multi-scale characterization and modelling framework. In contrast to the previous studies, which mainly focus on macroscopic measures of strength, the current study introduces a set of mechanical testing to be integrated with SEM, TEM, XRD, and finite-element modeling to provide a mechanistically consistent explanation of stabilization controlled by densification. This study (in contrast to the earlier studies, which only used the macroscopic strength enhancement) combines the multi-scale microstructural characterization (SEM-TEM-XRD) with numerical vindication to develop a mechanistically consistent densification-based stabilization framework.

2. Materials and Methods

This chapter explains the experimental and numerical process that was embraced to determine the stabilization of expansive soil by the use of waste marble dust and synthetic polyester fibers. The program was intended to measure the influence of marble dust as calcium-carbonate microfiller and fibers as a mechanical reinforcement agent and to determine the relationship between the measured mechanical performance and the underlying micro-structural variations. Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), and X-Ray Diffraction (XRD) were used as the supporting methods to conduct laboratory tests, and finite-element PLAXIS 2D modeling was taken to confirm the principles of load-settlement. Instead, special attention was given to reproducibility, structure-property correlation, and sustainability-sensitive material reuse.

2.1. Materials

2.1.1. Expansive Soil

The black cotton soil was sampled at a depth of about 1.5m in order to be free of organic contamination.

Initial index testing has indicated great plasticity and swelling range that meets the expectation of montmorillonite-laden clay. Table: 1 shows property of soil.

Table 1. Black cotton soil characteristics

SL. No.	Basic Properties	Values	Limit	Relevant IS code
1	Liquid Limit (%)	54.00	40-100	IS 2720 Part 5
2	Plastic Limit (%)	31.68	-	IS 2720 Part 5
3	Plasticity Index (PI)	22.32	-	IS 2720 Part 5
	Specific gravity G	2.63	2.65-2.8	IS 2720 Part 3
4	Optimum Moisture Content (OMC, %)	24	20-35	IS 2720 Part 7
5	Maximum Dry Density (g/cc)	1.65	≥1.59	IS 2720 Part 7
6	CBR (%) – Unsoaked	3.00	-	IS 2720 Part 16
	CBR (%) – Soaked	1.56	-	IS 2720 Part 16
7	Shear Strength (kg/cm²)	1.03	-	
8	Cohesion (kg/cm²)	0.515	-	IS 2720 Part 10

Reported measured parameters of strength in kg/cm2 are transformed to SI units to use in numerical modeling.

2.1.2. Waste Marble Dust

Marble dust was sourced out of a stone-processing plant, where it is produced as a slurry in the processes of cutting and polishing. The material was dried in ovens at 105 +- 5 degC, ground and sieved to a pass of 75 µm (microns), which allowed it to be used as fine $CaCO_3$ microfiller. Tables 2 and 3 detail its attributes.

Table 2. Simple physical properties of physical marble dust

SL. No.	Properties	Values
1	Color	White
2	Form	Powder
3	Odor	Odorless
4	Specific Gravity	2.71

Table 3. Chemical composition: marble dust

S.No.	Compound	Chemical Formula	Observed (%)	*Standard Range (%) **	Remarks
1	Calcium Carbonate	$CaCO_3$	95.1	90 – 98	Primary component
2	Silicon Dioxide	SiO_2	1.5	0.5 – 3	Trace impurity
3	Aluminum Oxide	Al_2O_3	0.5	0.2 – 1.5	Non-reactive filler
4	Iron Oxide	Fe_2O_3	0.6	0.2 – 1.0	Possible pigment/color source
5	Magnesium Oxide	MgO	0.6	0.2 – 1.0	From dolomitic marble sources
6	Sodium Oxide	Na_2O	0.25	< 0.3	Trace amount
7	Potassium Oxide	K_2O	0.25	< 0.3	Trace amount
8	Loss on Ignition (LOI)	—	43.2	40 – 45	Due to CO_2 release from $CaCO_3$

2.1.3. Polyester Fibers

A commercial synthetic polyester fibre of the nominal length of 6 mm was taken. The fibers were non-corrosive, chemically inert, and were not surface-treated. The fibre characteristics were provided by the supplier and are presented in Table 4.

Table 4. Basic property of synthetic polyester fibre

Sl.no	Properties	Values
1	Color	White
2	Thickness	1.5D
3	Length	Variable cut lengths
4	Density	1.39g/cc
5	Melting point	260^0C
6	Specific gravity	1.38

Fig. 1 Illustrates the physical appearance of soil samples, marble dust, and polyester fiber

Figure 1 shows the physical appearance of the materials used in this study, black cotton soil, waste marble dust, and synthetic polyester fibers, and their texture, shape, and visual qualities before mixing.

2.2. Mix Proportioning

The addition of marble dust was done in the replacement percentages of 10, 20, 30, and 40 wt.% of the dry soil mass. Polyester was added 0.5, 1.0, and 1.5 wt.%. To understand synergies, hybrid mixes composed of a combination of 1.0 wt.% of fiber and each content of marble dusts were made. The mix matrix was developed to determine an optimum stabilizer content, at the same time keeping the field constructability realistic.

2.3. Experiments on Mechanical and Bearing

Laboratory tests on the mechanical and bearing properties of the untreated and stabilized soils were determined through a series of laboratory tests. Normal Proctor compaction tests were done to identify the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of each mixture. Direct shear testing was then done under controlled normal stress to determine cohesion and internal friction angle. The load-bearing performance was measured by the California Bearing Ratio (CBR) test in soaked and unsoaked conditions. Also, a laboratory model footing tank was used to study the response of load-settlement, whereby a rigid steel plate was loaded sequentially as settlements were measured with calibrated dial gauges.

2.4. Microstructural and Mineralogical Categorization

To explain the stabilization mechanism, microstructural and mineralogical studies were conducted. The packing of the particles, pore refinement, and interaction between soil particles and polyester fibers were observed using Scanning Electron Microscopy (SEM). The representative samples were dried and mounted, and were coated with gold-sputter before being subjected to imaging. The platelets were studied in terms of arrangement and densification at the nanoscale due to the addition of marble dust using Transmission Electron Microscopy (TEM). Simultaneously, an X-ray Diffraction (XRD) experiment was performed in order to disclose the nature of the mineral phases, as well as any modification of the structure caused by stabilization, and XRD scans were acquired in a 2^{th} range between 5deg and 70deg.

2.5. Numerical Modeling (PLAXIS 2D)

The laboratory tests of footing were simulated in PLAXIS 2D to perform finite-element simulations. The Mohr-Coulomb constitutive model was used to model the behavior of soils. Experiments were directly used to obtain input parameters (unit weight, cohesion, and friction angle), and the estimation of the stiffness parameters was done based on known correlations. The validation and interpretation of the numerical results were performed in numerical form, not in design.

2.6. Methodology Framework and Testing Protocol

This experimental program was to provide the consistency of the procedure, reproducibility, and adherence to the accepted standards of testing in geotechnics. The soil samples were all made by air-dried and crushed material that went through a 4.75mm sieve to remove coarse material. Waste marble dust was dried in an oven with a temperature of 105 +- 5degC, coarse-ground, and sieved to produce dust smaller than 75 um, which allowed it to be used as a calcium carbonate micro filler. Polyester fibers were added in their raw state and dispersed by hand so that they do not clump up. There was mixing proportioning done on a percentage basis on dry weight. The concentration of marble dusts of 10, 20, 30, and 40 percent was chosen to determine pre-optimal, optimum, and excess-fines behaviour. The adopted fiber doses were 0.5, 1.0, and 1.5 percent, in accordance to the normal ranges of fiber reinforcement of fine-grained soils in discrete form. Dry mixing was followed by the addition of moisture to make sure that the fines and fibers were evenly distributed. Distilled water was subsequently added in small steps to the required moisture content. The mixtures were covered and left equilibrating over a period of 24 hours to generate homogeneity in terms of moisture before compaction. Testing Compaction testing was based on IS 2720 Part 7 (Standard Proctor), and the compacted specimens were compacted at their optimum moisture contents. Direct shear testing was performed to determine the parameters of shear strength, and followed the procedure of IS 2720. The California Bearing Ratio (CBR) test was conducted in soaked and unsoaked conditions according to the IS 2720 part 16. Bearing response and settlement behaviour were tested by a laboratory model footing tank that was loaded by stepping.

There was no curing period that was enforced because the stabilization process is controlled by both physical densification and mechanical reinforcement, but not time-dependent chemical reactions. As such, specimens were tested right after preparation and compaction. Each experiment was repeated three times, and the mean values are provided. SEM and TEM analyses were performed on typical fragments of the compacted specimens, micro structured.

