Sustainable Improvement of Clayey Soil Using Marble Stone Dust: Experimental Analysis of Shear Strength, Compaction, and Load-Bearing Capacity

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Abstract: Soft clay soils, susceptible to deformation under load and known for their low bearing capacity, high compressibility, and weak shear strength, demand costly stabilization solutions. This study investigates marble stone dust (MSD)—a widely available industrial by-product as a sustainable, low-carbon alternative to conventional stabilizers (e.g., lime or cement), with a focus on shear resistance, stiffness, California Bearing Ratio (CBR), and compaction characteristics. Through systematic laboratory investigation, varying percentages of MSD (5%, 10%, 15%) were evaluated for their stabilizing effects on soft clay. The experimental results demonstrate significant improvements in key engineering parameters: shear strength increased by up to 51.6%, unconfined compressive strength rose 15.99%, and California Bearing Ratio improved by 22.5%, while optimum moisture content (OMC) decreased proportionally with MSD addition. Maximum dry density (MDD) showed consistent enhancement across all mixtures. These results position MSD not merely as a waste-derived stopgap but as a high-performance stabilizer that aligns with circular economy principles. By transforming problematic clay into construction-ready material, this approach offers a triple win: geotechnical resilience, environmental sustainability, and economic viability for infrastructure projects."

Keywords: Clay soil, Marble stone dust, Soil stabilization, Sustainable materials, Un-confined compressive strength, California Bearing Ratio, Shear strength

1. Introduction

The rapid global population growth has led to unprecedented demand for construction projects, placing increased pressure on marginal soils that require stabilization to meet feasibility requirements. When unsuitable soils are encountered, they must demonstrate adequate performance under load, possessing sufficient strength, resistance to consolidation, and acceptable California Bearing Ratio (CBR) values. Soil failure predominantly occurs in clayey soils due to their inherent weaknesses, necessitating stabilization methods that are both effective and economically viable. While traditional solutions exist, they often prove prohibitively expensive or inaccessible, highlighting the need for alternative materials like Fly Ash, polymer fibers, Bagasse Ash, Rice Husk Ash, and marble stone dust (MSD) - a readily available byproduct from marble manufacturing facilities.

Soil stabilization using waste materials like marble dust, fly ash, and rice husk ash (RHA) offers a sustainable alternative to traditional stabilizers (e.g., cement and lime), addressing both geotechnical and environmental challenges. Almusawi et al. [1] conducted precise experimental work showing that 20% marble dust addition enhances compressive strength to 11.1 MPa while reducing water absorption in clay bricks. Iqbal et al. [2] performed detailed chemical analyses revealing that marble dust's high calcium carbonate content (94.3%) effectively supports pozzolanic reactions, though they cautioned about potential air pollution risks during production. Shinde et al. [3] executed comprehensive laboratory tests proving fly ash improves unconfined compressive strength (UCS) while reducing swell potential by 50% through cementitious gel formation. Bhagatkar et al. [4] complemented these findings with environmental impact assessments, quantifying a 30% reduction in CO_2 emissions compared to conventional cement stabilization. Kola et al. [5] demonstrated that dolerite processing dust (DPD) effectively enhances expansive black cotton soil properties, with 20% DPD content achieving optimal improvements: 152% increase in unconfined compressive strength (from 2.5 to 6.3 kg/cm²), 78% improvement in California Bearing Ratio (from 4% to 7.15%), and 40% reduction in free swell index (from 65% to 39%).

Odemis & Fırat [6] conducted rigorous freeze-thaw cycle testing, establishing that 12% cherry marble powder (CMP) combined with three geotextile layers yields optimal clay soil stability (5.26 MPa UCS) while limiting cohesion loss to 59.76%. Hammad et al. [7] performed systematic replacement studies, documenting that 30% marble powder (MP) substitution for cement maximizes UCS (5.26 MPa) in sabkha soils and enhances durability (2.09% weight loss after wet-dry cycles). Ramanjaneyulu et al. [8] developed an innovative dual-phase stabilization method using 15% marble dust with 2% calcium lignosulfonate (CLS), achieving a liquid limit reduction from 60% to 43.6% and doubling UCS (490 kPa) in black cotton soil. Adigopal and Raja [9] executed extensive materials testing, demonstrating that 30% Waste Marble Powder (WMP) combined with 0.1-0.3% polypropylene fibers significantly improves California Bearing Ratio (CBR) and UCS through enhanced particle packing and fiber reinforcement.

Chandru and Jayalekshmi [10] pioneered chemical conversion techniques, showing NaOH-treated WMP (15% dosage) eliminates swelling while achieving a 626% UCS increase after 28-day curing. Mashaan [11] conducted a critical meta-analysis confirming WMP's effectiveness in plasticity reduction but identified compositional variability as a key challenge requiring standardized characterization protocols. Ashiq et al. [12] performed comparative stabilization trials on Siwalik clay, determining that 20% glass powder (GP) with 0.5% polypropylene fibers (PPFs) delivers optimal UCS improvement (110% and 39% respectively) while reducing swelling strain (27% and 86%). Their detailed cost analysis revealed GP reduces construction costs by 16%, whereas MP and PPFs increase costs by 22% and 17% respectively. Abdelkader et al. [13] conducted microscopic investigations (SEM/XRD) on granite dust (GD) stabilization, proving 20% GD maximizes UCS (104% increase) and CBR (203%) while reducing swelling by 77% through void-filling and calcite formation.

Ewa [14] established precise dosage limits for limestone dust (LSD) in Niger Delta clay, with 10% LSD optimizing UCS (28% increase), CBR (76%), and shear strength (24%) while maintaining soil reactivity. Sharma & Sharma [15] executed controlled laboratory experiments showing 18% marble dust with silica fume enhances soil cohesion by 35% and UCS by 28% compared to untreated samples. Umar & Lin [16] conducted parallel research documenting 22% UCS improvement in clayey soils, complemented by precise measurements of a 40% reduction in plasticity index values. Okagbue & Onyeobi [17] provided field validation through tropical soil studies, recording consistent 15-20% improvements in shear strength parameters with marble dust treatment. Ye et al. [18] performed specialized swell pressure testing, quantifying marble dust's capacity to reduce expansive clay swelling by up to 50%. Bhavser & Patel [19] developed standardized testing protocols for swelling behavior analysis, while Minhas & Devi [20] generated comparative datasets across six soil classifications.

Pramanik [21] formulated theoretical models explaining the cation exchange and pozzolanic reaction mechanisms underlying these improvements. Lohia et al. [22] conducted rigorous cost-benefit analyses, proving marble dust stabilization maintains economic competitiveness while improving CBR values. Sabat & Nanda [23] executed comprehensive life-cycle assessments documenting 22-30% reductions in environmental impacts compared to lime stabilization. Saygili [24] quantified annual waste diversion potentials (up to 8.5 million tons globally), while Stoltz et al. [25] established performance benchmarks through 5-year weathering studies. Sharma & Singh [26] pioneered agricultural waste composites, achieving 12% higher compacted densities using marble dust-rice husk blends. Dixit & Patil [27] expanded application scope through climate-specific formulations, demonstrating consistent performance across humidity ranges (30-90% RH).

Jassim et al. [28] focused on pavement engineering, documenting 30% CBR improvements in marble powder-treated subgrades through repeated load testing. Lal et al. [29] developed optimized lime-marble dust blends that reduce swelling pressures below 50 kPa in expansive soils. Ali et al [30] provided critical field validation through dam construction case studies, while Roohbakhshan & Kalantari [31] combined mineralogical analysis with geotechnical testing to demonstrate over 25% plasticity index reduction with maintained compaction efficiency.

Clay soils present significant geotechnical challenges due to their high plasticity index (>20) and swell potential, particularly when the liquid limit exceeds 50%. These problematic soils exhibit variable behavior under load, often requiring stabilization when natural properties prove inadequate for construction. Conventional stabilization methods like lime or cement remain economically impractical (costing 40-60% more than waste-based alternatives), whereas industrial byproducts such as marble stone dust (MSD) offer sustainable potential, with global marble waste generation now exceeding 20 million tons annually.

