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Experimental Study on the Stabilization of Expansive Soil with Blended Fine Cinder Gravel and Waste Marble Dust: A Case Study of Jimma Town

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ABSTRACT

This study investigates the potential of Waste Marble Dust (WMD) and fine Cinder Gravel (CG) to enhance the engineering properties of expansive soils, which are prone to volume changes due to moisture fluctuations. The research aimed to stabilize expansive soils, classified as A-7-6(37) in the AASHTO system and CH in the USCS system, for use as sub-grade materials in road construction. Mechanical stabilization technique was used in this study. Soil material is dried in air and mixed with 8%, 12%, 16%, and 24% of CG and MD. The key findings include; Plasticity Index reduced from 34.09% to 10.28%, Free Swell Index decreased from 81.8% to 36.4%, Optimum Moisture Content decreased from 24.02% to 14.00%, Maximum Dry Density increased from 14.22 kN/m³ to 16.19 kN/m³, California Bearing Ratio (CBR) increased from 1.00% to 22.69% and Unconfined Compressive Strength (UCS) increased from 112.9 kPa to 311.7 kPa. Optimal stabilization was achieved at a 16% replacement of both WMD and CG, improving the soil's strength significantly. This study concludes that WMD and CG are effective stabilizers for expansive soils, meeting the requirements for sub-grade material in road construction and offering improved durability and performance.

Keywords: Expansive soil, Stabilization, Swelling, Shrinkage, Waste marble dust, Cinder gravel, Sub-grade soil, CBR value.

INTRODUCTION

In civil engineering, understanding the geotechnical characteristics of soil is essential, as these characteristics play a fundamental role in construction and design. Soft soils, which are commonly found in sedimentary environments, such as alluvial or marine deposits, exhibit low stiffness, high compressibility, and low shear strength. These properties make soft soils highly susceptible to deformation under load (Sorsa et al., 2020). Expansive soils are characterized by their ability to undergo significant volume changes; they swell when moisture increases and shrink during dry conditions. This behavior poses substantial risks to infrastructure, particularly to pavements and lightweight structures. The high swelling potential and low strength of expansive soils can lead to cracking and distress in pavements, resulting in significant financial losses and potential structural failures (Amena et al., 2022; Liang et al., 2024; Talib et al., 2024; Dessisa, 2022; Samer et al., 2023; Wang, 2021; Gang et al., 2023; Tefera et al., 2023).

Challenges with construction materials are evident in Africa, Australia, Europe, India, South America, the United States, and in parts of Canada. In tropical regions, unstable and low-strength soils can lead to significant problems. Soil stabilization is essential to enhance the soil's strength and durability, ensuring the long-term success of infrastructure projects in these areas (Sorsa et al, 2020; Newill & Assaye, 1980).

In Ethiopia, expansive soils cover an estimated area of 23.7 million acres, predominantly in the central region along major highways, such as Addis-Ambo, Addis-Weliso, Addis-Debrebirhan, Addis-Gohatsion, and Addis-Modjo. Additionally, expansive soils are found in areas like Mekele, Gambella, and southwestern Ethiopia, presenting significant challenges for infrastructure development in these regions (Mamuye & Geremew, 2018), particularly in towns, such as Jimma, presenting significant challenges for road construction. Weak sub-grade soil negatively impacts arterial asphalt pavements and cobblestone roads, resulting in higher maintenance costs and safety risks (Fentaw et al., 2021; Geremew, 2018).

To enhance expansive soil’s suitability for construction, various stabilizers and techniques are used. The main challenge is to find effective soil stabilizers that improve geotechnical properties while considering environmental and economic factors. This balance is essential for sustainable construction on expansive soils (Zada et al., 2023). The primary goals of soil stabilization are to improve shear strength, load-bearing capacity, permeability, and durability. There are two main techniques for stabilization; mechanical and chemical. Mechanical stabilization involves mixing expansive soils with non-expansive soils to improve the overall stability, particularly for coarse-grained soils. Chemical stabilization is more effective for clayey soils (Geremew, 2018; Dharini et al., 2023).

Researchers used cinder gravel for expansive soil stabilization, focusing on improving compaction and stability. Cinder gravel, with high water absorption and rich siliceous and aluminous minerals, combines with waste marble dust (WMD) to enhance soil cementing properties over time. WMD, high in calcium, acts as an effective cement substitute, increasing the strength and durability of expansive soils (Luo et al., 2020; Wang et al., 2020; Jassim et al., 2022; Niraj & Sharma, 2023; Pateriya et al., 2022; Shinde et al., 2024).

Several researchers have investigated the use of marble dust in concrete applications. Misra et al. (2010) conducted field studies, where they replaced 20% of the soil with slurry marble dust. They observed an increase in the California Bearing Ratio (CBR) value from 12% to 17%, concluding that substantial amounts of marble waste dust could be utilized in constructing road surfaces and embankments. Jassim et al. (2022) explored the use of marble dust as a stabilizing additive for tropical soil. Their findings indicated a reduction in plasticity by 22% to 25% and an increase in unconfined compressive strength (UCS) by 182.44% with the addition of 3% marble dust under various curing conditions. Singh et al. (2017) examined the partial substitution of cement with marble slurry in concrete. Their results showed an improvement in the mechanical properties of concrete with up to 15% cement replacement, confirming marble dust's effectiveness as a filler material. Firat et al. (2017) conducted laboratory tests to evaluate the effectiveness of waste materials, including marble dust, as road construction materials. The results revealed a significant increase in strength when marble dust was mixed with soil.

Fine cinder gravel also serves as an alternative soil stabilizer in road construction. According to the findings of Efamo and Adera (2024) a mixture containing 5% hydrated lime and 35% cinder ash demonstrated a remarkable increase in compressive strength by 448.62% and in California Bearing Ratio (CBR) by 374% after being cured for 28 days. Hearn et al. (2019) investigated the performance of cinder gravel, which exhibited good CBR values of 45% when combined with 20% plastic fines from weathered cinder gravel and 30% crushed basalt rock. The typical maximum dry density values obtained using this method ranged from 14.27 kN/m^3 to 17.66 kN/m^3. These values, along with the optimal moisture levels associated with them, can be utilized for construction purposes. Collectively, these studies suggest that cinder gravel and marble dust can effectively stabilize expansive soil and enhance its strength.

Recently, different other additives are used in stabilization of expansive soil, such as slag-nano silica (Xiushan, 2021), crush dust (Shanmuga et al., 2018), cement and lime (Abdelzaher et al., 2024), fly ash (FA) (Dereje, 2023), steel factory dust (Zozk Kawa Abdalqadir, 2024), zeolitic tuff (Hussein, 2023), and agricultural waste additives, like coffee husk, rice husk, sawdust, wheat straw, cornhusk, sugarcane bagasse, and bamboo powder, are used for stabilizing expansive soil in sub-grade (Frehaileab, 2023). However, there is limited literature on the combined use of marble dust and fine cinder gravel as stabilizers for expansive soil. This study focused on Jimma town, a key urban center in Ethiopia, where residual tropical soils create challenges for construction, particularly affecting asphalt roads and cobblestone pavements (Muhammed & Teferra, 2014).