To measure the stability of mineralogical phases and reveal possible phase changes, XRD analysis was to be conducted. PLAXIS 2D numerical simulations took an experimentally determined parameter to recreate the laboratory loading conditions and boundary conditions. The used methodology has the assurance of being reproducible and, in turn, comparable to the standard geotechnical testing procedures (IS 2720 series), thus making it possible to compare the results easily with those of the already existing literature.

2.7. Statistical Reliability of Experimental Data

The laboratories were conducted in triplicate to determine and reduce experimental error by chance. Reported values are obtained as means of independent specimens, prepared under the same conditions. The figures of the Coefficient of Variation (COV) of the key parameters, such as the maximum dry density, shear strength, and California Bearing Ratio (CBR), were acceptable (usually not more than 5 percent) and depicted low dispersion and good reproducibility. The variation observed is in line with the normal experimental scatter of stabilized fine-grained soils. The trends observed were statistically stable, and there was low variation in repeated trials, which proved the reliability of the experimental data. The fact that the cooperation of marble dust presence and MDD/strength is monotonic also supports the strength of the observed behavior.

3. Results and Discussion

Before getting into the actual result of the experiment, it is appropriate to contextualize the current stabilization methodology in the overall context of generally adopted soil modification strategies. Broadly speaking, the methods of stabilization of expansive nondisturbed soils can be classified according to the prevailing mechanism of improvement, namely, the use of chemically reactive binders, the use of industrial pozzolanic binders, and the use of non-reactive microfiller modifiers. This category offers a mechanistic foundation when explaining the performance patterns of the marble dust-fiber treated soils. These stabilization methods and the mechanisms that rule them are summarized in Table 5

Table 5. Stabilization mechanism concept comparison

Stabilizer Category	Representative Materials	Governing Mechanism	Curing Sensitivity	Environmental Implication
Chemically Reactive Stabilizers	Lime, Cement	Pozzolanic / Cementitious reactions	High	High embodied carbon
Industrial Pozzolanic Additives	Fly Ash, GGBS, Rice Husk Ash	Reaction-controlled bonding & matrix formation	Moderate	Moderate carbon footprint
Microfiller-Based Modifiers	Marble Dust ($CaCO_3$)	Void filling & particle packing enhancement	Negligible	Low-carbon reuse pathway

3.1. Compaction Behavior and Density Evolution

Table 6 gives the compaction properties of untreated and stabilized mixtures. The Maximum Dry Density (MDD) of the untreated black cotton soil is relatively low and is explained by the high clay content of the material and the flocculated structure of particles. At the same time, the Optimum Moisture Content (OMC) showed a gradual reduction with the addition of marble dust because the non-plastic calcium carbonate particles possessed a lower water absorption tendency and improved the packing arrangement within the soil matrix. When marble dust is incorporated, MDD rises gradually till 30 wt.% replacement, which suggests improved packing of particles by the microfiller effect of the small $CaCO_3$ particles. The slight decrease of MDD at 40 wt.% level of marble dust indicates that redundant fines might restrict the optimum packing approach since it encourages agglomeration of particles. Polyester fiber addition, per se demonstrates a small impact on MDD, yet it has an effect on enhancing compaction stability. The synergistic effect of filler densification and fiber dispersion is confirmed by the fact that the hybrid mixture with 30 wt.% marble dust and 1.0 wt.% fiber will have the highest dry density.

Table 6. Compaction properties of unmodified and modified soil mixtures

Sample designation	Marble dust content (wt.%)	Polyester fiber content (wt.%)	Maximum dry density, MDD (kN/m³)	Optimum moisture content, OMC (%)
Soil sample (SS)	0	0	16.19	12.0
SS + 10% MD	10	0	16.48	11.8
SS + 20% MD	20	0	16.87	11.0
SS + 30% MD	30	0	18.05	10.5
SS + 40% MD	40	0	17.95	10.0
SS + 0.5% F	0	0.5	16.38	13.0
SS + 1.0% F	0	1.0	16.78	14.0
SS + 1.5% F	0	1.5	16.48	14.0
SS + 1.0% F + 20% MD	20	1.0	17.07	13.0
SS + 1.0% F + 30% MD	30	1.0	18.54	12.0
SS + 1.0% F + 40% MD	40	1.0	18.34	12.0

3.2. Shear Strength and Load-bearing Performance

Parameters of shear strength obtained by laboratory measurements are tabulated in Table 7. Both cohesion and internal friction angle depend on the content of marble dust, which indicates a better inter-particle contact and resistance. Fiber-reinforced specimens exhibit slower failure response, which implies increased deformation resistance.

The increase in the values of California Bearing Ratio (CBR) during soaked and unsoaked conditions is shown in Figure 2. It is also evident that the hybrid stabilized blend exhibits the greatest CBR values, which serves as evidence of the efficiency of the combination of ceramic filler and fiber reinforcement fabrics to increase the load-bearing behavior.

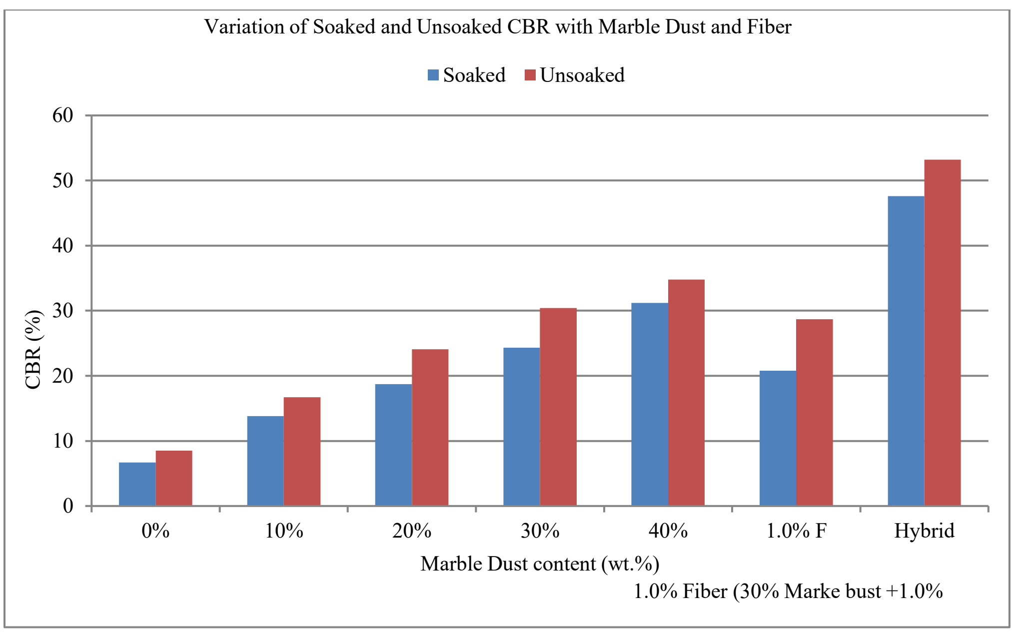

Fig. 2 Variation of soaked and unsoaked CBR values illustrating Densification-Controlled improvement with marble dust inclusion

Table 7. Shear strength parameter of untreated and stabilized mixtures

Sample designation	Cohesion, *c* (kN/m²)	Internal friction angle, *φ* (°)	Ultimate bearing capacity, *q*ult (kN/m²)	Net safe bearing capacity, *q*safe (kN/m²)
Soil sample (SS)	0.515	29.30	439.90	138.54
SS + 10% MD	0.545	29.61	464.33	146.54

SS + 20% MD	0.600	30.47	525.37	166.69
SS + 30% MD	0.700	31.02	600.94	191.29
SS + 40% MD	0.620	30.30	547.61	173.56
SS + 0.5% F	0.535	29.71	466.44	147.29
SS + 1.0% F	0.590	30.41	518.75	164.53
SS + 1.5% F	0.545	29.76	472.19	149.16
SS + 1.0% F + 20% MD	0.610	30.44	529.91	168.10
SS + 1.0% F + 30% MD	0.780	31.71	671.02	214.40
SS + 1.0% F + 40% MD	0.750	31.40	639.52	204.00

3.3. SEM-Based Microstructural Evolution

Figures 3-5 show the Scanning Electron Microscopy (SEM) micrographs, which depict microstructural development of expansive black cotton soil in the presence of marble dust stabilization, fiber reinforcement, and both in unison. All the images were taken at similar magnification to allow direct evaluation of the particle arrangement, pore structure, and reinforcement interaction.