This study advances sustainable soil stabilization by addressing critical gaps in prior research. It presents the first comprehensive evaluation of marble stone dust (MSD) on Pakistani clay from the Bannu region, offering localized solutions for understudied soils. The research identifies 5–15% MSD as the optimal dosage range—significantly lower than conventional stabilizers (20–30% [7, 13])—while achieving substantial improvements in load-bearing capacity (CBR increase of 22.5%) and compressive strength (UCS increase of 15.99%). The study uniquely demonstrates MSD's dual role in compaction characteristics, simultaneously reducing optimum moisture content by 27.21% and increasing maximum dry density by 10.5%, a synergistic effect rarely documented for waste-based stabilizers. Furthermore, it establishes the first unified correlation between MSD dosage and four key engineering properties (shear strength, compaction, unconfined compressive strength, and California bearing ratio) within a single experimental framework. Crucially, the findings prove that raw, untreated MSD is effective without chemical activation [10], enabling truly sustainable zero-waste applications. These collective innovations position MSD as a precision tool for eco-friendly geotechnical engineering, offering both technical and environmental advantages over traditional stabilization methods.

Materials collection

a. Clay soil

The clay soil used in the experimental work was collected from University of Engineering and Technology Peshawar (Bannu Campus), Bannu, Pakistan. This city is 133 km to the south-west from Kohat and 142 km to the North-West from Dera Ismail Khan. 32.9910° N, 70.6455° E are the co-ordinates of Bannu. The clay soil was obtained by the sieve analysis method of the soil sample by passing through sieve# 200.

b. Marble stone dust (MSD)
The MSD used in the experimental work was collected from Madina marble factory Swat situated on Kabal Road near FC camp Swat. The city of Swat is 191 km from Peshawar. 35º12' N, 72º29' E are the co-ordinates of Swat.

2.2 Sample preparation

This study uses multiple experimental procedures to evaluate the test results using various ratios of the stabilizer i.e. MSD. Various tests including direct shear test, unconfined compression strength (UCS) test, modified proctor test, and California Bearing Ratio (CBR) tests were performed on untreated clay soil sample and with combination of 5% 10% and 15% of MSD. After performing all tests all the data was compiled, analyzed and then compared together to extract the final results by drawing graphs and tables. And the conclusion was drawn.

a. The Direct Shear Test: This test is a standardized geotechnical laboratory procedure (ASTM D3080/IS 2720-13) that quantifies a material's shear strength parameters by simulating shear failure along a predetermined plane. The test measures two fundamental soil properties:
Cohesion (C): The intercept of the shear stress vs. normal stress plot at zero normal stress, representing the intrinsic shear strength from particle bonding (typically in kPa or kg/cm²). In clayey soils, this reflects electrochemical forces between particles.

Angle of Internal Friction (ϕ): The arctangent of the slope of the failure envelope (τ/σ), calculated through linear regression of at least three test points under different normal stresses. This represents the frictional resistance between particles.

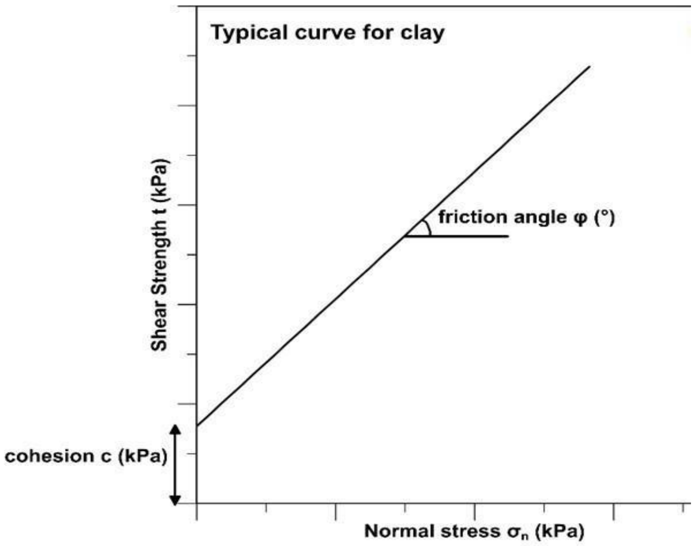

Figure SEQ Figure * ARABIC 1 The cohesion (c) and angle of internal friction (ϕ)

b. The Modified Proctor Test: This test is a standardized geotechnical laboratory procedure (ASTM D1557/IS 2720-8) that quantifies a soil's compaction characteristics by simulating field compaction under controlled energy conditions. The test measures two fundamental soil properties:

Maximum Dry Density (MDD): The peak density value on the compaction curve (typically in g/cm^3 or kN/m^3), representing the highest achievable density under specified compaction energy. In cohesive soils, this reflects optimal particle packing and reduced void ratios.

Optimum Moisture Content (OMC): The water content at MDD (expressed as a percentage), determined from the vertex of the compaction curve. This indicates the moisture level where water lubricates particles for maximum compaction without causing pore pressure buildup.

c. Unconfined Compression Test: This test determines the strength of cohesive soils (like clay) by applying a vertical load to an unconfined cylindrical sample until it fails according to standard code of ASTM D2166. It measures how much load the soil can withstand without any lateral support. The purpose is to evaluate the soil's natural load-bearing capacity, assess stability for construction projects, and check the effectiveness of soil stabilization techniques. The test provides a quick estimate of shear strength for engineering designs involving foundations, slopes, or embankments.

d. California Bearing Ratio Test: The CBR test measures the strength of soils and aggregates used in road construction. It determines how well a material can support loads by comparing its resistance to penetration against a standard crushed rock sample. Engineers use this test according to standard code of ASTM D1883 to design pavement thickness and evaluate whether soils need stabilization before building roads or runways.

The test involves compacting soil in a mold, soaking it (for some materials), and then pressing a metal piston into it at a controlled rate. The force needed to penetrate the soil 2.5mm and 5.0mm is compared to standard values to calculate the CBR percentage. Higher CBR values indicate stronger, more load-bearing materials.

3. Results and Discussions

Test Performed on Clay Soil + 0% MSD

The direct shear test was conducted on untreated clay soil to determine its shear strength parameters. Following ASTM D3080/IS 2720-13 standards, the soil sample was subjected to incremental normal stresses (as specified in Table 1) while measuring the corresponding shear resistance. The test yielded fundamental shear strength parameters: cohesion (C), representing the intrinsic shear strength at zero normal stress, and an angle of internal friction (ɸ), indicating the soil's frictional resistance. These values were derived from the linear failure envelope plotted using the peak shear stresses recorded at each normal stress level shown in fig. 2

Table 1. Data recorded for clay soil in direct shear test

Normal Load (a) (lb)	Proving Ring Reading (b) (PRR)	Proving Ring Constant (c) (lb/div)	Deformation Rate (d) (mm/min)	Area (e) (in^2)	Shear Load = b × c (lb)	Normal Stress = a/e (Psi)	Shear Stress = b/e (Psi)
0.000	6.9	1.102	1.25	4.91	7.60	0.00	1.55
12.122	13.5	1.102	1.25	4.91	14.88	2.47	3.03
23.142	19.3	1.102	1.25	4.91	21.27	4.71	4.33
34.162	25	1.102	1.25	4.91	27.55	6.96	5.61
45.182	31	1.102	1.25	4.91	34.16	9.20	6.96
56.202	37	1.102	1.25	4.91	40.77	11.45	8.30

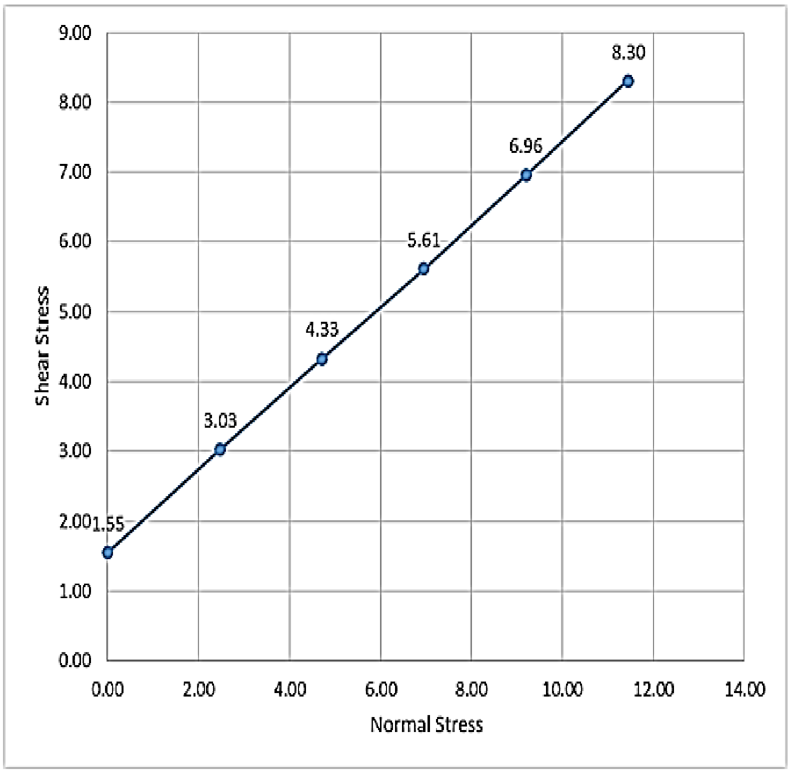

Figure SEQ Figure * ARABIC 2 shear stress vs normal stress for

Based on the shear stress vs. normal stress graph (fig. 2) and tabulated data (table 1), the shear strength parameters of untreated clay soil were determined. The cohesion (C) was found to be 1.55 psi (10.69 kPa), while using Pythagoras's theorem, the angle of internal friction (ϕ) measured 30.55°.