In Jimma, expansive soils, characterized by high swelling indices and low California Bearing Ratio (CBR) values, poorly resist axial loads, leading to pavement issues (Geremew, 2018). One innovative approach is soil treatment with stabilizing materials to enhance engineering properties through mechanical stabilization (Fentaw et al., 2021). This research focuses on using locally available industrial waste materials, specifically marble dust and cinder gravel, as stabilizers. The study was conducted in two main stages. In the first stage, the engineering characteristics of the natural soil was examined. In the second stage, the additives (fine cinder gravel and marble dust mixed with the air-dried soil at dosages of 8%, 12%, 16%, and 24% of soil mass to enhance its suitability for sub-grade formation.

MATERIALS AND METHODS

Materials

Expansive Soil

The expansive soil sample for this research was collected along the Jimma-Mizan road in Becho Bore Kebele, near Shanan Gibe hospital, and Bosa Addis. Three sample pits were excavated at 500-meter intervals, retrieving disturbed samples from a depth of 2.0 meters.

Both soil samples were classified as high expansive clays A-7-6 (37). The Bore sample is weaker than the Bosa Addis sample, necessitating specific stabilization strategies. Since over 40% of Jimma town's asphalt construction occur on Bore sites, an iterative approach to experimentation and treatment is crucial. The basic natural properties of soil are summarized in Table 1, and the grain size distribution of natural soil is shown in Figure (3).

Cinder Gravel Dust

Cinder gravel, also known as volcanic gravel or scoria, is a porous, lightweight aggregate formed from volcanic eruptions. Its rough, vesicular surface and high porosity make it ideal for various construction applications (Wang et al., 2021, Hearn et al., 2019, Negesa et al., 2023). The cinder gravel used in this research was collected from Kunurus Kebele, near Chefo Gebreal Church, along the Addis Abeba to Jimma roadside in the southwest Shewa zone.

Waste Marble Dust

The waste marble dust (WMD) used in this research was sourced from the Addis Ababa National Mining Enterprise, Gulele Marble Industry. The WMD, collected from the factory's sludge drain, is a by-product of the water-jet cutting process of marble blocks.

Methods

This research addresses key questions through experimental findings, combining a literature review with laboratory experiments. It evaluates the performance of expansive sub-grade soil and stabilization mix designs using blended cinder gravel and waste marble dust as stabilizers in varying ratios.

The study involves reviewing relevant literature, collecting samples, and analyzing the physical and chemical properties of the materials. Test results will assess the impact of the stabilizers on expansive sub-grade soil, with findings and recommendations presented in the conclusion. Details of the study design are illustrated in Figure (1).

Experimental Tests

Soil Grain Size Analysis Test and Soil Classification

Grain size analysis quantifies the proportions of different particle sizes in a soil sample. The gradation of coarse-grained soil retained on the No. 200 sieve was determined using sieve analysis per ASTM D6913 (ASTM International, 2017) specification. For fine-grained soil that passed the No. 200 sieve, hydrometer analysis was conducted according to ASTM D7928 (ASTM International, 2017), revealing 12% sand, 48% clay and 40% silt. The combined particle size distribution curve is shown in Figure (3), and the soil is classified using AASHTO, USC, and Skempton systems.

Chemical Composition of Natural Soil

Understanding the chemical composition of expansive soil is crucial for engineering, as it predicts soil behavior. Tests on soil samples (see Table 3) revealed that Silicon Dioxide (SiO_2), Aluminum Oxide (Al_2O_3), and Iron Oxide (Fe_2O_3) accounted for 90.76%, exceeding the ASTM C-618 requirement of 70%, which indicates good pozzolanic properties, making the soil suitable for road construction due to its cementitious compounds.

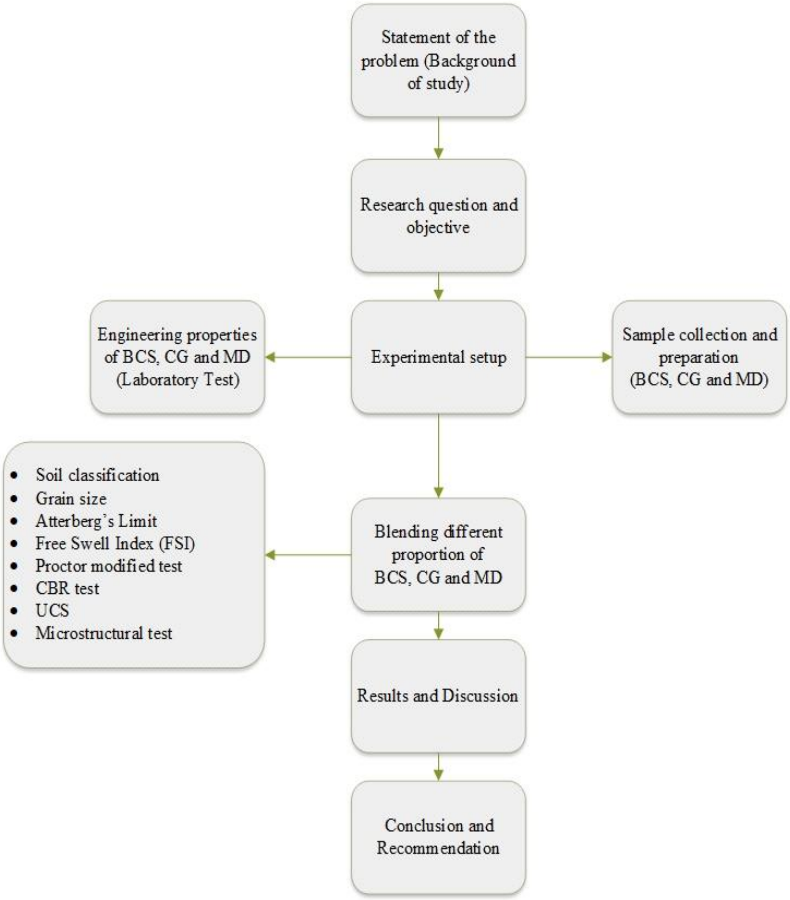

Figure (1): Research design frame

Chemical Composition of Fine Cinder Gravel Dust (CG)

The chemical composition of Cinder Gravel dust (CG) varies based on its volcanic origin, typically containing elements, such as silicon, aluminum, iron, calcium, potassium, and sodium. According to ASTM C618 standards, CG qualifies as a pozzolan if its combined Silicon Dioxide (SiO_2), Aluminum Oxide (Al_2O_3), and Iron Oxide (Fe_2O_3) content exceeds 70%. Laboratory analysis confirmed that CG contains 74.75% of these compounds, surpassing the ASTM 618 requirement, as shown in Table 3. Additionally, CG exhibits cementitious properties due to the presence of compounds, like calcium oxide, alumina, and iron oxide, making it suitable as a pozzolanic material.