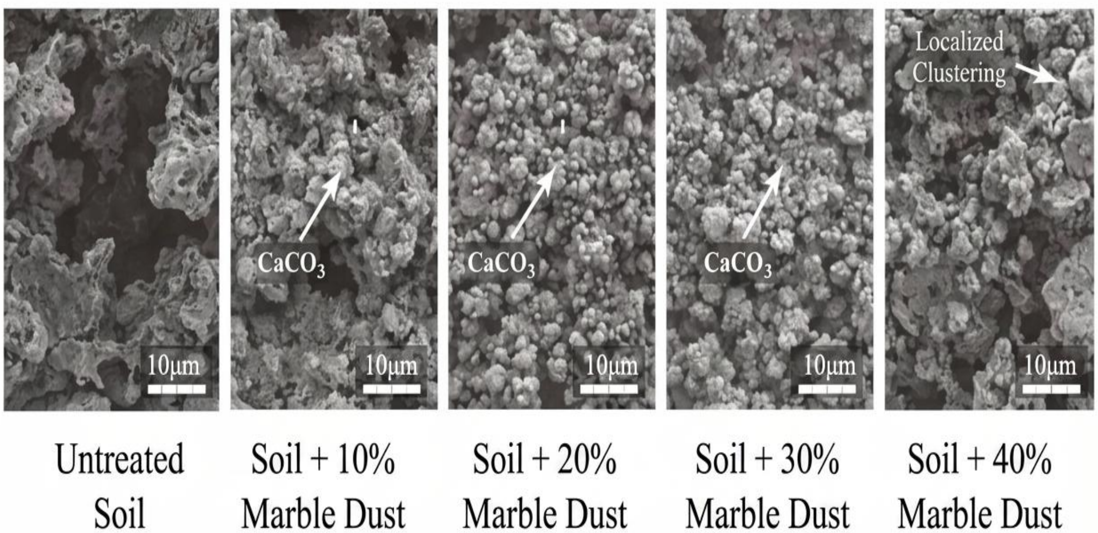

Fig. 3 SEM images of the influence of the increase in the content of marble dust (MD) on the microstructure of expansive soil: (a) untreated soil (SS), (b) SS + 10% MD, (c) SS + 20% MD, (d) SS + 30% MD, and (e) SS + 40% MD. The pictures depict the progressive void-filling and particle-packing enhancement by the addition of CaCO3 microfiller, and the optimal densification at 30 percent MD and localized clustering at high content (40 percent MD) (scale bar = 10 um).

3.3.1. Marble Dust Stabilization

Figure 3 SEM micrographs depict how the soil fabric was altered with the addition of greater amounts of marble dust. Untreated soil (Figure 3(a)) has a loose and flocculated structure characterized by big interconnected pores and weak contacts between the particles, hence the low dry density and high compressibility.

As marble dust (10% addition) is added (Figure 3(b)), fill-in of the voids using fine CaCO3 particles is partly achieved, resulting in a minor increase in packing density. When the percentage of marble dust is raised to 20 (Figure 3(c)), the distribution of microfiller will be more homogenous, which will lead to the formation of fewer pore spaces and a better connection between the particles. The homogenized microstructure of the specimen with 30% marble dust (Figure 3(d)) shows the smallest number of voids and a high degree of interlocking of particles.

This matches the optimum situation of compaction behavior. At increased marble dust content (40%) (Figure 3(e)), localized clustering and agglomeration of fine particles are observed. The heavy fines upset the skeleton of the soil and decrease the packing efficiency in comparison with the optimal one.

The observations fulfill this by confirming the assertion that a densification process is the major process that controls the stabilization of marble dusts, with the process relying on the filling of the voids and rearrangements of particles instead of chemical bonding.

SEM-observed pore refinement and physical densification also corroborate that the stabilization mechanism is regulated by physical densification in that the increase in maximum dry density observed matches closely with the pore refinement observed.

3.3.2. Fiber Reinforcement

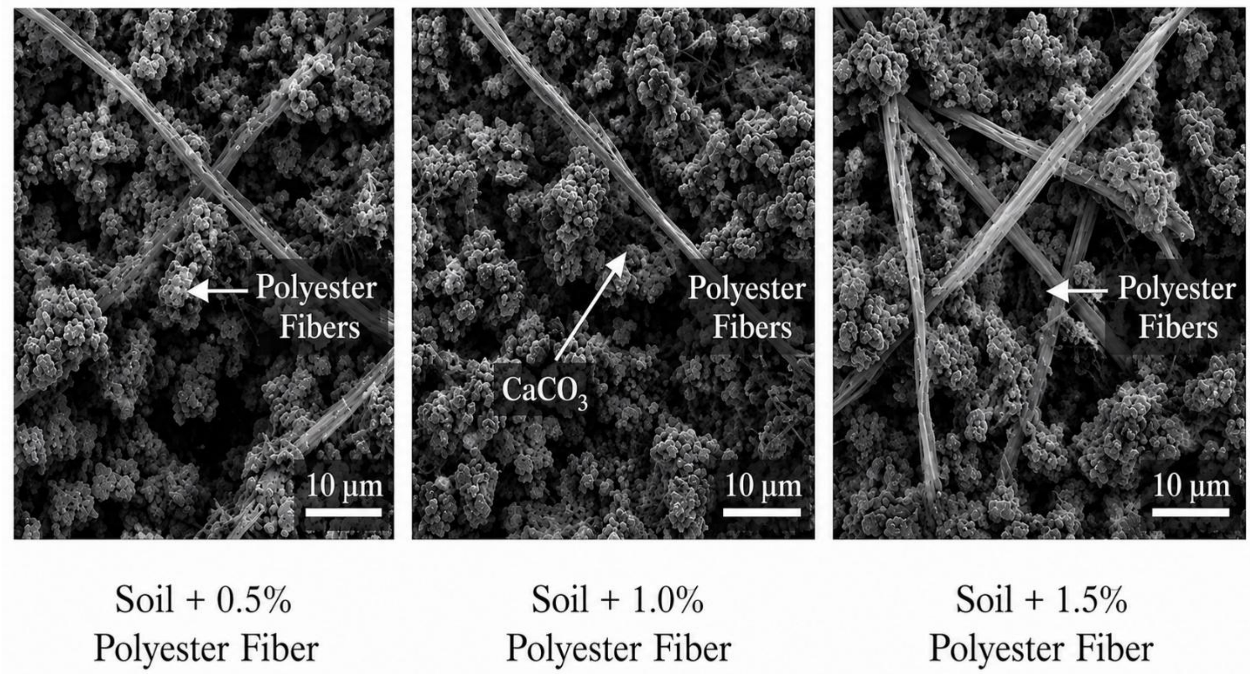

Fig. 4 SEM images of fiber-reinforced expansive soil: (a) SS + 0.5% polyester fiber (F), (b) SS + 1.0% F, and (c) SS + 1.5% F. The photographs demonstrate the formation of fiber bridging networks in the soil matrix and are characterized by a progressive growth of fiber interaction and fiber interlocking as the fiber content increases (scale bar = 10 um).

SEM of fiber reinforced specimen (Figure 4) has indicated the importance of polyester fibers in altering the soil structure by interacting with the soil mechanically. In 0.5 percent fiber content (Figure 4(a)), discrete fibers are randomly dispersed throughout the soil matrix to create localized bridges of soil particles. As inter-particle connectivity increases, the structure is also not very tight, with visible gaps. When the fiber content is at 1.0% (Figure 4(b)), a well-developed fiber network is seen. The fibers are more evenly distributed and create continuous links bridging between particles of soil, and increase interlocking and stress transfer among the particles. Such a state is associated with enhanced mechanical performance.

Fiber clustering and overlapping can be observed at the 1.5% fiber content (Figure 4(c)). Over fibers form uneven areas and other spaces, which decrease packing. In general, fiber reinforcement enhances the behavior of soil by strengthening its structure and reducing the deformation capacity mainly by a mechanical form of bridging behavior without changing the packing of the particles and the mineral structure significantly. The SEM observations affirm that it is the fiber reinforcement that plays a main role of mechanical bridging and redistribution of stress than densification.