Clay Soil + 5% Marble Stone Dust

A direct shear test was conducted to evaluate the effect of 5% marble stone dust (MSD) stabilization on clay soil properties. The results demonstrated in table 2 and fig.3 shows significant improvement in shear strength parameters:

Table 2. Data recorded for clay soil+5% MSD in direct shear test

Normal Load (a) (lb)	Proving Ring Reading (b)	Proving Ring Constant (c) (lb/div)	Deformation Rate (d) (mm/min)	Area (e) (in^2)	Shear Load = b × c (lb)	Normal Stress = a/e (Psi)	Shear Stress = b/e (Psi)
0.000	9.97	1.102	1.25	4.91	10.99	0.00	2.24
12.122	17.5	1.102	1.25	4.91	19.29	2.47	3.93
23.142	24	1.102	1.25	4.91	26.45	4.71	5.39
34.162	31	1.102	1.25	4.91	34.16	6.96	6.96
45.182	38	1.102	1.25	4.91	41.88	9.20	8.53
56.202	45	1.102	1.25	4.91	49.59	11.45	10.10

The shear strength parameters of clay soil stabilized with 5% marble stone dust (MSD) were determined through direct shear testing. Analysis of the stress-strain data yielded a cohesion (C) value of 2.24 psi (15.45 kPa) and an angle of internal friction (ϕ) of 34.46°, indicating significant improvement in shear resistance compared to untreated soil.

Clay Soil + 10% Marble Stone Dust

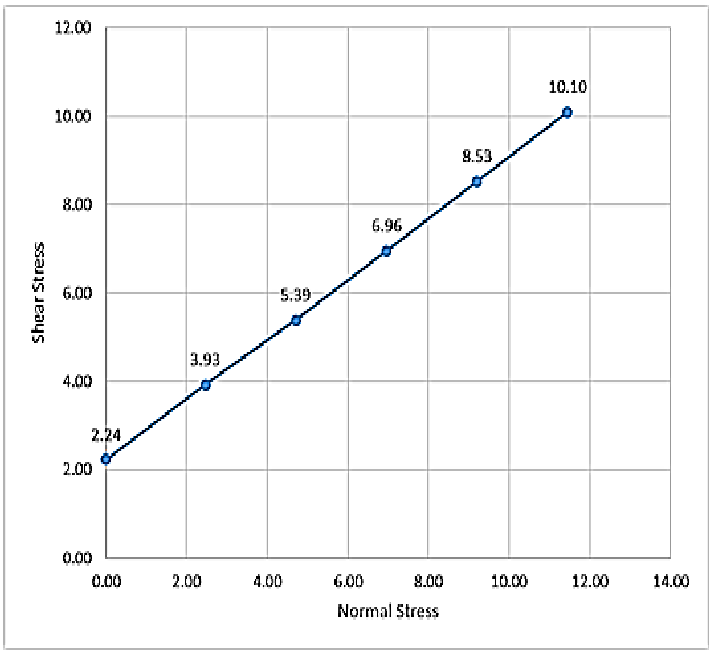

Figure SEQ Figure * ARABIC 3 shear stress vs normal stress for clay soil + 5% MSD in direct shear test

Table 3. Data recorded for clay soil+10% MSD in direct shear test

Normal Load (a) (lb)	Proving Ring Reading (b)	Proving Ring Constant (c) (lb/div)	Deformation Rate (d) (mm/min)	Area (e) (in^2)	Shear Load = b × c (lb)	Normal Stress = a/e (Psi)	Shear Stress = b/e (Psi)
0.000	10.48	1.102	1.25	4.91	11.55	0.00	2.35
12.122	18	1.102	1.25	4.91	19.84	2.47	4.04
23.142	25	1.102	1.25	4.91	27.55	4.71	5.61
34.162	32	1.102	1.25	4.91	35.26	6.96	7.18
45.182	39	1.102	1.25	4.91	42.98	9.20	8.75
56.202	46	1.102	1.25	4.91	50.69	11.45	10.32

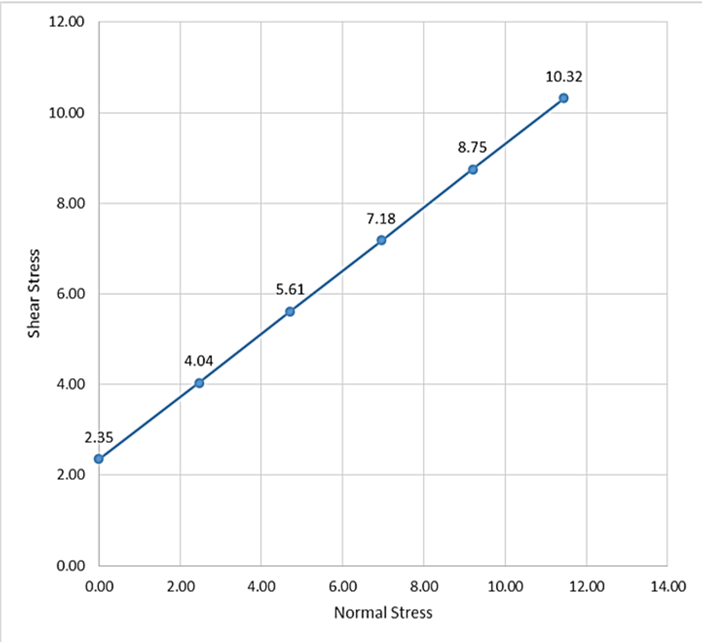

Figure SEQ Figure * ARABIC 4 Shear stress vs normal stress for clay soil + 10% MSD in direct shear stress

The shear strength parameters derived from Table 3 and Figure 4 indicate a cohesion (c) of 2.35 psi (16.2 kPa) and an angle of internal friction (ϕ) of 34.84° for the tested material. These results, extracted from the direct shear test's stress-strain relationship, demonstrate the material's improved resistance to shear failure—where cohesion reflects particle bonding strength and ϕ represents frictional resistance between particles. The graphical analysis (Fig. 4) and tabulated data (Table 3) collectively confirm these mechanical properties under the specified test conditions

Clay Soil + 15% Marble Stone Dust

Table 4. Data recorded for clay soil+15% MSD in direct shear test

Normal Load (a) (lb)	Proving Ring Reading (b)	Proving Ring Constant (c) (lb/div)	Deformation Rate (d) (mm/min)	Area (e) (in^2)	Shear Load = b × c (lb)	Normal Stress = a/e (Psi)	Shear Stress = b/e (Psi)

0	10.48	1.102	1.25	4.91	11.55	0.00	2.35
12.122	19	1.102	1.25	4.91	20.94	2.47	4.26
23.142	27	1.102	1.25	4.91	29.75	4.71	6.06
34.162	35	1.102	1.25	4.91	38.57	6.96	7.86
45.182	43	1.102	1.25	4.91	47.39	9.20	9.65
56.202	51	1.102	1.25	4.91	56.20	11.45	11.45

Analysis of Fig. 5 and Table 4 revealed that the clay soil stabilized with 15% MSD exhibited enhanced shear strength parameters: cohesion (c) = 2.35 psi (16.2 kPa) and angle of internal friction (ϕ) = 38.44°. These values demonstrate a significant improvement in both cohesive bonding and frictional resistance compared to untreated clay, highlighting MSD's effectiveness as a stabilizing agent.