Chemical Composition of Waste Marble Dust (MD)

Waste Marble Dust (WMD) is predominantly composed of calcium carbonate, which reacts with Silicon Dioxide (SiO_2), Aluminum Oxide (Al_2O_3), and Iron Oxide (Fe_2O_3) to produce cementitious compounds that enhance the soil's pozzolanic properties. Chemical composition tests on Waste Marble Dust (WMD), as shown in Table 3, confirm its pozzolanic properties. Despite its non-compliance with ASTM C618, marble dust offers several benefits that justify its use. Research confirms that it is readily available, environmentally sustainable, and possesses unique properties that make it suitable for soil stabilization (Jassim et al., 2022, Abdelkader et al., 2021). MD reacts with calcium hydroxide [$Ca(OH)_2$] in the presence of water to form calcium silicate hydrate (C-S-H), a cementitious compound. This reaction makes WMD effective in stabilizing black cotton soil by creating a more homogeneous mix when blended with other soil components or agents, improving the soil's structural integrity.

Mixture Used for Soil Stabilization (Mechanical Stabilization)

The soil samples were air-dried, reduced to required size as per test type and pulverized, with additives mixed in by adding them to the soil and dry mixing. Various blends of cinder gravel and waste marble dust were combined in four ratios for cinder (8%, 12%, 16%, and 24% of the soil's dry weight) and marble dust (8%, 12%, 16%, and 24%). Five total combinations were evaluated, including untreated soil as a reference. Table 2 summarizes the cinder and marble dust mixtures.

Table 1. Basic natural soil properties

Parameters	Test Sample Site 1 Jimma Town's Expansive Soil Bacho Bore	Test Sample Site 2 Jimma Town's Expansive Soil Bosa Addis
Natural Moisture Content, %.	10.8	10.52
Percentage of Passing ASTM No.200 sieve, %	97.27	93.8
Liquid Limit, %	70	68.67
Plastic Limit, %	36	32.65
Plasticity Index, %	34	26.2
AASHTO Soil Classification	A-7-6 (37), Silt=40%, clay=48%	A-7-5 (37)
USCS	CH	CH
Maximum Dry Density= g/cm^3	1.41	1.26
Specific Gravity	2.12	2.6
Free Swell Index, %	81.82	79.81
Optimum Moisture Content, %	24.02	35.8
Soaked CBR Value, %	1	1.5
CBR Swell, %	2.21	2.51
Cohesion C (kPa)	56.4	54.3
Unconfined Compressive Strength qu (kPa)	112.9	113.5
Color	Dark Gray	Gray

Table 2. Blends of materials utilized in the study

S. No.	Mixture	% Soil	% Cinder Gravel	% Waste Marble Dust
1	Natural soil	100	0	0
2	Soil+8% CG+8% MD	84	8	8
3	Soil +12% CG+12% MD	76	12	12
4	Soil +16%CG +16% MD	68	16	16
5	Soil +24% CG+24% MD	52	24	24

Table 3. Chemical composition of soil, cinder gravel and marble dust

Composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	MnO	P_2O_5	TiO_2	H_2O	LoI
MD	2.03	0.01	0.13	51.18	4.6	0.74	0.28	0.06	0.67	0.61	0.13	41.4
CG	52	12.38	10.37	10.33	7.1	2.88	0.9	0.04	0.44	0.8	0.87	2.02
BCS	82.86	4.12	3.78	0.98	0.46	1.22	1.04	0.16	0.05	0.73	1.35	3.78

RESULTS AND DISCUSSION

Engineering Properties of Untreated Expansive Soil and Treated Soil

Laboratory tests conducted on the natural soil sample reveal that 97.27% of the soil passes through the No. 200 sieve, indicating a high fine content. The soil exhibits a liquid limit of 70%, a plastic limit of 36%, and a plasticity index of 34%. The maximum dry density (MDD) is 13.83 kN/m³, and the optimum moisture content (OMC) is 24.02%. The soil has a California Bearing Ratio (CBR) of 1%, an unconfined compressive strength (UCS) of 112.9 kPa, and a free swell index (FSI) of 81.82%.

According to the AASHTO classification system, the soil is classified as A-7-6 (37), while under the Unified Soil Classification System (USCS), it is classified as CH. Based on Skempton's criteria, the soil has a low (inactive) potential for expansion. Skempton classifies soils based on their activity coefficient (Ac). The Ac values for both the natural soil and the additive modified soil are presented in Table 4. These classifications suggest that the soil is highly expansive, with a significant potential for volume change in response to moisture variations. The engineering properties of soil are summarized in Table 1, while Table 2 summarizes the cinder gravel and marble dust mixtures.

Table 4. Relation between clay activity coefficient and the potential of expansion

Parameters	PI	% Finer than 2 µm=	48%
		$Ac = \frac{PI}{\%finer\ than\ 2\mu m}$	Potential expansion
Natural soil (ES)	34.09	0.710	Low (inactive)
ES +8% CG +8% MD	11.41	0.240	Low (inactive)
ES +12% CG +12% MD	10.4	0.217	Low (inactive)
ES +16% CG +16% MD	10.28	0.214	Low (inactive)
ES +24% CG +24% MD	10.99	0.230	Low (inactive)
Skempton classified potential expansion of soil depending on Ac value. If Ac<0.75=low (inactive), if 0.75<Ac<1.25=medium and if Ac>1.25=high (active) potential expansion			

Table 4 shows that the activity coefficient (Ac) values for all treated soil samples are significantly lower than that of natural soil (0.71), with treated samples ranging from 0.214 to 0.240, placing them in the low potential expansion category. The addition of cinder gravel (CG) and marble dust (MD) improves the soil by reducing its plasticity and activity, making it more suitable for stabilization and enhancing its load-bearing capacity.

The reduction in plasticity index (PI) and activity coefficient (Ac) is due to that the cinder gravel introduces coarser particles that dilute finer clay, while marble dust fills voids between particles, creating a denser structure that reduces water retention. This combination results in a more stable, less plastic, soil, which is advantageous for engineering applications, as it decreases the risk of differential settlement and improves overall stability.

Effect of Cinder Gravel and Marble Dust on Atterberg Limit

The Atterberg liquid limit (LL), plastic limit (PL), and plasticity index (PI) were determined following (AASHTO, 2020) standard test methods. An oven-dried soil sample passing through a 425-µm sieve was soaked for 24 hours and tested using the Casagrande method, with four trials to ensure accuracy. Results presented in Table 5 and Figure (2) how significant improvements in the PI of expansive black cotton soil treated with varying proportions of marble dust (MD) and cinder gravel (CG).

Adding 8%, 12%, 16%, and 24% MD and CG reduced the PI by 67%, 69%, 70% and 68%, respectively. The optimal blend, with 16% MD and 16% CG, achieved a PI of 10.28, with a 70% decrease. These treatments enhance soil stability, demonstrating that increased stabilizer content improves plasticity characteristics. Marble dust contains calcium carbonate, which can react with the clay minerals in the soil. This reaction can lead to the formation of cementitious compounds that further reduce the soil's plasticity (Jassim et al., 2022; Sabat and Nanda, 2011; Mahawayi, 2022).