3.3.3. Hybrid Stabilization

SEM micrographs of the hybrid stabilized soil (Figure 5) show the interaction of the presence of marble dust and polyester fibers on the microstructure of the soil. In the specimen of 20 percent marble dust of 1 percent of fiber (Figure 5(a)), the partial fillment of the void through the CaCO3 particles and the interval fillment through the fiber between aggregates of soil are witnessed. The structure exhibits enhanced packing as compared to untreated soil, although there are still some voids.

The soil matrix at 30 percent marble dust combined with 1.0 percent fiber (Figure 5(b)) indicates a very dense and well-distributed structure. The CaCO3 particles are capable of filling inter-particle gaps effectively, and polyester fibers create continuous bridging structures that, in addition to increasing the interlocking of particles and their transfer of loads. This arrangement is the most suitable hybrid state, which corresponds to the highest compaction and strength properties. As the content of marble dust increases (Figure 5(c) with 40% fiber), a localized concentration of fine particles is formed. Even though fiber bridging ensures structural integrity, too much fines minimally decrease the packing performance.

The hybrid system, in general, has a coupled stabilization effect such that the marble dust and polyester fibers increase the packing density and structural integrity, respectively, by filling the voids and providing mechanical support respectively. The integrated SEM data prove the fact that the process of densification and fiber reinforcement mechanism synergy dictates the better performance of hybrid stabilization.

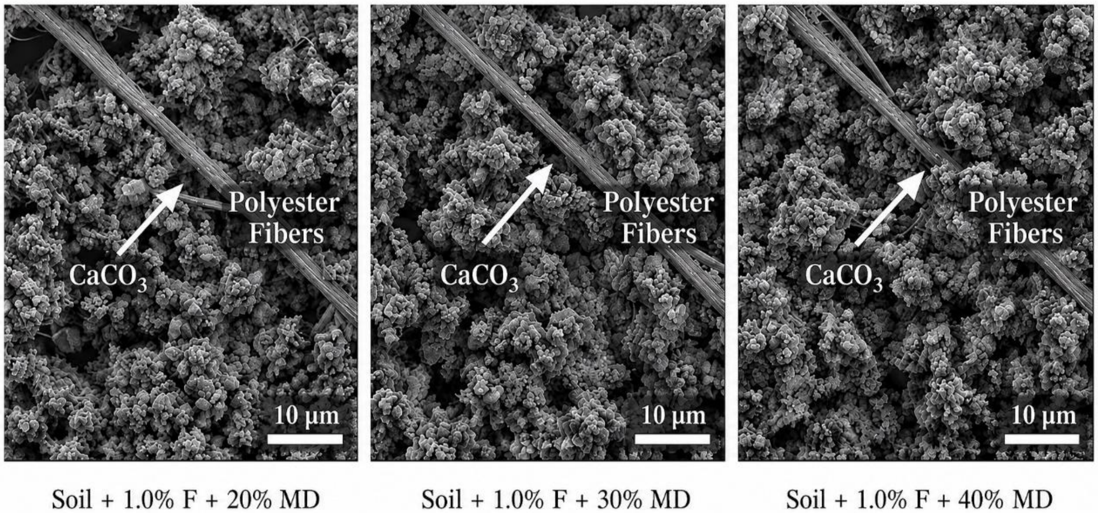

Fig. 5 SEM images of hybrid stabilized expansive soil: (a) SS + 1.0 percent and polyester fiber (F) + 20 percent and marble dust (MD), (b) SS + 1.0 percent and F + 30 percent and MD, (c) SS + 1.0 percent and F + 40 percent and MD. The pictures depict the synergistic action of CaCO3. optimal packing and structural integration with math and localized clustering with an increase in different marble dust content at 30% MD and fiber bridging induced by microfiller (scale bar = 10 um).

3.4. Analysis of TEM and Nanoscale Structural Refinement

Figures 6-8 show the micrographs of Transmission Electron Microscopy (TEM) of the structural evolution of expansive black cotton soil at the nanoscale under the influence of marble dust stabilization, fiber reinforcement, and their combination. All of the images were taken at similar magnifications in order to be able to analyze clay platelet organization and the distance between the particles and the interaction between their reinforcement directly.

3.4.1. Marble Dust Stabilization

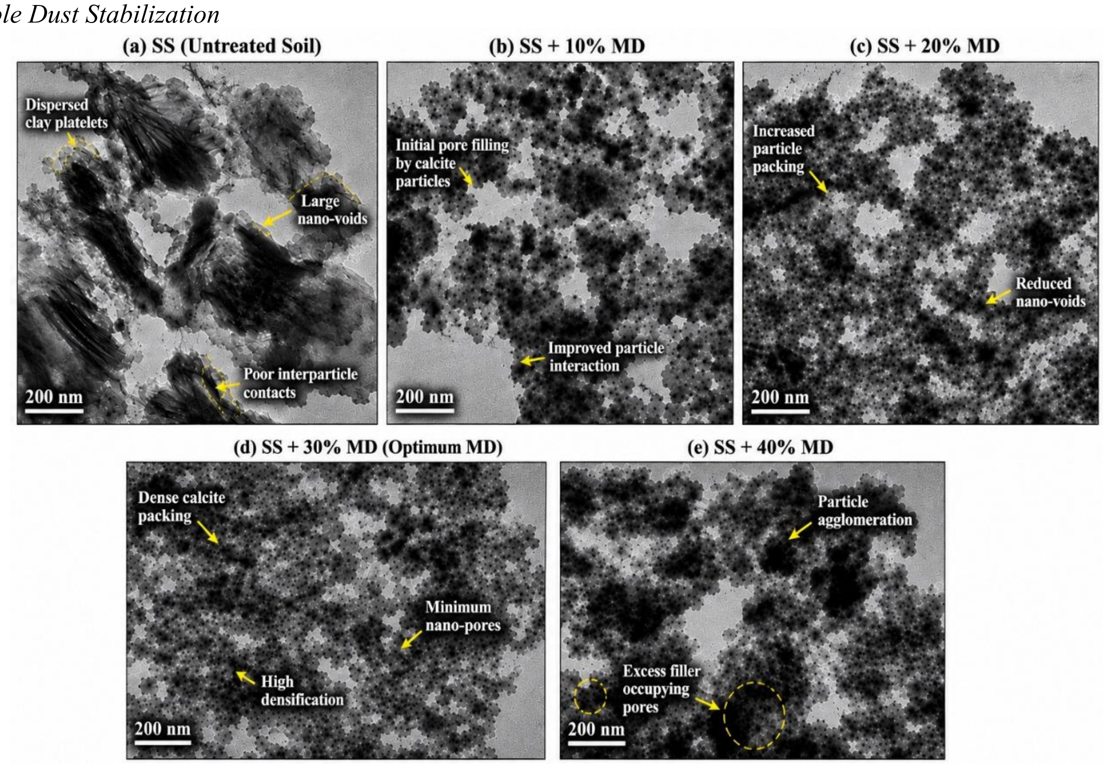

Fig. 6 Transmission Electron Microscopy (TEM) images of nanoscale structural development of expansive soil with different content of marble dust (MD): (a) untreated soil (SS), (b) SS + 10% MD, (c) SS + 20% MD, (d) SS + 30% MD, and (e) SS + 40% MD. The pictures show an increasing decrease of inter-particle distance and improved particle packing with the addition of CaCO3 microfiller, and optimum nanoscale densification of particles at 30% MD, and localized clustering at high content (scale bar = 200 nm).

Figure 6 TEM micrographs indicate how the nanoscale soil structure gradually changes as the content of the marble dust increases. Figure 6(a) shows that the untreated soil (Figure 6(a)) has loosely stacked platelets of clay that have considerable spaces in between and are dispersed in nature, facilitating the absorption and swelling characteristics of the soil. As 10 percent marble dust is added (Figure 6(b)), coarse CaCO3 particles start to fill in interstitial places, leading to partial confinement of platelets of clay, and an initial narrowing of the space between platelets. With 20% marble dust (Figure 6(c)) more homogenous arrangement of platelets can be observed, which means a better packing of the mixture and less void space. The sample with 30% marble dust (Figure 6(d)) is the sample with the most compact nanoscale structure, with the presence of tightly packed platelets of clay with the minimum spacing. This indicates well-confined and reduced diffuse double-layer thickness, which is the best-case scenario of compaction and strength behavior. Increasingly high marble dust content (40 percentage) (Figure 6(e)), localized clustering, and aggregation of CaCO 3 particles can be observed. This interferes with the regular organization of platelets and slightly decreases the efficiency of densification in comparison with the optimum situation. These experiments prove that the stabilization of marble dusts is controlled by a nanoscale densification process, which entails a decrease in the distance between particles and an increase in the packing, and not a chemical conversion. The near coincidence between the TEM-observed decrease of the inter-particle spacing and the experimentally determined increase of maximum dry density indicates that the stabilization is regulated by the nanoscale densification.