Overall Comparison:

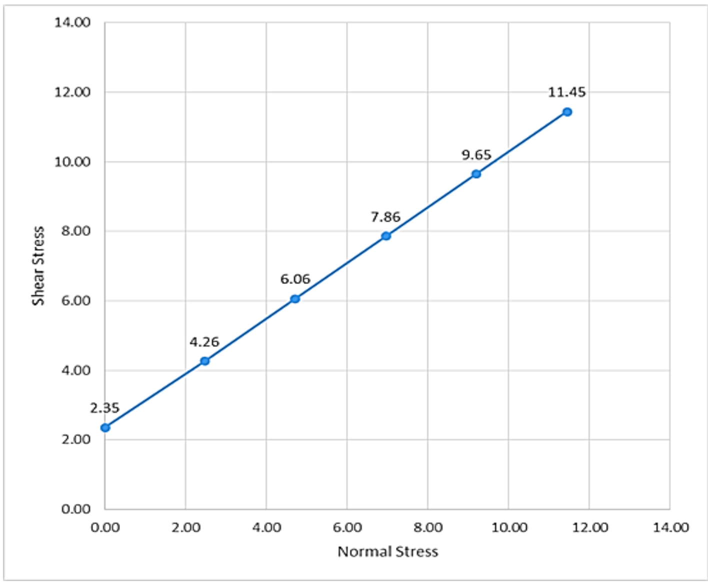

Figure SEQ Figure * ARABIC 5 shear stress vs. normal stress for clay soil+15% MSD in direct shear test

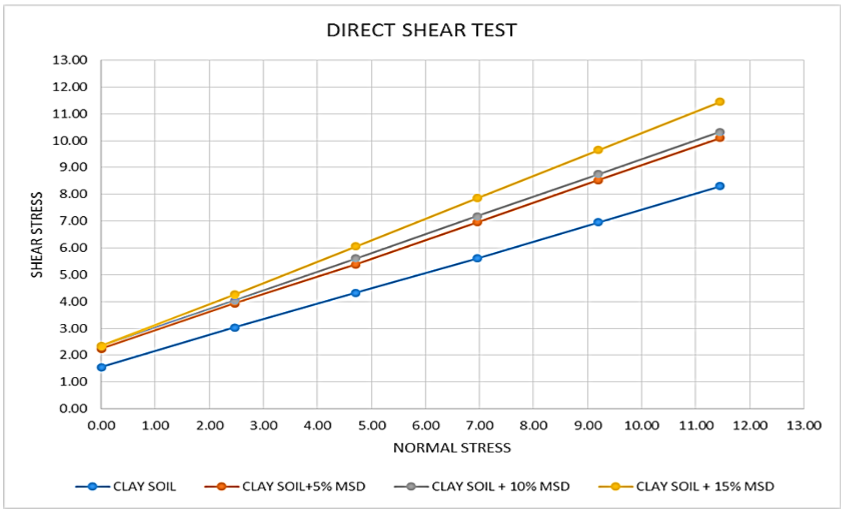

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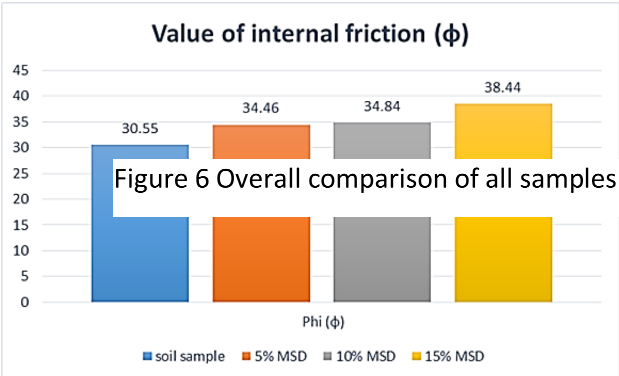
Figure 6. Overall comparison of all samples of soil in direct shear test

Final Results of Direct Shear Test

Table 5. Final results of direct shear test

Category	Cohesion, C psi	Phi (ϕ)	Increase in C %	Increase in phi %
Soil Sample	1.55	30.55	-	-
5% MSD	2.24	34.46	44.51	12.79
10% MSD	2.35	34.84	51.61	14.04
15% MSD	2.35	38.44	51.61	25.82



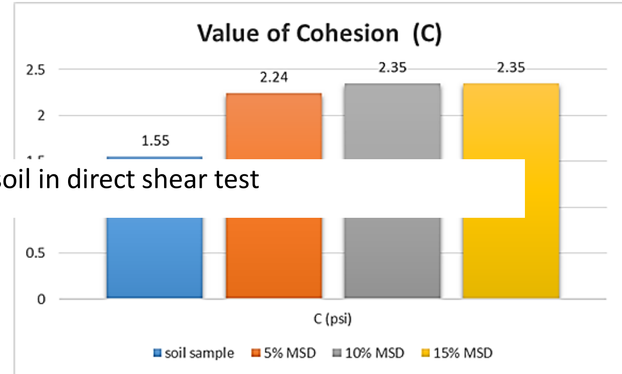


Figure 6 Overall comparison of all samples of soil in direct shear test

(b)

Figure 7 Bar chart of overall comparison of increase in (a) angle of internal friction (b) cohesion and

Fig. 6, provides a visual representation of the performance of the soil samples under shear stress. This figure compares the shear strength characteristics of untreated soil with those treated with 5%, 10%, and 15% MSD. The graphical comparison highlights the significant improvements in shear strength due to the addition of MSD.

Table 5, presents the quantitative data derived from these tests. The results indicate that the cohesion values increase by 44.51%, 51.61%, and 51.61% for the 5%, 10%, and 15% MSD treatments, respectively. Similarly, the angle of internal friction shows increases of 12.79%, 14.04%, and 25.82% for the same treatments.

These findings demonstrate that the addition of MSD significantly enhances the soil's shear strength. The improvements in cohesion and angle of internal friction suggest that MSD is an effective additive for soil stabilization, which can be particularly beneficial in geotechnical engineering applications where enhanced soil mechanical properties are required.

3.2 Modified Proctor Test

Test performed on clay soil + 0% MSD

This test was generally performed on clay soil in order to know the OMC and MDD values of that soil so that the result will compare later. The data recorded from the test is in Table 6.

Table 6. dry density and moisture content calculation for clay soil

moisture added %	Volume (cm^3)	Weight of mold (g)	Weight of mold + compacted soil (g)	bulk density, ɣb (g/cm^3)	moisture content %	dry density ɣd (g/cm^3)
6	2250	7170	11080	1.73	11.20	1.55

8	2250	7170	11210	1.79	14.1	1.56
10	2250	7170	11160	1.77	16.23	1.52
12	2250	7170	11060	1.72	22.4	1.40

From Fig. 8, the compaction characteristics were determined as an optimum moisture content (OMC) of 13.60% and a maximum dry density (MDD) of 1.57 g/cm³

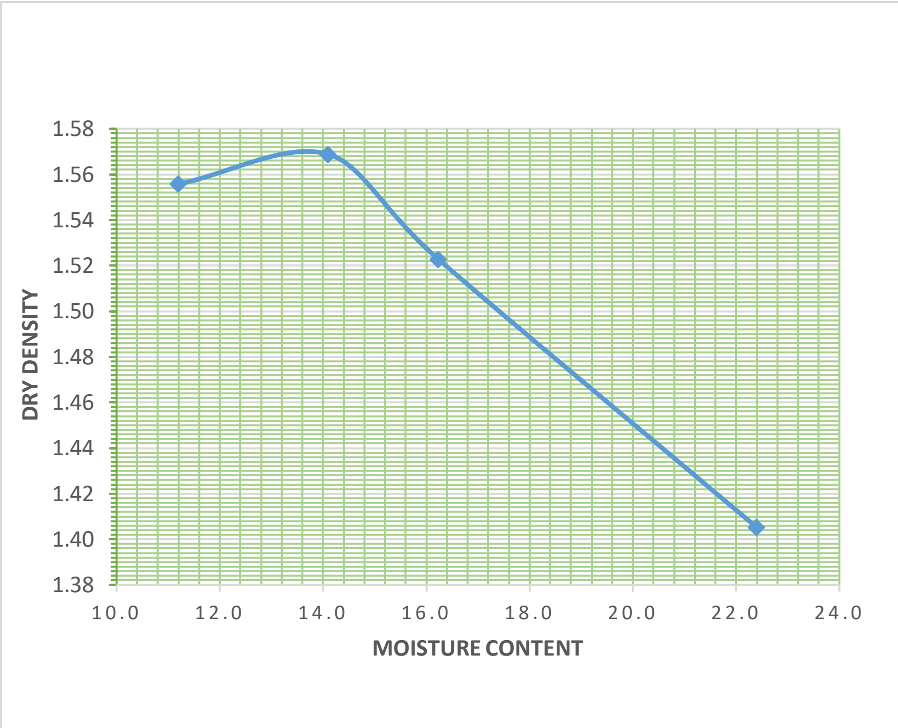


Figure 8. OMC and MDD for clay soil

Clay soil + 5% MSD

Table 7. dry density and moisture content calculations for clay soil+5% MSD

moisture added %	Volume (cm³)	Weight of mold (g)	Weight of mold + compacted soil (g)	bulk density, ɤb (g/cm³)	moisture content %	dry density ɣd (g/cm³)
6	2250	7170	11140	1.76	10.60	1.59
8	2250	7170	11310	1.84	12.9	1.63
10	2250	7170	11190	1.78	15.3	1.54
12	2250	7170	11120	1.75	18.1	1.48