The liquid limit (LL) and plastic limit (PL) of soil decrease with increasing percentages of cinder gravel (CG) and marble dust (MD) from 69.73% to 30.67%, and from 35.64% to 20.38%, respectively. Marble, which contains calcium carbonate ($CaCO_3$), reacts with soil alumina and silica to form cementitious compounds that reduce plasticity and enhance stability. Similarly, cinder gravel, rich in silica and alumina, participates in pozzolanic reactions that further stabilize the soil. CG and MD lead to an exchange of cations, such as calcium and magnesium, with sodium ions. This exchange decreases the soil's tendency to swell and shrink, resulting in lower liquid limits (LL) and plasticity indices (PI).

Table 5. Atterberg limit test results

Sample	LL (%)	PL (%)	PI (%)	Decrease in PI (%)	ERA (2002) requirement	Remark
Expansive soil (ES)	69.73	35.64	34.09	0	Pi < 30%	Poor
ES +8 % MD + 8 % CG	35.28	24.87	11.41	67%		Satisfied
ES +12 % MD + 12 % CG	32.47	22.07	10.4	69%		Satisfied
ES+ 16 % MD + 16 % CG	30.67	20.38	10.28	70%		Satisfied
ES+ 24 %MD + 24 %CG	32.32	21.33	10.99	68%		Satisfied

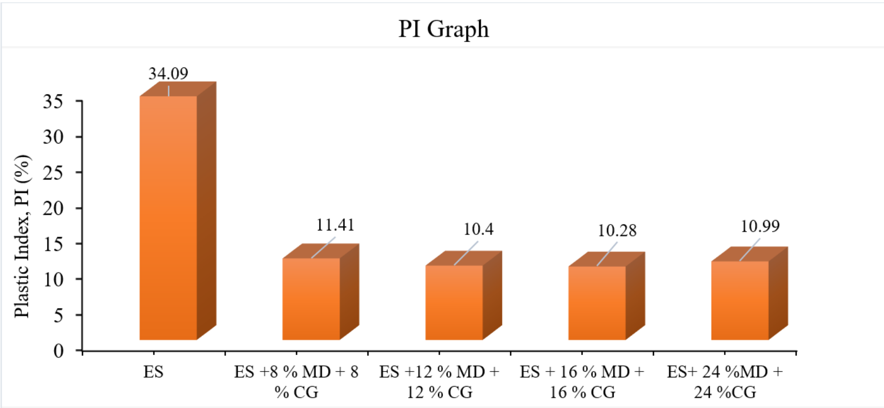

Figure (2): Atterberg limit test results

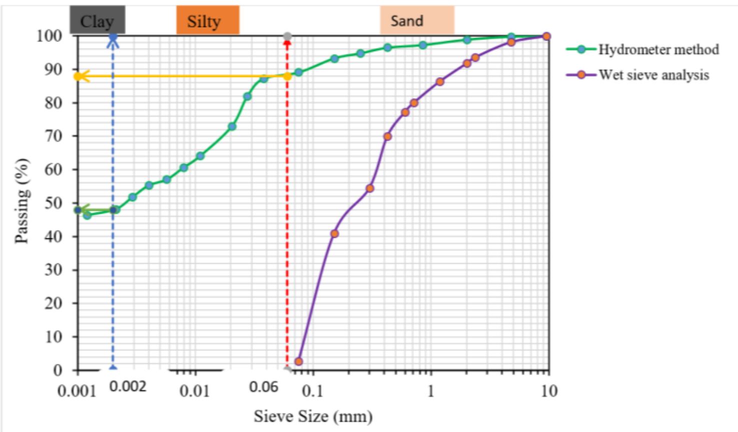

Figure (3): Natural soil particle size distribution curve

Figure (3) illustrates the particle size distribution of a soil sample using two different methods: the hydrometer method and wet sieve analysis. This graph is interesting and relevant, because it provides a comprehensive view of the soil particle size distribution, which is crucial for understanding the soil's physical properties and behavior. From the graph, the soil is classified as clay 48% (<0.002mm), silty 40% (0.06 mm-0.002 mm), and 12% (0.06mm-2mm) of sand soil according to MIT soil classification. The results show that the soil is a highly expansive soil. This information is essential for various engineering applications, such as foundation design, soil compaction, and erosion control. The combination of both methods allows for a complete analysis of both fine and coarse particles, giving a more accurate representation of the soil sample.

Effect of Cinder Gravel and Marble Dust on Unit Weight of Soil

Modified Proctor compaction tests were conducted on the soil to establish the relationship between moisture content and dry density for specific compaction efforts, as outlined in (AASHTO, 1995). Figure (4) illustrates that as the percentage of cinder gravel (CG) and marble dust (MD) increases, the maximum dry density increases from 14.22 kN/m^3 to 16.19kN/m^3, while the optimum moisture content decreases from 24.02% to 14%. This trend indicates improved soil stability and reduced water absorption.

At 16% CG and 16% MD, the soil achieves its highest density and lowest moisture content, making this combination the most effective for enhancing the soil's properties. However, increasing the CG and MD content to 24% results in a slight reduction in density compared to the 16% mix, along with an increase in moisture content. This suggests that 16% is the optimal percentage for the best improvement in soil characteristics.

The data indicates that the ideal mix for enhancing the properties of expansive black cotton soil is 16% CG and 16% MD. This combination yields the highest density and the lowest moisture content, signifying optimal compaction and stability. Utilizing this optimal mix in construction projects may lead to more stable foundations and minimize issues related to soil expansion and contraction. The trends observed are consistent with past research (Amadi, 2014; Mishra et al., 2022; Sambre et al., 2024), which indicates that the addition of stabilizing agents, such as cement, quarry dust, rice husk ash (RHA), lime, and fly ash, generally increases the Maximum Dry Density (MDD) and decreases the Optimum Moisture Content (OMC) of expansive soils.