The agreement of the observations of SEM and TEM is a multi-scale confirmation of the densification mechanism, which connects the nanoscale rearrangement of particles with the macroscopic engineering functioning.

3.4.2. Fiber Reinforcement

Figure 7 shows TEM micrographs of fiber-reinforced specimens and reveals the effect of polyester fibers on the nanoscale structure of soil. Isolated fibers are installed at 0.5% fiber content (Figure 7(a)), and the fibers are not interacting much with the surrounding particles. The platelet arrangement has not been altered significantly, meaning that there was little effect on nanoscale packing. When the fiber content is up to 1.0% (Figure 7(b)) fibers are more evenly distributed and offer localized confinement to the rest of the particles. However, there is no great decrease in the inter-particle spacing, which proves that platelet arrangement is not affected by the addition of fibers. Where fiber content stands at 1.5 percent (Figure 7(c)) fiber clustering and overlapping are also observed, thus leading to localized heterogeneity and possible micro-voids. Comprehensively, fiber reinforcement influences the behavior of soil either due to mechanical interaction and confinement, but not due to the alteration of nanoscale structure or mineral arrangement. The TEM analysis verifies the fact that the fiber reinforcement does not change the nanoscale particle arrangement, which is why it is possible to interpret that the effect of fiber reinforcement is entirely mechanical and not physicochemical. This observation is supplemental with SEM results, in which fiber bridging improves the performance of macroscopes without affecting densification.

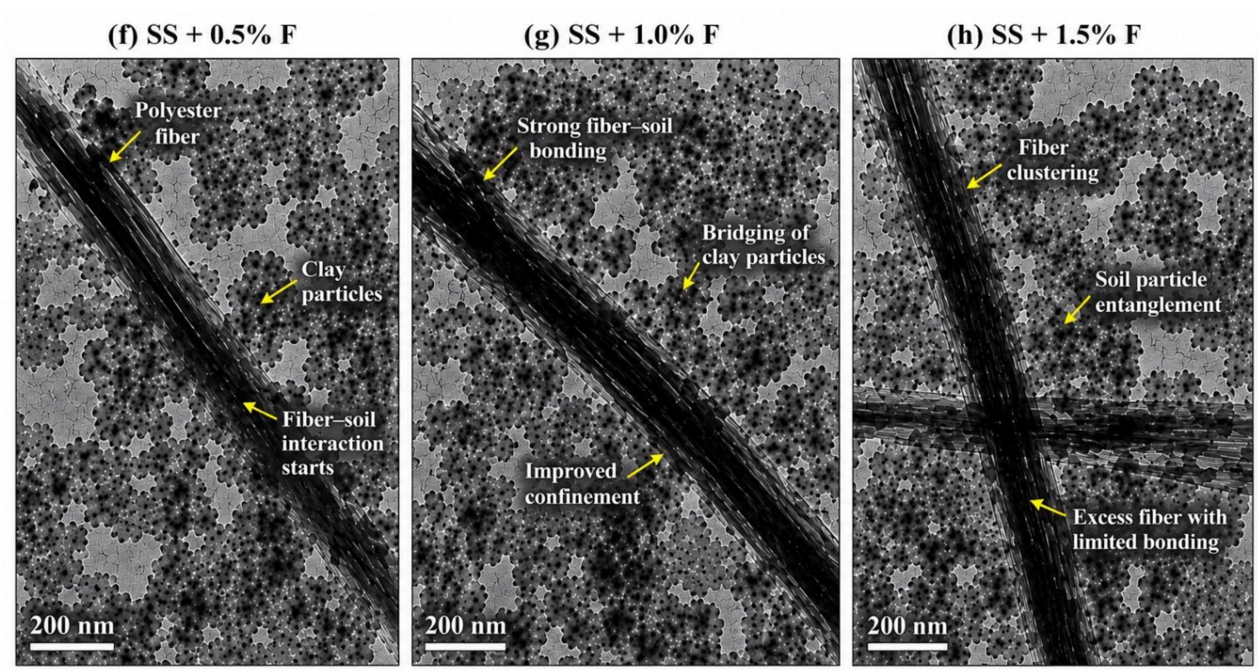

Fig. 7 TEM images of fiber-reinforced expansive soil: (a) SS + 0.5% polyester fiber (F), (b) SS + 1.0% F, and (c) SS + 1.5% F. The photos depict the behavior of the clay particles and the polyester fibers on the nanoscale, demonstrating the fiber entrapment and entrapment of fibers in the soil matrix without substantial distortion of platelet fine structure (scale bar = 200 nm).

3.4.3. Hybrid Stabilization

The TEM micrographs of hybrid stabilized specimens (Figure 8) prove the joint effect of marble dust and synthetic fibers of polyester on nanoscale soil structure.

In the specimen that has 20 percent marble dust with 1.0 percent fiber (Figure 8(a)), the inter-particle spaces are occupied by $CaCO_3$ particles, and part of the platelets of clay are entrap within the structure, and the remainder of the structure is occupied by fibers. The finest refined nanoscale structure is observed at 30%marble dust containing 1.0 percent fiber (Figure 8(b)). Clay platelets are closely stacked with little spacing as a result of the good microfiller action and the fibers, further confine and stabilize. This is the best hybrid state, which is the best engineering performance.

At increased content of marble dust (Figure 8(c) 40), the packing is locally disrupted by the localization of CaCO3 particles. Even though fibers remain connected, high prices of fines decrease the performance of nanoscale densification. In general, the hybrid system exhibits a coupled stabilization mechanism, in which nanoscale densification induced by marble dust and mechanical confinement and stress transfer by polyester fibers are involved. The TEM results prove that the synergistic effect of densification on nanoscale and mechanical confinement on fibers determine the improved performance of hybrid stabilization. The correlation between SEM and TEM results offers the multi-scale confirmation of the stabilization process related to the relationship between nanoscale particle rearrangement and pore-scale densification and macroscopic engineering response.

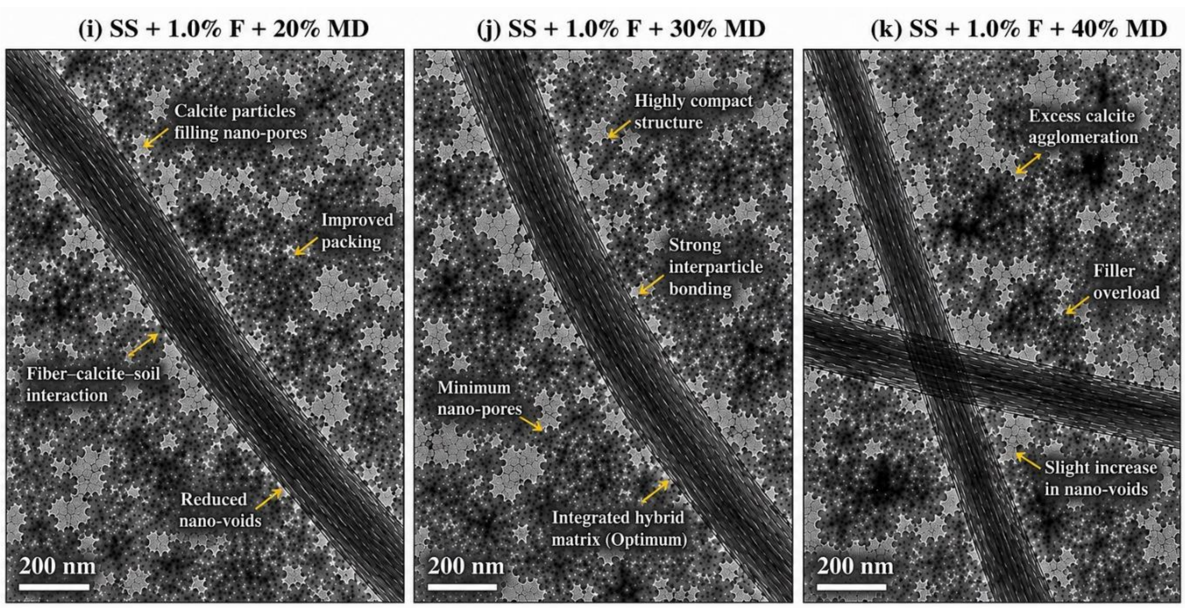

Fig. 8 TEM images of hybrid stabilized expansive soil:(a) SS + 1.0% polyester fiber (F) + 20% marble dust (MD),(b) SS + 1.0% F + 30% MD, (c) SS + 1.0% F + 40% MD. The pictures are used to describe a combination of CaCO3 microfiller-induced confinement and fiber interaction at the nanoscale, which shows the best packing of the particles at 30% MD and local clustering at higher content of the marble dust (scale bar = 200 nm).