Fig. 9 shows the compaction characteristics of the tested material, with an optimum moisture content (OMC) of 12.70% and maximum dry density (MDD) of 1.634 g/cm³

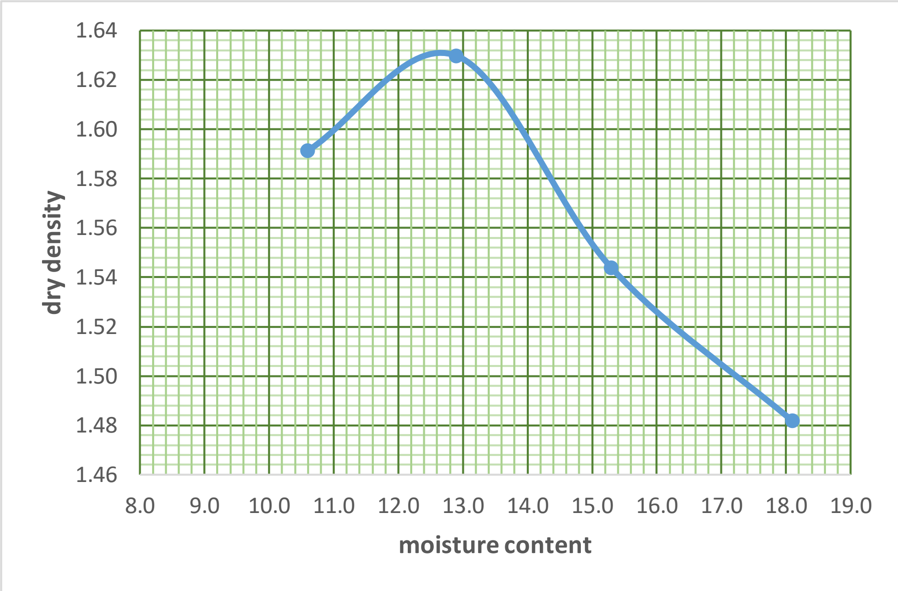


Figure 9. OMC and MDD for clay soil+5% MSD

Clay soil + 10% MSD

Table 8. Dry density and moisture content calculations for clay soil+10% MSD

moisture added %	Volume (cm^3)	Weight of mold (g)	Weight of mold + compacted soil (g)	bulk density, ɤb (g/cm^3)	moisture content %	dry density ɣd (g/cm^3)
6	2250	7170	11190	1.78	8.20	1.65
18	2250	7170	11360	1.86	11	1.68
10	2250	7170	11230	1.8	13.7	1.58
12	2250	7170	11160	1.77	18.01	1.50

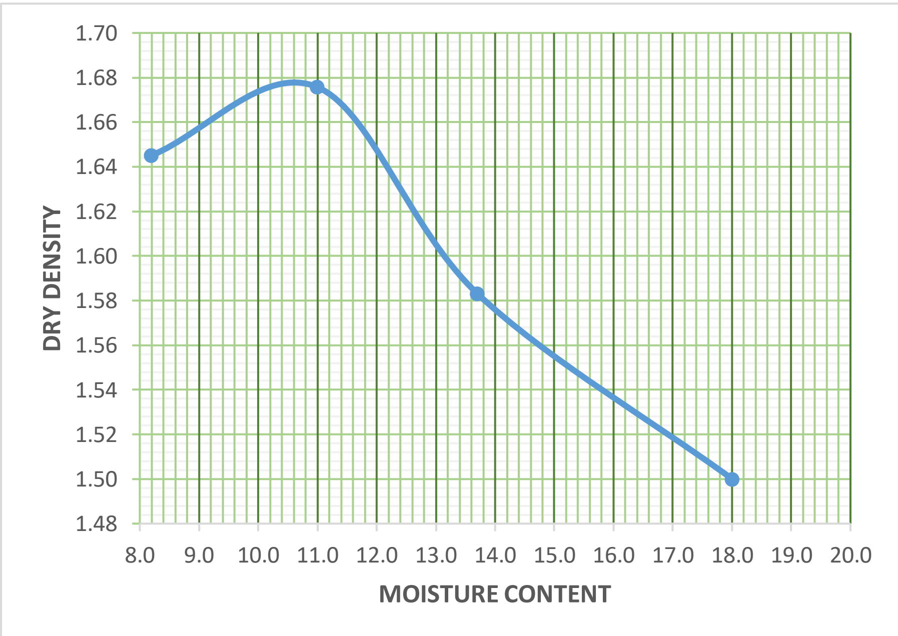


Figure 10. OMC and MDD for clay soil+10% MSD

Fig. 10 shows the compaction characteristics of the stabilized material, with an optimum moisture content (OMC) of 10.65% and maximum dry density (MDD) of 1.679 g/cm³. These values indicate improved compaction efficiency compared to untreated soil.

Clay soil + 15% MSD

Table 9. Dry density and moisture content calculations for clay soil+15% MSD

moisture added %	Volume (cm³)	Weight of mold (m)	Weight of mold + compacted soil (m)	bulk density, ɤb (g/cm³)	moisture content %	dry density ɣd (g/cm³)
6	2250	7170	11220	1.8	8.00	1.67
8	2250	7170	11410	1.88	10.2	1.71
10	2250	7170	11270	1.82	12.9	1.61
12	2250	7170	11200	1.79	15	1.56

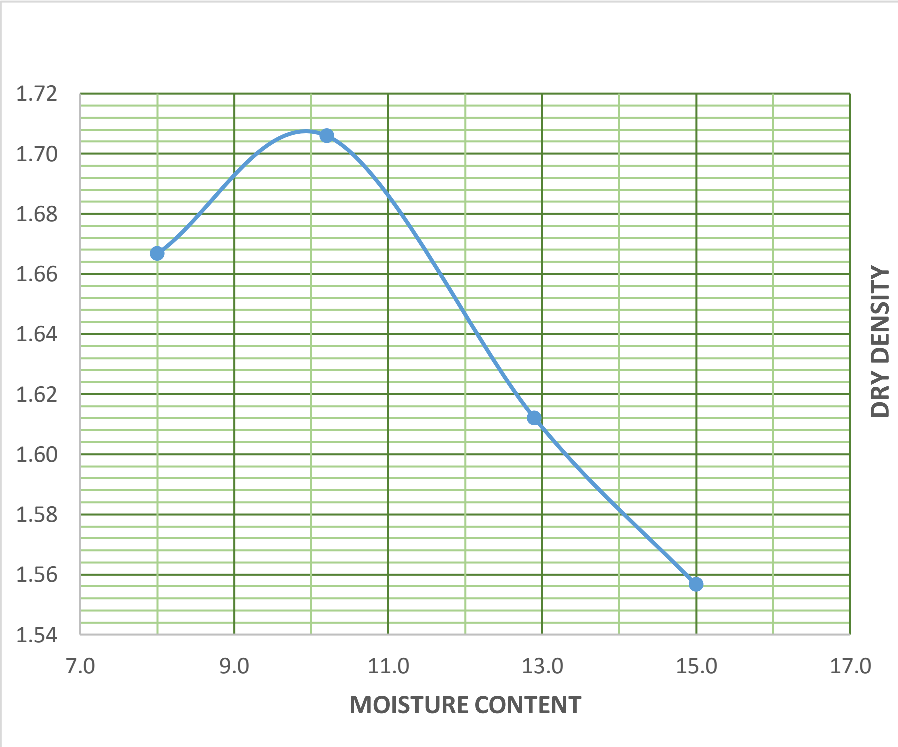


Figure 11. OMC and MDD for clay soil+15% MSD

Figure 11 demonstrates the compaction characteristics of the stabilized material, achieving a maximum dry density (MDD) of 1.708 g/cm³ at an optimum moisture content (OMC) of 9.90%. These results indicate superior compaction efficiency relative to standard values.