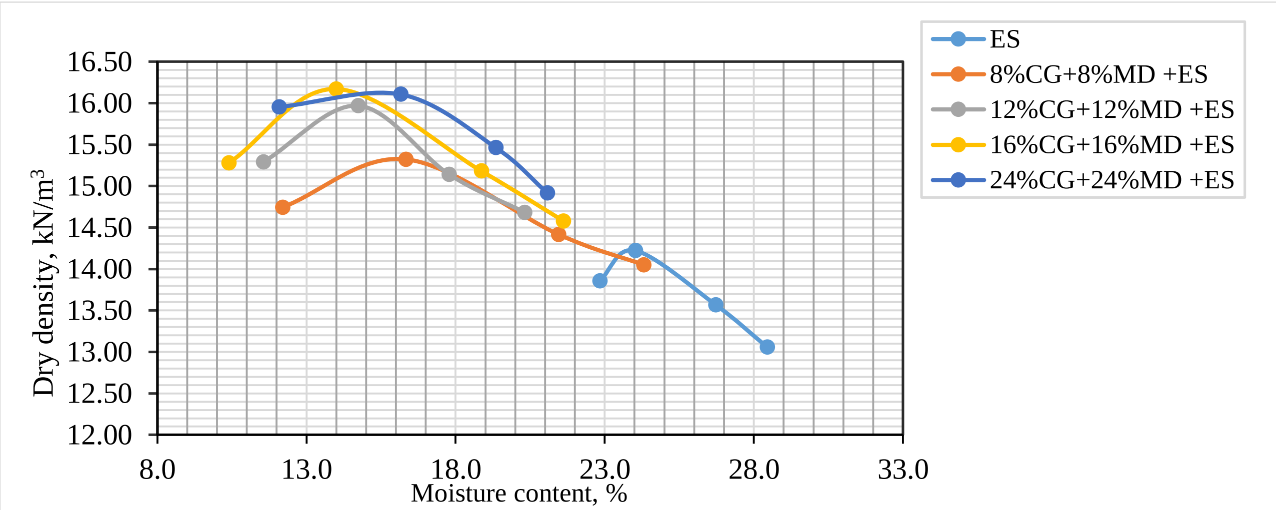

Figure (4): Summary of OMC and MDD of the sample

Effect of Cinder Gravel and Marble Dust on CBR and CBR Swell

According to AASHTO T-193, the California Bearing Ratio (CBR) values of expansive black cotton soil (EBCS) and its mixes with varied percentages of cinder gravel (CG) and marble dust (MD) were determined after a 96-hour soaking period under a surcharge weight of 4.55 kg (AASHTO, 1993). Figure

(5) shows that the CBR value for BCS is extremely low (1%), suggesting inadequate load-bearing capability. The CBR value increases as the proportion of stabilizer increases, with the greatest improvement recorded at 16% CG and 16% MD, attaining a CBR value of (22.69%), considerably over the ERA standard, showing a considerable increase in load-bearing capability. Interestingly, CBR value drops with 24% stabilizer concentration, indicating an ideal range for CG and MD addition. The addition of mixed waste marble dust and cinder gravel (8%, 12%, 16%, and 24%) increased the CBR by 535%, 1173%, 2169%, and 362%, respectively.

The CBR swell falls from 14.6% to 2.96% by 79.73%, the soil's load-bearing ability improves and its inclination to expand when being wet diminishes. This association shows that the soil has been stabilized, most likely by the addition of elements, like MD-CG dust, which lowers the soil's expansiveness. Higher CBR values typically imply more stable soil that can better support loads, while a lower swell index indicates less susceptibility to volume changes due to moisture fluctuations. These reduced swell characteristics are generally recognized as a decreased affinity for water of the calcium-saturated clay and the formation of a cementitious matrix that resists volumetric expansions (Geremew, 2018; Luo et al., 2020). Together, these changes point to an enhanced soil performance, making it more reliable for construction and reducing potential problems, such as uneven settlement or pavement distress especially in Jimma town.

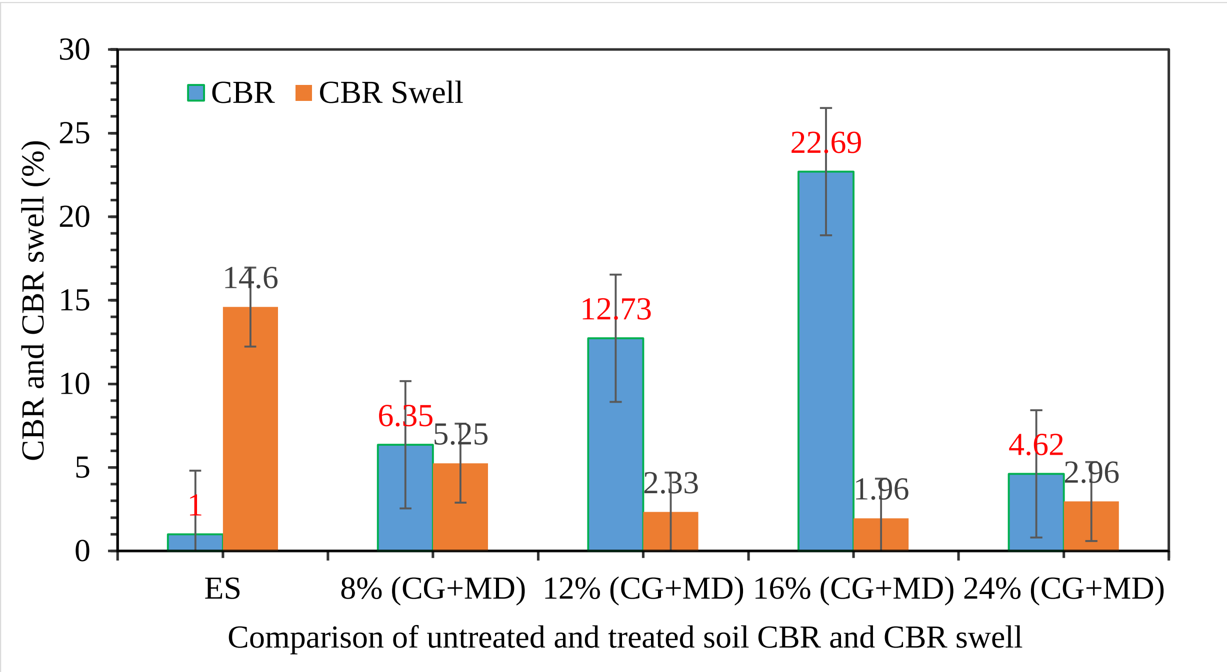

Figure (5): Summary of CBR and its swell results

Effect of Cinder Gravel and Marble Dust on Free Swelling Index (FSI)

The Free Swelling Index (FSI) assesses the swelling potential of materials, notably expansive soils and coals (Chelgani et al., 2016; Fei, 2006). The technique comprises taking two oven-dried, 10g each, soil samples passing through the 425-µm sieve, and placing them separately in two 100-ml graduated jars. One cylinder was filled with distilled water, while the other was filled with kerosene up to the 100-ml mark. The free swelling index is calculated using the final volume of soil after 24 hours as per Eqn. (1).

$$FSI = \frac{(Vw-Vk)}{Vk}*100 \quad (1)$$

where, FSI is free swelling index, V_w=final volume in water and V_k=final volume in kerosene.

The data in Table 6 illustrates the impact of different percentages of MD and CG on expansive soil's (ES) Free Swelling Index (FSI). The test is performed per ASTM D4829-21 (ASTM, 2021). Pure ES has the largest swell (81.8%), suggesting tremendous expansion. However, as the proportions of MD and CG grow, the FSI drops, with the greatest reduction (56%)

occurring at a 16% MD and 16% CG blend, resulting in a more stable soil mix. Interestingly, increasing the additives to 24% results in a lower reduction in FSI (34%), indicating that there is an optimal point at which the blend efficiently reduces swell. This tendency emphasizes the stabilizing role of MD and CG in improving soil performance.