3.5. XRD Analysis and Phase stability

X-ray Diffraction (XRD) patterns in Figure 9 show mineralogical properties of untreated Black Cotton Soil (SS) and the soils that were stabilized with different percentages of Marble Dust (MD), Polyester Fiber (F), and their hybrids in Table 8. The untreated soil has strong diffraction peaks of montmorillonite, and secondarily, it has kaolinite and quartz, which attest to the expansive clay nature of the soil. The high plasticity, swelling tendency, and poor load-bearing performance experienced when in the untreated state are attributed to the presence of montmorillonite that is highly plasticized with low angles of reflection. The introduction of a marble dust (SS + 10-40% MD) causes the appearance of clear diffraction peaks, namely, the ones that belong to the most common calcite (CaCO3) at 2th [2θ] 29.4deg, 39.4deg, and 47-48deg. These calcite peaks become more and more intense as the content of the marble dust increases, which shows that the content of calcium carbonate in the soil matrix is higher. At the same time, the relative strength of clay mineral peaks reduces because of the partial replacement and dilution of clay particles by the fines of marble dust. A well-balanced diffraction pattern is achieved at 30% of marble dust, with calcite peaks being strong and clay mineral peaks still being identifiable, which implies that there is an optimum where the population of the particles to be packed and densified. At 40 percent marble dust, the domineering peaks on the diffract gram are at calcite, and this shows that there is too much filler in the composite, and this is in line with the slight decrease in mechanical performance that occurs above the optimal level of marble dust. The XRD pattern of the fiber-reinforced samples (SS + 0.5-1.0% F) is essentially similar to the untreated soil, and there are no new diffraction peaks or peak shifts in them. This proves that polyester fibers are X-ray amorphous and they do not cause any mineralogical alterations in the soil. The enhancement of the engineering behaviour of the fibre-reinforced soils is therefore the result not of chemical or mineralogical transformation, but simply of mechanical reinforcement mechanisms, e.g., cracks bridging and stress redistribution. The diffraction patterns in the hybrid stabilized soils (SS + 1.0% F + 20-40% MD) have both clay minerals and calcite peaks. The mix with 1.0% of fiber and 30% of marble dust exhibits the most desirable mineralogical balance with big peaks of calcite and the reflection of clay minerals. This suggests good void filling and densification with the use of marble dust and deformation restraint with the help of fibers. The fact that no new crystalline phases have been found in all stabilized samples proves that no pozzolanic or cementitious processes take place, and that the process of soil improvement is determined by physical densification and mechanical reinforcement, which is entirely consistent with the observation of SEM-TEM and behavioral trends of the experiments.

Table 8. List of XRD of samples of the untreated and hybrids (marble-dust and stabilized soil)

Sample ID	2θ (°)	Identified Mineral	Crystal Plane (hkl)	Interpretation / Significance
SS	6.1–6.4	Montmorillonite	(001)	Expansive clay mineral; high swelling potential
	12.3–12.6	Kaolinite	(001)	Secondary clay mineral
	20.7–20.9	Quartz	(100)	Inert silica phase
	26.6–26.8	Quartz	(101)	Dominant sand fraction
SS + 10% MD	29.3–29.5	Calcite	(104)	Initial marble dust contribution
	39.3–39.6	Calcite	(113)	Filler-induced densification
SS + 20% MD	29.3–29.5	Calcite	(104)	Increased $CaCO_3$ content
	43.1–43.4	Calcite	(202)	Void-filling dominant
SS + 30% MD	29.3–29.5	Calcite	(104)	Optimum marble dust content
	39.3–39.6	Calcite	(113)	Maximum densification
	47.4–47.7	Calcite	(018)	Enhanced particle packing
SS + 40% MD	29.3–29.5	Calcite	(104)	Excess filler dominance
	48.5–48.8	Calcite	(116)	Agglomeration effect
SS + 0.5% F	6.1–6.4	Montmorillonite	(001)	Clay mineral unchanged
	26.6–26.8	Quartz	(101)	Fiber is X-ray amorphous
SS + 1.0% F	6.1–6.4	Montmorillonite	(001)	No mineralogical change
	20.7–20.9	Quartz	(100)	Mechanical reinforcement only
SS + 1.5% F	6.1–6.4	Montmorillonite	(001)	Excess fiber does not alter minerals
	26.6–26.8	Quartz	(101)	Confirms non-reactive fiber
SS + 1.0% F + 20% MD	29.3–29.5	Calcite	(104)	Combined filler + fiber effect
	39.3–39.6	Calcite	(113)	Improved stiffness
SS + 1.0% F + 30% MD	29.3–29.5	Calcite	(104)	Optimum hybrid stabilization
	39.3–39.6	Calcite	(113)	Maximum load transfer
	47.4–47.7	Calcite	(018)	Peak bearing capacity
SS + 1.0% F + 40% MD	29.3–29.5	Calcite	(104)	Excess filler
	48.5–48.8	Calcite	(116)	Slight performance reduction

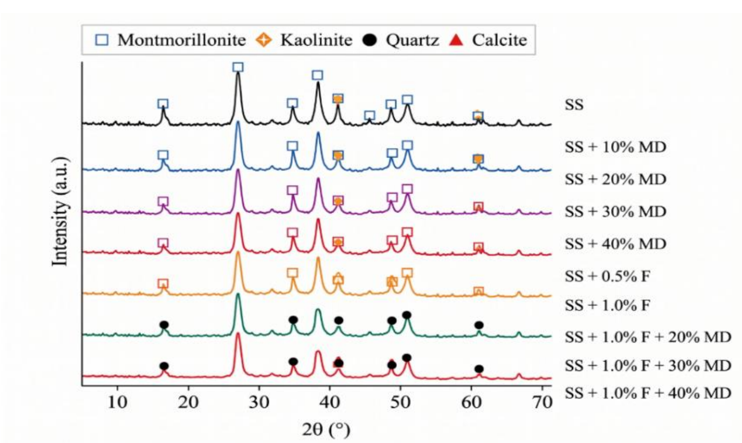

Fig. 9 XRD of samples of the untreated and the marble-dust-stabilized soil

3.6. Correlation between Microstructure and Property

A combination of the above interpretation reveals that there is a direct correlation between microstructural refinement and enhanced mechanical behavior. Higher examples of dry density and strength translate to decreased levels of porosity and greater particle contacts as seen in SEM and TEM analyses. It is the combination of the densification effects of the microfiller and the mechanical restraint that is provided by the fibers that results in the superior performance of the hybrid stabilized mixture.

3.6.1. Research on Integrated Mechanism validation

This is observed to be a stabilization mechanism that is always confirmed in several scales and procedures. SEM experiment confirms that pore-scale densification occurs by filling voids and enhancing particle packing, and TEM experiments reveal that a nanoscale decrease in inter-particle spacing and clay platelet confinement occur. XRD analysis also indicates that no additional mineral phases are created, which means that stabilizing is controlled not by chemical reactions but by physical modification. These microstructural changes are closely related to the experimentally observed increase in maximum dry density, shear strength, and bearing capacity. Moreover, the behavior of PLAXIS 2D simulations is similar to the behavior of loads with setcitllements as stabilized soils experience less deformation and more stiffness. This consistency in microstructural, experimental, and numerical findings is sufficient evidence to state that the underlying mechanism is densification-controlled stabilization concomitant to mechanical reinforcement, such that it offers a mechanistically consistent and multi-scale validated explanation.