OVERALL COMPARISON

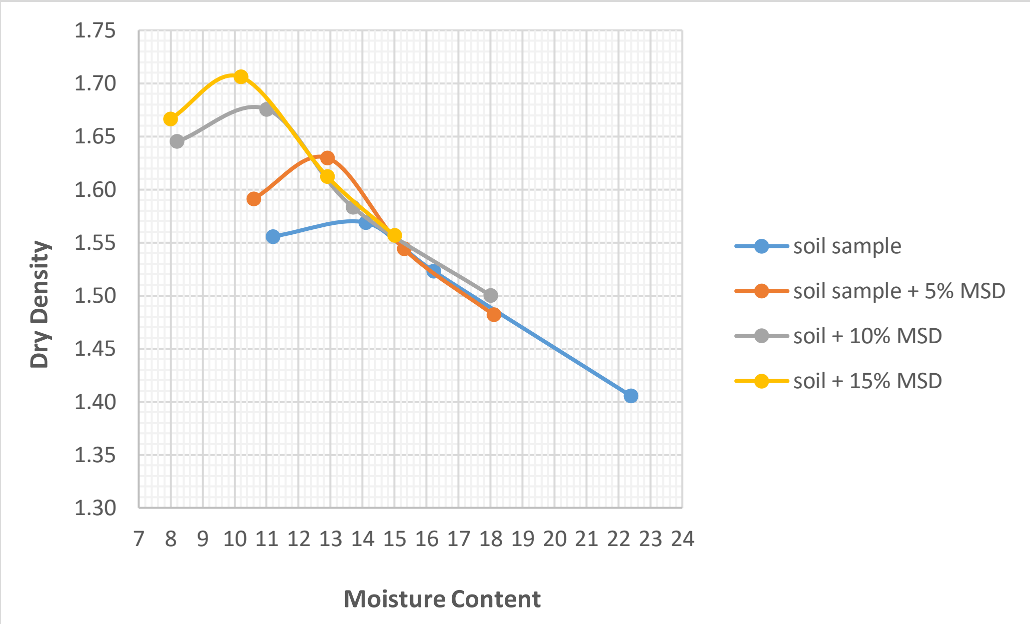


Figure 12. Overall comparison between OMC and MDD of all tested sample

Table 10. Data of all tests of all samples together

Sample	OMC (%)	MDD (g/cm³)	Decrease in OMC (%)	Increase in MDD (%)
soil	13.6	1.575		
soil+5% MSD	12.7	1.67	6.62	6.03
soil+10% MSD	10.65	1.679	21.69	6.60
soil+15% MSD	9.9	1.741	27.21	10.54

Figure 12, comparison between OMC and MDD of all tested samples," visually represents the relationship between the OMC and MDD for the untreated soil and the soil treated with 5%, 10%, and 15% MSD. The figure illustrates the trend in dry density as the moisture content varies, highlighting the impact of MSD on these parameters.

Table 10, presents the quantitative data for OMC and MDD, along with the percentage decrease in OMC and the percentage increase in MDD compared to the untreated soil sample. The results indicate that the addition of MSD leads to a significant reduction in OMC and an increase in MDD. Specifically, the OMC decreases by 6.62%, 21.69%, and 27.21% for the 5%, 10%, and 15% MSD treatments, respectively. Concurrently, the MDD increases by 6.03%, 6.60%, and 10.54% for the same treatments.

These findings suggest that MSD effectively enhances the compaction characteristics of the soil. The reduction in OMC indicates that less water is required to achieve maximum density, which can be advantageous in field applications. The increase in MDD demonstrates that the soil becomes denser and more stable with the addition of MSD. The data presented in this section underscore the potential of MSD as a beneficial additive for soil modification.

3.3 Un-Confined Compression Strength Test (UCS)

Table 11. Details of molds for UCS

Sample	Soil	5%	10%	15%
Dia (in)	1.5	1.5	1.5	1.5
Weight (g)	145.8	143.9	131.8	118.6

length (in)	2.82	2.8	2.86	2.79
Length/Dia	1.88	1.86	1.90	1.86
Area (in^2)	1.76	1.76	1.76	1.76625
Volume (in^3)	4.98	4.94	5.05	4.927838
Unit weight (g/in^3)	29.27	29.09	26.09	24.06735
Unit weight (g/cm^3)	1.68	1.73	1.77	1.82

Test performed on Clay soil + 0% MSD

This experimental study first characterized the native soil properties through standard geotechnical testing without any stabilizer. Following baseline establishment, marble stone dust (MSD) was introduced as a stabilizing agent. The collected test data revealed significant improvements in key soil parameters, as detailed below:

Table 12. Data collected from loading frame for clay soil in UCS

Dial Gauge reading	proving ring reading	Proving ring constant (kg/div)	deformation (mm)	Strain (%)	Corrected area A_o (mm^2)	Load (kg)	Axial Stress (kg/mm^2)
0	0	0.5	0	0.00	0.0	0	0.000
50	33	0.5	0.5	0.70	1147.5	16.5	0.014
100	63	0.5	1	1.40	1155.6	31.5	0.027
150	78	0.5	1.5	2.09	1163.9	39	0.034
200	91	0.5	2	2.79	1172.2	45.5	0.039
250	99	0.5	2.5	3.49	1180.7	49.5	0.042
300	92	0.5	3	4.19	1189.3	46	0.039
350	84	0.5	3.5	4.89	1198.1	42	0.035

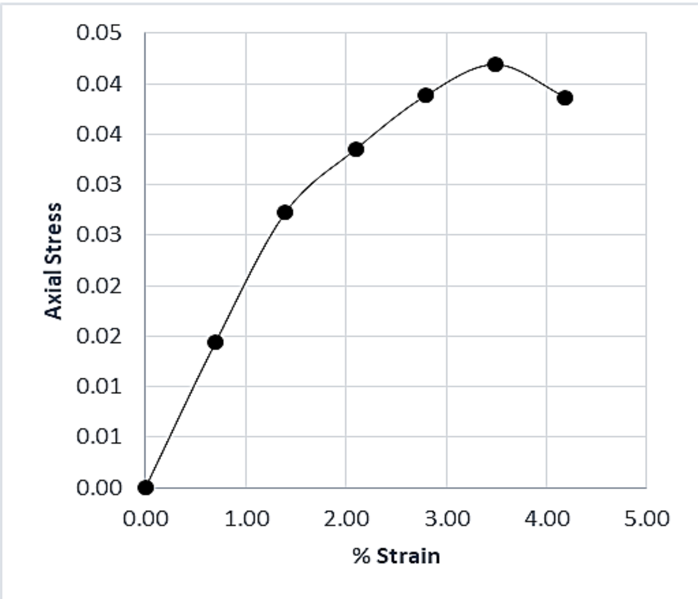


Figure 13. Strain vs. Stress graph for clay soil

Clay Soil + 5% MSD

Data collected from the test for clay soil + 5% marble stone dust is in table 13:

Table 13. Data collected from loading frame for clay soil+5% MSD in UCS

Dial Gauge reading	Proving ring reading	Proving ring constant (kg/div)	Deformation (mm)	Strain (%)	Corrected area A_o (mm^2)	Load (kg)	Axial Stress (kg/mm^2)
0	0	0.5	0	0.00	0.0	0	0.000
50	49	0.5	0.5	0.70	1147.5	24.5	0.021
100	68	0.5	1	1.40	1155.6	34	0.029
150	92	0.5	1.5	2.09	1163.9	46	0.040
200	108	0.5	2	2.79	1172.2	54	0.046
250	110	0.5	2.5	3.49	1180.7	55	0.047
300	103	0.5	3	4.19	1189.3	51.5	0.043
350	95	0.5	3.5	4.89	1198.1	47.5	0.040