Effects of Blended MD-CG on Unified Comprehensive Strength of Soil

The Unconfined Compressive Strength (UCS) is a vital indicator of soil strength and stability when subjected to loads (Yao et al., 2015). Samples were prepared according to (ASTM, 2010) standard procedures, mixing soil with stabilizers, like cinder gravel and marble dust, for uniformity. The mixture was compacted to the desired density and cured for a specified period. The degree of saturation significantly affects UCS; therefore, samples were created at their optimum moisture content for maximum strength. Careful moisture control ensured consistency across all samples, enhancing the reliability of UCS values. To ensure repeatability, UCS tests were performed on three specimens for each stabilizer content, using the average value. This approach minimizes errors and provides a more accurate representation of soil strength. Verifying that expansive soil's UCS meets ERA manual specifications is crucial for sub-grade design, supporting long-term durability and performance (ASTM, 2016).

Figure (6) illustrates how the addition of cinder gravel (CG) and marble dust (MD) influences the unconfined compressive strength (qu) and cohesion (C) of natural soil. As the CG and MD percentages increase, both qu and C generally improve, peaking at 16% (CG and MD) with an average qu of 311.7 kPa and C of 155.9 kPa. Beyond this point, at 24% CG and MD, the strength and cohesion decrease. This outcome agrees with the findings of previous research (AlZubaidi et al., 2013; Amadi, 2014; Abdelkader et al., 2021; Abdulla & Majeed, 2021).

Table 6. Effects of marble dust and cinder gravel on free swell index (FSI)

Sample	Measuring Cylinder (ml)		Reading after 24 hrs (ml)		FSI (%)	Decrease (%)
	Kerosene	Distilled water	Kerosene	Distilled water		
Expansive soil (ES)	11	13	11	20	81.8	
ES +8 % MD + 8 % CG	12	13	12	18	48.3	41%
ES +12 % MD + 12 % CG	12	13	12	17	41.7	49%
ES+16 % MD + 16 % CG	11	13	11	15	36.4	56%
ES+ 24 %MD + 24 %CG	13	14	13	20	53.8	34%

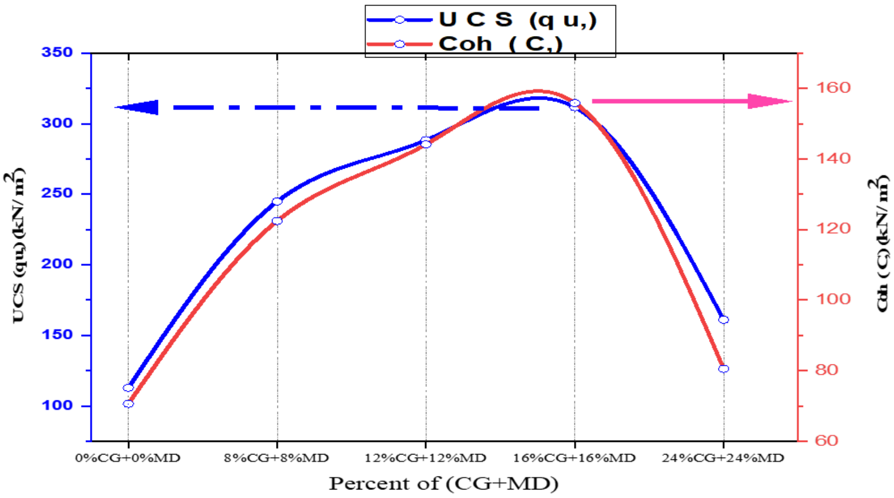

Figure (6): Effects of marble dust and cinder gravel on unconfined compressive strength of soil

Effects of Blended MD-CG on Micro-structural Soil Particle Configuration

The micro-structural arrangement of soil particles is fundamental to the stability and behavior of stabilized expansive soils. The use of Scanning Electron Microscopy (SEM) alongside analytical techniques offers significant insights into the micro-structural transformations that take place during the stabilization process. This enhanced understanding informs the development of effective stabilization strategies and improves predictions of soil behavior across various environmental conditions (Ahmed, 2015; Tang et al., 2020).

Figure (7) shows SEM images at 1000x and a longer working distance (20µm) magnification highlighting micro-structural changes in expansive soil (ES) stabilized with different percentages of cinder gravel (CG) and marble dust (MD). Figure (9) illustrates the SEM image porosity analysis, in which untreated soil is with a porosity value of 46.15% compared to soil treated with 8% exhibiting a porosity of 31.52%, thus indicating a less compacted structure. As the stabilizer content increases to 12% and 16%, porosity decreases to 13.48% and 10.16%, respectively, reflecting better particle packing and enhanced stabilization, with the 16% blend showing the least porosity. However, at 24% stabilizer content, porosity rises again to 15.34%, suggesting potential over-stabilization that could affect the mixture’s effectiveness.

Figure (8) highlights the impact of higher magnification (3000x) and a shorter working distance (10 µm) on resolution. Increased magnification enhances the ability to observe finer details, while a reduced working distance minimizes electron beam spread, leading to sharper focus and improved image clarity. These conditions are critical for precise micro-structural analysis (Zeng et al., 2024).

These findings underscore that the porosity of the soil decreased from 51.93% to 15.66% for untreated soil and at optimum blend of CG and MD offers the best balance of stability and reduced porosity for expansive-soil stabilization (Figure (9)). This micro-structural insight is vital for optimizing soil-stabilization strategies, particularly in engineering applications, such as road construction, where enhancing load-bearing capacity and durability is essential (Jalal et al., 2021).