3.7. Mechanistic Interpretation to Stabilization Behaviour

The engineering of behavior improvement observed is controlled mainly by physical densification and mechanical reinforcement mechanisms than chemical transformation. Addition of marble dust brings on-board fine $CaCO_3$ particles that fill-up inter-aggregate pores and therefore decreases the pore value and increases the density of contact between the particles. This microfiller activity enhances the soil structure, limits the movement of clay platelets, as well as advance a more stable load-transfer skeleton. The ensuing decrease in void ratio is what translates to a higher dry density, shear resistance, and lower compressibility. Further strengthening of the mechanical response with polyester fibers includes the tensile restraint and confinement effect. Fiber inclusion is used as a connecting material between solid particles of soil, preventing local degradation and giving time to progressive failure. It is the joint filler-fiber system that increases stiffness complementarily, therefore void filler dominates structural densification, whereas fibers dominate localization of strain and crack propagation. The fact that no new crystalline phase is observed in XRD patterns is a confirmation that the improvement of performance is achieved by fabric modification, but not because of a binder-driven mineralogical reaction. Thus, density-controlled effects related to pore refinement and mechanical stabilization can be considered as strength and bearing capacity gains. These interpretations are independently validated by the numerical simulations, which show that experimentally studied strength and density growth is directly proportional to decreased settlement and increased plastic deformation time.

3.8. Experimental Summary

The experimental findings prove that the marble dust is an efficient microfiller in ceramics, but polyester fibers are effective in reinforcing the structure, and do not change mineralogy. Physical densification and structural refining controls the stabilization mechanism, which is compatible with filler-reinforced ceramic composite systems. The densification-controlled enhancement in the stabilization of the marble dust soils is a different concept compared to the chemically reactive stabilization systems. Compared to lime or fly ash treatment, where strength development is controlled by hydration and pozzolanic bonding, the development of strength changes in marble dust stabilization is achieved firstly by the processing of physical fabric and secondly by the improvement of particle packing strength. This process can reduce the dependency to be cured and variability related to ***reaction-controlled*** processes, thus enhancing the predictability of performance. The stabilization strategy is thus a mechanically enabled direction of change aligned with sustainability stipulations of reusing materials.

3.9. Sustainability and Comparative Stabilization Perspective

The stabilization behaviour of the soils containing marble dust can be explained using the context of sustainable methods of improving the ground. Rice Husk Ash (RHA), fly ash, and Ground Granulated Blast Furnace Slag (GGBS) are some of the widely used industrial by-products in place of problematic soils as an alternative stabilizer. These materials are mostly based on the pozzolanic or cementitious reaction, in which the development of strength is controlled by the chemical bonding and curing-dependent reactions. Although efficient, reaction-controlled stabilization systems are sensitive to the presence of moisture, the time of curing, and the compatibility of all the chemicals that can create field performance variability. By comparison, however, marble dust stabilization is controlled largely by physical densification processes. Being another calcium carbonate-based, inert microfiller, marble dust influences soil behaviour by filling the voids, reinforcing the packaging of the particles, and optimising the size of the pore structure. This process does away with curing addiction and minimises uncertainties regarding reaction kinetics. In terms of sustainability, the stabilization process based on microfillers has a good environmental profile in the sense that it does not incur high embodied carbon, as is the case with cementitious binders. The alternative method proposed lowers embodied carbon, which is produced by high temperatures in binder production and curing reliance compared to cement-based stabilization. Reuse of the waste dust of marble also helps in achieving the aspirations of the circular-economy because it directs the fine particulate remains out of the disposal streams. In contrast to chemically reactive additives, which need energy-consuming processing or activation, marble dust may be added directly after little conditioning. The resulting increases in density, strength, and settlement resistance are thus obtained by means of mechanically controlled fabric remodelling, which is a low-carbon material reuse route in line with sustainable geotechnical.

3.10. Field application/scalability

Although the current study is done on the basis of controlled laboratory research, the stabilization mechanisms that govern it are essentially scale-free. The control of marble dust modification is accomplished through the particle packing and void-filling phenomena, and the polyester fibers provide the effects of mechanical restraint and confinement. These are not dependent on chemical reactions or curing kinetics in relation to time, and this implies that the same behavioural tendencies could be anticipated when field compaction is used, so long as moisture control and energy input are controlled.

Pragmatically, marble dust as a microfiller-type stabilizer offers positive constructibility properties, since the densification, instead of a reaction-sensitive strength increase effect, controls the improvement process. This minimizes the uncertainty of variability of curing and sensitivity to the environment that is usually witnessed in chemically stabilized soil. Field implementation is thus likely to have uniform performance patterns, especially when the application is to do subgrade improvement and settlement control.

4. Numerical Analysis Using PLAXIS 2D

4.1. Purpose of Numerical Simulation

PLAXIS 2D finite element software was used to perform numerical analysis to give a mechanistic explanation of the experimentally recorded load-settlement behavior and to verify the effect of marble dust stabilization and polyester fiber stabilization on an experimental scale. The numerical investigation was not to develop a field-scale design methodology, but to supplement the data obtained through the experiment by analyzing the deformation behavior, the distribution of stress, and the development of failures.

4.2. Model Boundary Conditions and Model Configuration

The numerical model was taken in the plane strain conditions, which modelled the lab test of the model footing. To reduce the impact of boundary effects, the dimensions of the soil domain has been chosen in both horizontal and vertical dimensions as five and four times the footing width, respectively. The footing was represented as a hard plate element that was lying on the face of the soil. The soil mass was modeled with the help of a 15-node triangular finite element, and local refinement was used with a medium mesh density to ensure that the stress concentration and settlement behavior are represented with a high degree of accuracy. The vertical boundaries were constrained horizontally and free vertically, and the bottom boundary was restrained both horizontally and vertically. The surface on the ground was maintained free.

4.3. Constitutive Model and Input Parameters

The Mohr-Coulomb elastic-perfectly plastic constitutive model was used to model soil behavior. The input parameters, such as unit weight, cohesion, and angle of internal friction, were taken directly through laboratory test results, whereas the parameters of stiffness were estimated through regular correlations with stabilized clay-rich systems. The input parameters adopted in the PLAXIS numerical simulations are listed in Table 9, which is taken with the direct properties of compaction and shear strength that are measured in the laboratory.

- The value of modulus E that was obtained by Young was correlated with parameters of compaction density and shear strength.
- Dilatancy angle (ψ) was assumed as $\psi = \varphi - 30°$ for dense stabilized mixtures and zero for loose or untreated soil.
- The Mohr-Coulomb elastic-perfectly plastic constitutive model was used to model all the materials.

Table 9. PLAXIS input of untreated and stabilized soil mixtures

Sample designation	Unit weight, γ (kN/m³)	Young's modulus, *E* (MPa)*	Poisson's ratio, *ν*	Cohesion, *c* (kN/m²)	Friction angle, *φ* (°)	Dilatancy angle, *ψ* (°)	Constitutive model
Soil sample (SS)	16.19	8.0	0.30	0.515	29.30	0	Mohr–Coulomb
SS + 10% MD	16.48	10.0	0.30	0.545	29.61	0	Mohr–Coulomb
SS + 20% MD	16.87	14.0	0.30	0.600	30.47	0	Mohr–Coulomb
SS + 30% MD	18.05	20.0	0.30	0.700	31.02	1	Mohr–Coulomb
SS + 40% MD	17.95	18.0	0.30	0.620	30.30	1	Mohr–Coulomb
SS + 0.5% F	16.38	10.0	0.32	0.535	29.71	0	Mohr–Coulomb
SS + 1.0% F	16.78	13.0	0.32	0.590	30.41	1	Mohr–Coulomb
SS + 1.5% F	16.48	11.0	0.32	0.545	29.76	0	Mohr–Coulomb
SS + 1.0% F +	17.07	16.0	0.32	0.610	30.44	1	Mohr–Coulomb

20% MD							
SS + 1.0% F + 30% MD	18.54	25.0	0.32	0.780	31.71	2	Mohr–Coulomb
SS + 1.0% F + 40% MD	18.34	23.0	0.32	0.750	31.40	2	Mohr–Coulomb

4.4. Loading Procedure

The analysis was done based on staged construction. During the first stage, the forces of gravity loaded were used to create in-situ stress. Activation of the footing was then done, after which the vertical load was applied gradually. To produce numerical curve load-settlement curves that compared to experimental ones, settlement was observed at the bottom of the footing at the center of each increment of loads.

4.5. PLAXIS Findings and Discussion

Figure 10(a) shows the load-settlements curves of PLAXIS prediction. The untreated soil has quick settlement at comparatively low weight levels, and this implies low stiffness and early yielding. Conversely, soils that are stabilized exhibit decreasingly flatter load-settlement curves as a result of densification of marble dust and fiber reinforcement, which indicates the increased stiffness. The stabilized mixture in the form of a hybrid that has 30 wt.% of the marble dust and 1.0 wt.% of the fiber shows the lowest settlement and the most resistant to the load, as is integrated with the experimental results. Figure 10(b) shows the vertical displacement contours of untreated soil, which illustrates a deep and widespread settlement bulb, and that of stabilized soils, which show them shallow and narrower. The behavior establishes an enhanced load transfer in stabilized systems. The total vertical stress contours (Figure 10(c)) indicate that the distribution of stress under the footing in the stabilized mixtures, especially the hybrid system, is greater and more intense. The concentrated stress bulb implies an augmented bearing resistance and augmented redistribution of stress owing to a greater density and shear strength. The plastic point distributions in (Figure 10(d) indicate that at low load levels, there are large areas of yielding of untreated soil. Stabilized soils, on the other hand, yield slowly, plastic points being concentrated towards the edges of the footings. The hybrid stabilized mixture experiences the least degree of plastic deformation, meaning it has a better shear failure resistance.