Clay Soil + 10% MSD

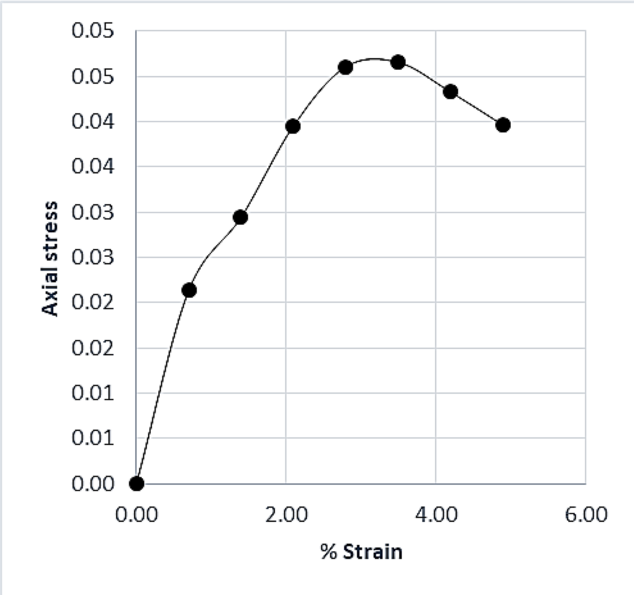


Figure 14. Strain vs. Stress graph for clay soil+5% MSD in UCS

Table 14. Data collected from loading frame for clay soil+10% MSD in UCS

Dial Gauge reading	Proving ring reading	Proving ring constant (kg/div)	Deformation (mm)	Strain (%)	Corrected area A_o (mm^2)	Load (kg)	Axial Stress (kg/mm^2)
0	0	0.5	0	0.00	0.0	0	0.000
50	51	0.5	0.5	0.70	1147.5	25.5	0.022
100	76	0.5	1	1.40	1155.6	38	0.033
150	96	0.5	1.5	2.09	1163.9	48	0.041
200	112	0.5	2	2.79	1172.2	56	0.048
250	114	0.5	2.5	3.49	1180.7	57	0.048

300	105	0.5	3	4.19	1189.3	52.5	0.044
350	98	0.5	3.5	4.89	1198.1	49	0.041

Clay Soil + 15% MSD

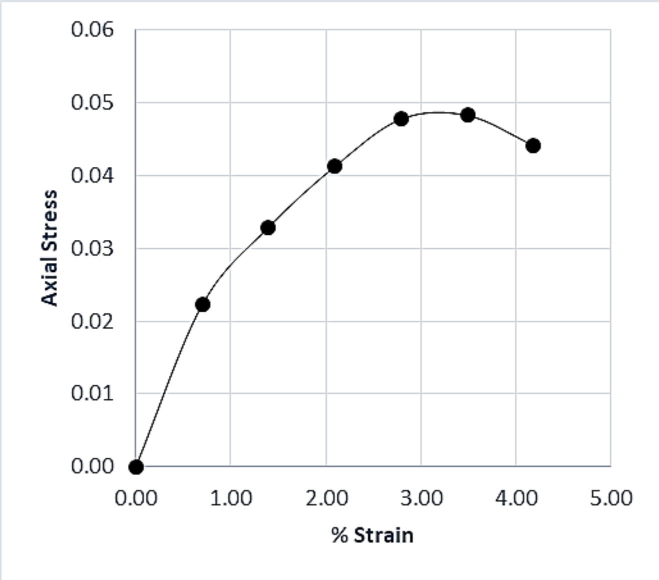


Figure 15. Strain vs. Stress graph for clay soil+10% MSD in UCS

Table 15. Data collected from loading frame for clay soil+15% MSD in UCS

Dial Gauge reading	Proving ring reading	Proving ring constant (kg/div)	Deformation (mm)	Strain (%)	Corrected area A_o (mm^2)	Load (kg)	Axial Stress (kg/mm^2)
0	0	0.5	0	0.00	0.00	0	0.000
50	54	0.5	0.5	0.70	1147.52	27	0.024
100	82	0.5	1	1.40	1155.65	41	0.035
150	103	0.5	1.5	2.09	1163.89	51.5	0.044
200	117	0.5	2	2.79	1172.25	58.5	0.050
250	116	0.5	2.5	3.49	1180.72	58	0.049
300	110	0.5	3	4.19	1189.33	55	0.046
350	101	0.5	3.5	4.89	1198.06	50.5	0.042

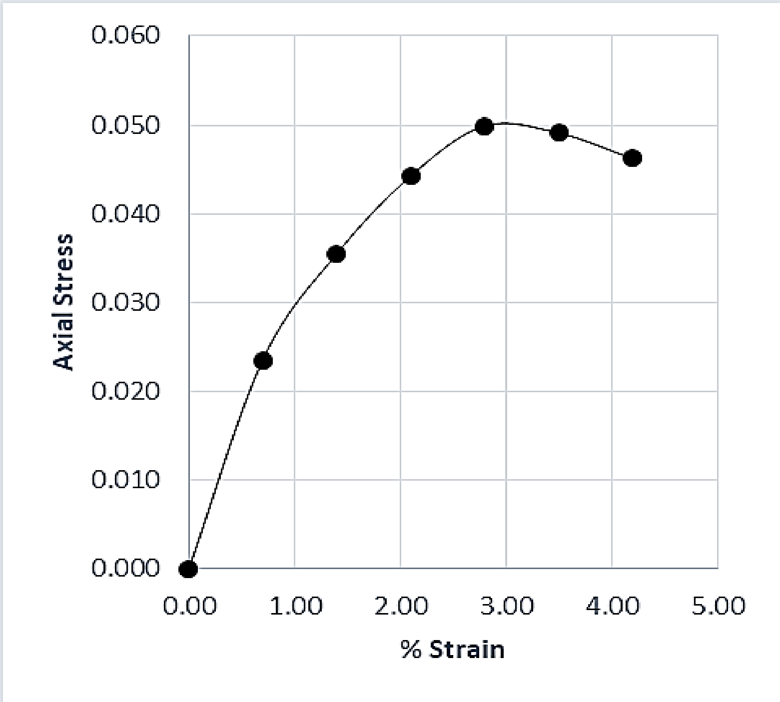


Figure 16. Strain vs. Stress graph for clay soil+15% MSD in UCS

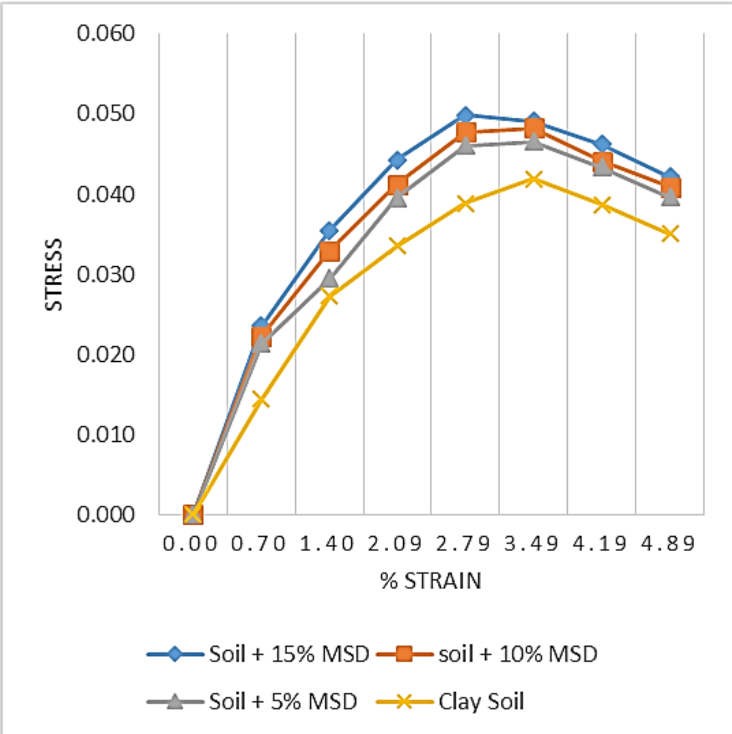


Figure 17. Overall comparison of all strain vs. stress graphs for all samples in UCS

Table 16. Summary of all axial stresses' values in UCS

Category	Axial Stress(kg/mm²)
Clay soil	0.042
Soil + 5% MSD	0.047
Soil + 10% MSD	0.048
Soil + 15% MSD	0.050
Increase (%)	15.99

Figure 17, provides a visual representation of the stress-strain behavior of the soil samples. The figure illustrates how the axial stress varies with strain for untreated soil and soil treated with 5%, 10%, and 15% MSD. The graph clearly shows that the axial stress increases with the addition of MSD, indicating enhanced shear strength.

Table 16, presents the quantitative data for axial stress for each sample. The results indicate that the axial stress increases from 0.042 kg/mm² for untreated clay soil to 0.047 kg/mm², 0.048 kg/mm², and 0.050 kg/mm² for soil treated with 5%, 10%, and 15% MSD, respectively. This represents an overall increase of 15.99% in axial stress with the addition of MSD as shown in fig 18.