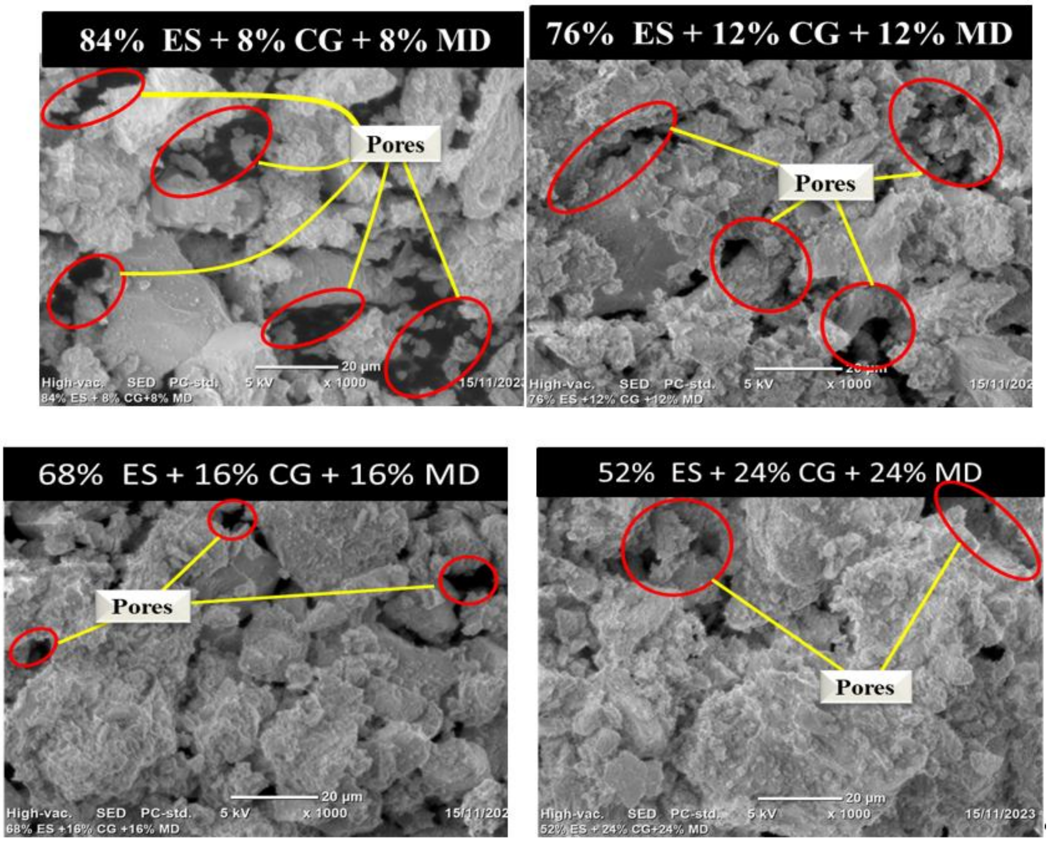

Figure (7): Effect of MD and CG on micro-structural integration of stabilized soil (×1000/ 20µm)

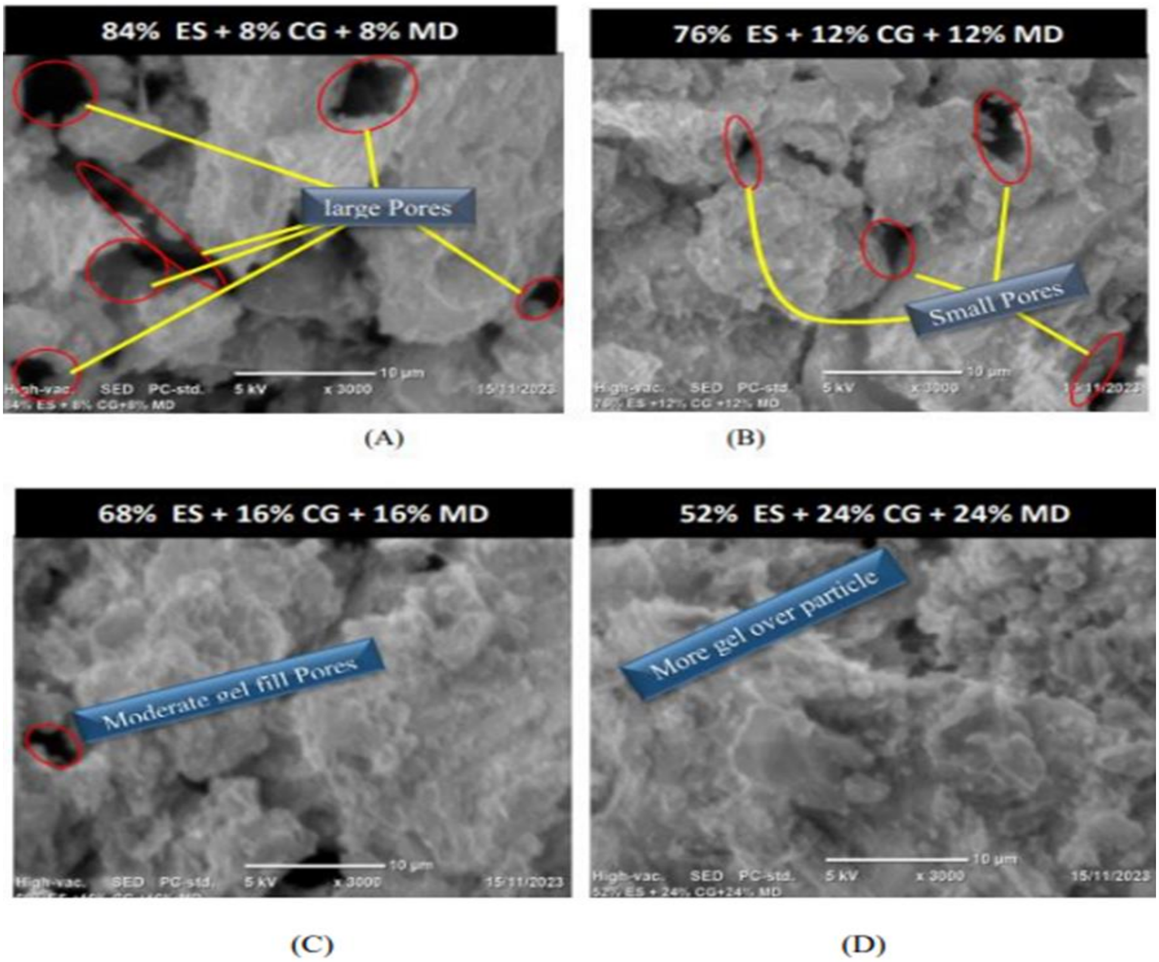

Figure (8): Effect of MD and CG on micro-structural integration of stabilized soil (×3000)/ 10µm)

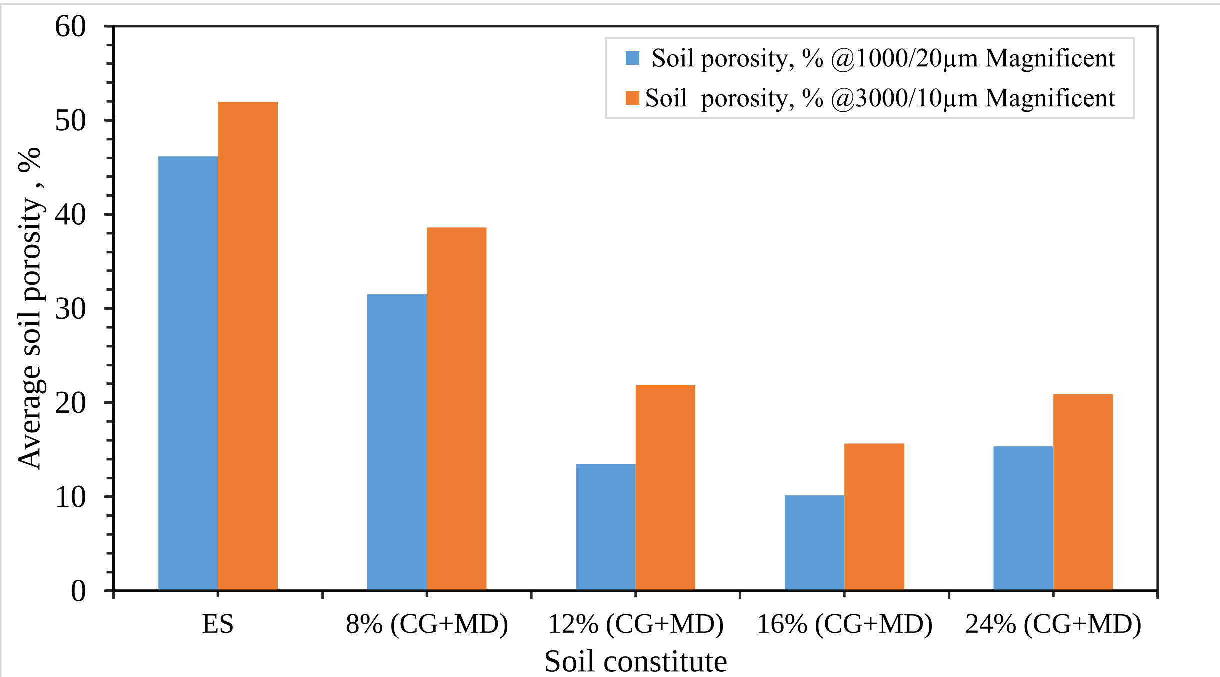

Figure (9): Comparison of porosity of untreated and treated soil for SEM analysis