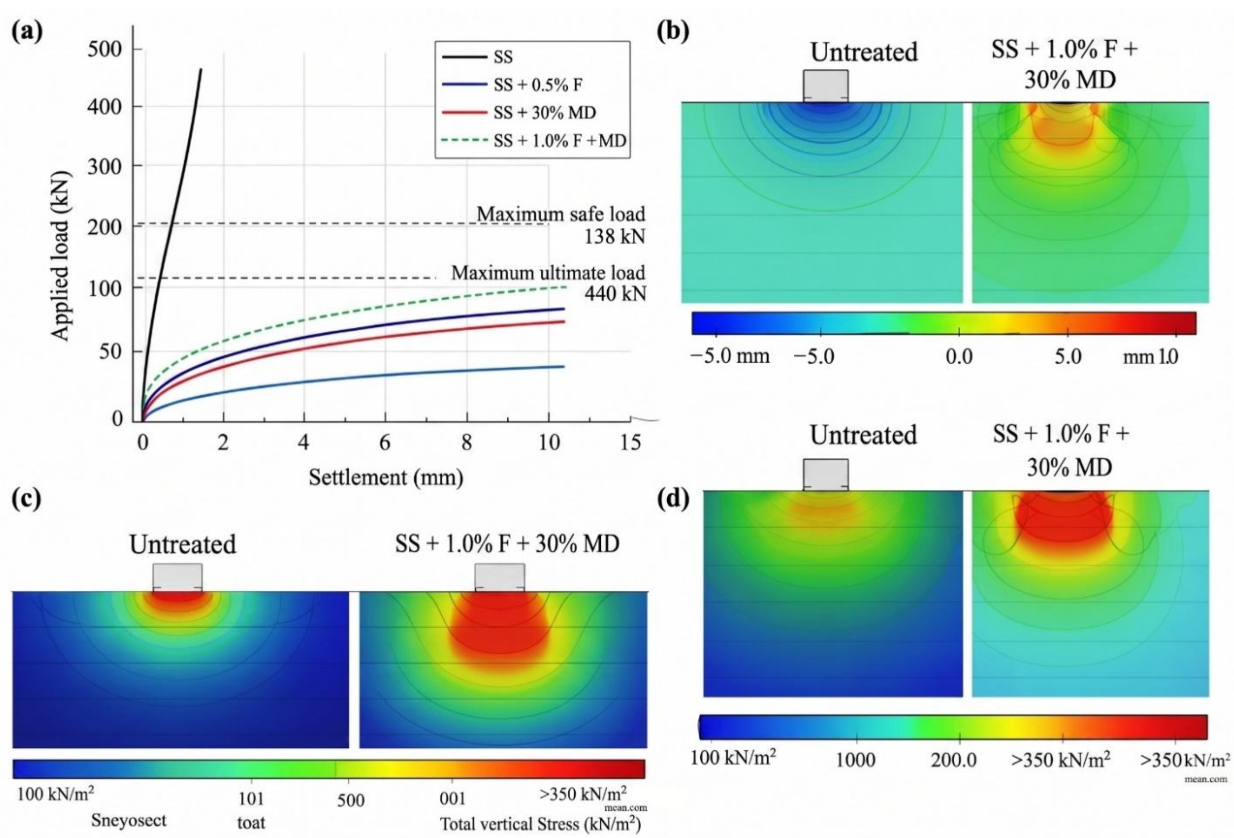

Fig. 10 PLAXIS numerical data: (a) Load-settlement curves, (b) Contours of vertical displacement, (c) Overall profile of vertical stress, and (d)Development of plastic point

The correlation between numeric and experimental outcomes is performed. There was a good correlation between experimental load-settlement trends and PLAXIS predictions. The numerical and experimental methods were consistent in the ranking of mixtures basing on stiffness and load-carrying capacity. It is explained by minor inconsistencies due to idealized constitutive assumptions and scale effects that exist in laboratory modeling. On the whole, the numerical findings can be considered to have strong support to the experimentally determined optimum stabilization condition.

4.6. Numerical Analysis Summary

PLAXIS numerical analysis has verified the existence of benefits in the process of stabilization with marble dust and polyester fibers, which increase stiffness, minimize settlement, and postpone the development of failure. It is shown that the hybrid system performs better in terms of numerical ability, confirming the experimentally determined microstructure-property relations. The numerical test, therefore, is a good validation tool that can be used to complement the experimental results.

The qualitative behaviour of the numerical predictions is in good agreement with experimental behaviour, especially in terms of the trend in stiffness enhancement and reduction in the settlement. Combustions that performed well in laboratory testing by showing greater maximum dry density and shear strength always yielded less displacement contours when used in a finite-element analysis and yielded less flat load-settlement curves. The presence of this correspondence shows that the governing improvement mechanism is well represented by the density-dependent parameter evolution instead of mineralogical change. The patterns of the simulated distribution of stress help to further justify the densification-controlled stabilization mechanism based on microstructural observations.

The stabilized soils exhibit concentrated and shallow bulbs of stress under the footing, which is in line with the improvement of the transfer of loads and decrease in compressibility. On the other hand, the untreated soils behaviour is marked with wider displacement regions and precipitous yielding at an earlier stage, which is reflective of the experimentally recorded increased settlement vulnerability. The idealized constitutive assumptions of the Mohr-Coulomb model and the scale effect on laboratory testing can all be viewed as minor deviation between numerical and laboratory responses. However, behavioural trends are consistent, thus verifying that experimentally observed strength and stiffness increases have a mechanically coherent foundation. The scale-independent characteristics of stabilization under densification further implies that the numerical tendencies followed can be qualitatively extrapolated to field conditions, under the conventional geotechnical compaction controls.

5. Conclusions

The paper examined the application of waste marble dust, which is a byproduct of processing ceramic and stones and using the waste material together with synthetic polyester fibre in stabilizing expansive black cotton soil in a materials science outlook. The conclusions made are as follows, based on the experimental, microstructural, and numerical findings:

1. Marble dust is used in the form of a microfiller, and it is mainly a calcium carbonate with the ability to pack the particles and densifying the matrices without causing any chemical or mineralogical changes.
2. The addition of marble dust greatly enhanced the dry density and shear strength to a maximum level of 30 wt.per cent after which the additional fines decreased the packing capacity.
3. Synthetic polyester fibers provided better deformation resistance and post-peak behaviour by the action of the mechanical restraint and stress redistribution mechanisms
4. SEM and TEM analyses showed the development of the microstructure with stabilization, such as a lower pore connection and limited platelet arrangement of clay.
5. XRD indicated that all stabilized samples were stable in phase and no new crystalline phases were formed, indicating that the stabilization mechanism in all the stabilized samples was through physical modification and not chemical reaction.
6. The hybrid stabilization system with 30 wt.% marble dust and 1.0 wt.% polyester fiber had the most optimal density, strength, and resistance to deformation.
7. The PLAXIS 2D numerical analysis revealed excellent correlation between experimental load-settlement behavior and numerical analysis, proving the microstructure-property relations in the experiment.
8. These findings show a viable and value-added pathway to the reuse of marble dust in the field of engineering and ground improvement of ceramic-related materials.
9. This study shows that marble dust stabilization of expansive soils can be strictly interpreted through densification-controlled mechanisms through both multi-scale microstructural characterization and finite-element simulation, which goes beyond the conventional strength-based evaluations that are commonly reported in the previous literature.

All in all, the work brings out the possibility of waste in the form of ceramic processing as a possible microstructural modifier in clay-based systems, which can be used to develop materials in an environmentally friendly manner in accordance with the principles of the circular economy. The research shows that, in the first application in a ceramic waste use scenario, it is possible to use marble dust as a non-mineralogically stable microfiller of expansive soils and offer a technically viable and sustainable stabilization solution. Long-term stability and field validation should be part of future research.

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