These findings demonstrate that MSD significantly improves the shear strength of the soil, as evidenced by the increase in axial stress. The enhanced shear strength is crucial for applications where soil stability and load-bearing capacity are critical, such as in foundation engineering and slope stabilization.

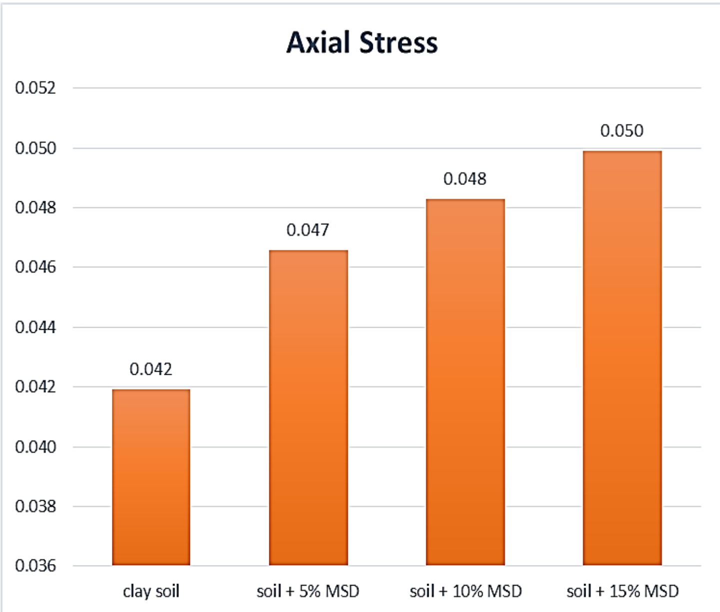


Figure 18. Bar chart of all axial stresses' value in UCS

3.4 CALIFORNIA BEARING RATIO TEST

Test performed on clay soil + 0% MSD

The CBR test was first conducted on untreated clay soil to establish baseline properties prior to stabilization. The initial test results are presented below

Table 17. data calculation for CBR value for Clay soil

Penetration (mm)	Proving ring reading	Proving ring constant (kg/div)	Load (kg)	CBR (%)
0.5	8	5	40	-
1	15	5	75	-
1.5	22	5	110	-
2	31	5	155	-
2.5	40	5	200	20
3	45	5	225	-
4	51	5	255	-
5	56	5	280	18.67
7.5	73	5	365	-
10	81	5	405	-
12.5	112	5	560	-

Clay Soil + 5% MSD

Table 18. data calculation for CBR value for Clay soil+5% MSD

Penetration (mm)	Proving ring reading	Proving ring constant (kg/div)	Load (kg)	CBR (%)
0.5	10	5	50	-
1	18	5	90	-
1.5	25	5	125	-
2	36	5	180	-
2.5	43	5	215	21.5
3	47	5	235	-
4	56	5	280	-
5	62	5	310	20.67
7.5	78	5	390	-
10	86	5	430	-
12.5	119	5	595	-

Clay Soil + 10% MSD

Table 19. data calculation for CBR value for Clay soil+10% MSD

Penetration (mm)	Proving ring reading	Proving ring constant (kg/div)	Load (kg)	CBR (%)
0.5	14	5	70	-
1	21	5	105	-
1.5	28	5	140	-
2	38	5	190	-
2.5	46	5	230	23
3	50	5	250	-
4	60	5	300	-
5	65	5	325	21.67
7.5	81	5	405	-

10	99	5	495	-
12.5	134	5	670	-

Clay Soil + 15% MSD

Table 20. data calculation for CBR value for Clay soil+15% MSD

Penetration (mm)	proving ring reading	proving ring constant (kg/div)	Load (kg)	CBR (%)
0.5	17	5	85	-
1	26	5	130	-
1.5	31	5	155	-
2	44	5	220	-
2.5	49	5	245	24.5
3	54	5	270	-
4	65	5	325	-
5	69	5	345	23
7.5	87	5	435	-
10	107	5	535	-
12.5	144	5	720	-

OVERALL COMPARISON:

Analysis of Tables 17-20 demonstrates a clear correlation between MSD content and improved bearing capacity. The CBR values show progressive enhancement with increasing MSD percentages, as evidenced by the results combined in table 21:

Table 21. summary of all CBR values of all samples and % increase

category	CBR value (%)	Increase in CBR Value (%)
Soil	20	
soil + 5% MSD	21.5	7.5
soil + 10% MSD	23	15.0
soil + 15% MSD	24.5	22.5

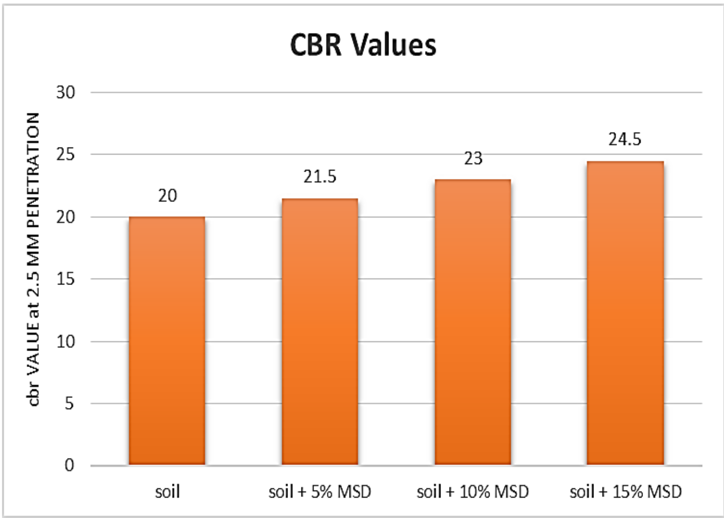


Figure 19 graphical summary of all CBR values of all samples

Table 21, provides the quantitative data for the CBR values of untreated soil and soil treated with 5%, 10%, and 15% MSD. The results indicate a clear trend: the CBR values increase with the addition of MSD. Specifically, the CBR value rises from 20% for untreated soil to 21.5%, 23%, and 24.5% for soil treated with 5%, 10%, and 15% MSD, respectively. This represents percentage increases of 7.5%, 15.0%, and 22.5% for the respective MSD treatments.

Figure 19, visually represents these findings. The graph illustrates the progressive increase in CBR values with higher percentages of MSD, reinforcing the data presented in Table 21. These results demonstrate that the addition of MSD significantly enhances the load-bearing capacity of the soil. The increased CBR values indicate improved soil strength, which is essential for constructing stable and durable roadways and other infrastructure projects.

CONCLUSION

From the research carried out to check the engineering properties after addition of a stabilizer i.e. Marble Stone Dust, the following main points are concluded:

The addition of MSD significantly increases the cohesion (C) and the angle of internal friction (Φ) of the soil. This improvement in shear strength parameters indicates that MSD-treated soil is more resistant to shear failure, making it suitable for applications requiring higher stability.

The research demonstrates that with the increase in MSD content, the Optimum Moisture Content (OMC) decreases, while the Maximum Dry Density (MDD) increases. This suggests that MSD-treated soil requires less water to achieve optimal compaction and attains a denser state, which is beneficial for construction projects.

The axial stresses or unconfined compression strength of the soil increase with the addition of MSD. This enhancement in UCS indicates that MSD-treated soil can withstand higher loads, which is crucial for foundation and structural support.

The California Bearing Ratio (CBR) values increase with the addition of MSD, indicating improved load-bearing capacity of the soil. This makes MSD-treated soil more suitable for subgrade and base courses in road construction. The research conclusively shows that MSD is an effective stabilizer for clayey soil, enhancing multiple engineering properties such as shear strength, compaction characteristics, unconfined compression strength, and load-bearing capacity.

These findings underscore the potential of MSD as a valuable additive for soil stabilization in various geotechnical and civil engineering applications. The use of MSD not only improves the mechanical properties of soil but also contributes to more sustainable construction practices by utilizing industrial by-products

Engineering properties	Clayey Soil	Clayey soil + 5% MSD	Clayey soil + 10% MSD	Clayey soil + 15% MSD	Properties
Cohesion, c (psi)	1.55	2.24	2.35	2.35	Increased
Angle of internal friction, ϕ (degree)	30.55	34.46	34.84	38.44	Increased
OMC (%)	13.6	12.7	10.65	9.9	Decreased
MDD(g/cm^3)	1.575	1.67	1.679	1.741	Increased
UCS (kg/mm^2)	0.42	0.47	0.48	0.499	Increased
CBR (%)	20	21.5	23	24.5	Increased

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