Table 7. Comparison of some stabilizers' effects on engineering properties of ES

	Engineering expansive-soil properties							
Stabilizer	**OMC (%)**	**MDD (kN/m^3)**	**LL**	**PL**	**PI**	**CBR (%)**	**UCS (kPa)**	**FSI (%)**
Lime and Cement (Phanikumar & Raju 2020)	28.94	14.24	64	33	31	11.5	577	55
GGBS (Nanda et al., 2024)	29.5	13.8	66	35	31	12	250	45
(RHA)+Lime (Pushpakumara & Mendis, 2022)	27.4	14.2	60.5	35.5	25	14	121.7	58
Fly ash + Lime (Sambre et al., 2024)	27.4	13.54	60	32	28	8	224	54
CG+MD	14	16.17	30.67	20.4	10.29	22.69	311.29	36.4

Table 7 indicates that lime and cement are the most effective materials for enhancing unconfined compressive strength (UCS). However, they moderately decrease plasticity and swelling. The combination of cinder gravel (CG) and marble dust (MD) is particularly effective in minimizing plasticity and swelling, achieving the lowest values in the Plasticity Index and Free Swell Index (FSI). This combination also enhances the California Bearing Ratio (CBR), making it suitable for pavement and sub-grade stabilization. Additionally, fly ash combined with lime and rice husk ash (RHA) showed moderate reductions in strength and plasticity. These materials are suitable for less critical applications. Ground granulated blast-furnace slag (GGBS) offers reasonable improvements in strength, but is less effective in reducing plasticity and swelling.

Overall, the optimal stabilizer content of 16% for cinder gravel (CG) and marble dust (MD) is identified based on experimental results. The underlying mechanisms driving this behavior are primarily due to the chemical and physical interactions between the stabilizers and the soil. CG and MD contribute to the stabilization process by filling the voids in the soil matrix, enhancing particle bonding, and reducing the plasticity of the soil. The pozzolanic reactions between the stabilizers and the soil particles result in the formation of cementitious compounds, which improve the soil's strength and stability (Sambre et al., 2024; Phanikumar & Raju, 2020,). To further validate the optimal stabilizer content, the micro-structural changes observed in the SEM images correlated with mechanical properties, such as unconfined compressive strength (UCS), shear strength, and durability. This correlation establishes a clear link between the observed micro-structural features and the improved performance of the stabilized soil, providing a more robust basis for the findings.

The decline in performance observed at 24% stabilizer content is a significant issue that demands thorough investigation. Several key factors contribute to this behavior. At higher concentrations, the stabilizer tends to over-saturate the soil matrix, which directly undermines the effectiveness of particle bonding. This over-saturation weakens the soil structure, as the excess stabilizer fails to enhance strength and may disrupt existing soil-stabilizer interactions (Yang et al., 2020). Moreover, increased stabilizer content leads to greater brittleness in the stabilized soil. While an initial addition of a stabilizer effectively enhances strength and stability, excessive amounts can make the soil more vulnerable to cracking and failure under stress, ultimately compromising performance.

Additionally, the principle of diminishing returns is clearly at play here. Beyond a certain point, the incremental benefits of adding more stabilizers diminish significantly. At 24% stabilizer content, further additions do not yield meaningful improvements in the soil's properties, leading to a plateau or even a decline in overall performance. This, due to the chemical interactions between the stabilizer and the soil, leads to reach a saturation point at higher contents. Beyond this point, additional stabilizers may not participate in beneficial reactions, leading to a decline in performance (Firoozi et al., 2017; Puppala et al., 2014).

CONCLUSIONS

1) The expansive soil under investigation is classified as A-7-6 (37) silt clay according to AASHTO standards and CH under the USCS. It has a Skempton's activity coefficient (Ac) of 0.71, a high plasticity index of 34.09%, a free swell index (FSI) of 81.8%, and a low California Bearing Ratio (CBR) of 1%. These characteristics indicate poor engineering properties, making this soil unsuitable for direct use in road construction. The initial condition of this expansive soil presents several performance-related challenges. Its high plasticity, low density, and insufficient strength, as indicated by the Skempton Ac value, exacerbate moisture-induced volume changes, often leading to severe structural problems like cracking and differential settlement.
2) To enhance its engineering properties, the soil is stabilized using cinder gravel and marble dust. Extensive laboratory analyses of cinder gravel (CG) and waste marble dust (WMD) revealed notable differences in their chemical compositions, which are critical for their effectiveness as soil stabilizers. Stabilizing the soil with varying percentages of CG and WMD (8%, 12%, 16%, and 24%) showed significant improvements in soil characteristics. The optimal combination of 16% CG and 16% WMD resulted in a remarkable reduction in the plasticity index and swell index by 70% and 56%, respectively. Furthermore, there were significant enhancements in CBR and unconfined compressive strength (UCS), with increases of 2169% and 176.1%, respectively.
3) These findings have broader implications for the construction industry in Jimma town. The enhanced engineering properties of the stabilized soil promise improved structural integrity, which is crucial for road and infrastructure development in regions with expansive soils. This stabilization technique facilitates more durable construction and promotes sustainability by repurposing waste materials, thereby supporting eco-friendly construction practices. Improved soil conditions stimulate economic growth by enhancing transportation networks and accessibility, ultimately strengthening the local economy. In light of climate variability, the ability of this stabilized soil to resist moisture fluctuations further underscores its value, providing resilience against potential soil-related damages.
4) In summary, stabilizing expansive soils with cinder gravel and waste marble dust represents a powerful solution beyond traditional methods. This innovative approach offers a compelling blend of performance, sustainability, and economic viability, addressing the immediate challenges posed by expansive soil conditions and positioning Jimma town for sustainable development and infrastructure resilience in the future.

RECOMMENDATIONS

1) Future research should prioritize assessments of long-term durability, including freeze-thaw and wet-dry cycles.
2) The findings presented here are exclusively derived from laboratory studies involving fine cinder gravel and marble dust, with no field trials or real-world case studies to substantiate the results. Therefore, further research is warranted.
3) A comprehensive cost analysis of utilizing cinder gravel (CG) and marble dust (MD) as stabilizers is necessary, as it is crucial for evaluating the practical feasibility of this method for future research
4) Future research should investigate the potential environmental impacts, including leachate effects, and evaluate the sustainability of using marble dust and cinder gravel, particularly in the context of their application in both paved and unpaved roads.

Data Availability

The authors included all data supporting the findings of this study.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this article.

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