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Investigation of engineering properties of clayey soil experimentally with the inclusion of marble and granite waste

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Abstract. Granite and marble are widely produced and utilized in the construction industry, resulting in significant waste production. It is essential to manage this waste appropriately and repurpose it in recycling processes to ensure sustainability. The utilization of waste materials such as marble and granite waste (MGW) has become increasingly important in geotechnical engineering to improve the physical and mechanical properties of weak soils. This study investigated the applicability of utilizing MGW and cement (C)-MGW mixtures to improve clayey soil. A series of model plate loading tests were carried out in a specialized circular test tank to assess the influence of MGW and C-MGW mixing ratios on clayey soil samples. The samples were prepared by blending MGW and C-MGW in predetermined proportions. It is found that the bearing capacity of clay soil increased by approximately 71% when using MGW and C additives. Moreover, the consolidated settlement values of the clay soil decreased up to 6 times compared to the additive-free case.

Keywords: clayey soil; marble and granite waste; model test; soil improvement; waste disposal

1. Introduction

In geotechnical engineering, weak soils are improved and strengthened by using several methods. These methods generally use a strengthening material together within the soil. The properties of the material used and its interaction with the soil play a major role in soil improvement. Therefore, the researchers primarily focused on the properties of these materials and their interaction with the soil. For example, one of the popular materials, geosynthetics, took part in many studies in the literature. Recently, authors have examined the properties of geosynthetics and how they interact with various soil types (Kayadelen *et al.* 2018, Altay *et al.* 2019, Çanakçı *et al.* 2019, Kahyaoğlu and Şahin 2021, Bora *et al.* 2022, Önal *et al.* 2022, Kaplan *et al.* 2022, Kayadelen *et al.* 2023, Önal *et al.* 2023). Numerous studies have been carried out on lime, marble powder, and fly ash materials, as well as on geosynthetics. The use of lime, marble powder and fly ash within the soil has been studied in detail in the literature. (Saygılı 2015, Çanakçı *et al.* 2015a, Çanakçı *et al.* 2016, Sharman and Sivapullaiah 2016, Sahu *et al.* 2017, Jha and Sivapullaiah 2018, Ikeagwuani *et al.* 2019, Abdullah *et al.* 2019, Çınar *et al.* 2019, Ignat *et al.* 2019, Zhang and Jiang 2020, Çınar *et al.* 2020, Andavan and Pagadala 2020, Altay *et al.* 2021a, Altay *et al.* 2021b). Researchers have also explored ways to enhance soil strength through the technique of Microbially Induced Calcite Precipitation (MICP). Cui *et al.* (2017) improved the strength parameters of granular soil by using a type of bacteria called "Sporosarcina pasteurii" to apply the MICP method. The authors stated that the technic depending on the usage of precipitation was environmentally friendly. One of the most important findings obtained by the researchers was that the improvement in the soil significantly depended on the degree of cementation. Another paper related to MICP mentioned that the liquefaction resistance of Fraser River Sand soil was improved with that precipitation (Riveros and Sadrekarimi 2020). Additionally, researchers have worked on soil improvement with bio cementation on organic soil and peat (Sidik *et al.* 2014, Çanakçı *et al.* 2015b, Çanakçı *et al.* 2015c). One of the materials used in soil improvement is cement (C), which is very popular in this regard. An experimental study by Raftari *et al.* (2014) investigated the enhancement of kaolin clay using cement treatment. The study involved mixing soil samples with 5%, 7.5%, 10%, 12.5%, and 15% cement by mass and analyzing the resulting changes in consolidation and strength properties.

The results showed that an increase in the cement ratio led to improvements in the unconfined compressive strength and elasticity modulus of the samples. The void ratios of the soil samples also varied according to the cement percentages. As the percentage of cement increased, the void ratio of the soil samples decreased. The benefits of cement treatment effect on the unconfined compressive strength were also investigated by Naseri *et al.* (2016). In particular, they used graphene oxide nanosheets in their

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experiment and they found out that the strength of soil increased significantly. Pantazopoulos and Atmatzidis (2012) have worked on the dynamic properties of microfine cement grouted sands. Their experimental study used grouted sand specimens with diameters of 50 mm and heights of 112 mm. Bender element test and torsional resonant column test were conducted on the specimens to observe the effect of shear strain, confining pressure, gradation, cement type, and water/cement ratio on the dynamic properties of grouted sands. The most important finding in the study was that the water/cement ratio was the most important parameter affecting the dynamic properties of the soil. Cai *et al.* (2020) examined the soil beneath a heavy-haul railway and conducted field tests to analyze the dynamic properties of cement-grouted expansive soil. Their findings indicated that grouting along the soil layer depth reduces dynamic stress, dynamic displacement, and acceleration. Additionally, they noted that the water content of the subgrade soil plays a crucial role in its dynamic response. The study conducted by Zainuddin *et al.* (2019) aimed to improve the quality of weak marine clay through the use of granite dust obtained from demolished tile material (DTM). The authors observed that the addition of granite powder resulted in a decrease in the plasticity and pH of the soil. As a result, the maximum dry density of the soil increased from 1.34 t/m^3 to 1.48 t/m^3, while the optimum water content decreased from 32% to 22%. Moreover, a longer curing period led to an increase in the unconfined compressive strength of the soil. Xiao and Xu (2019) examined the change in the strength parameters of silty soil using granite powder with cement in their experimental study. The effect of granite powder amount, cement amount, cement type, and curing time on soil strength was investigated. It was concluded that unconfined compressive stress increased with the increase of all these variables.

In a study conducted by Eltwati *et al.* (2020), CBR experiments were carried out using granite powder at varying percentages of 4%, 8%, 12%, 16%, and 20%. The findings revealed that the maximum dry density was boosted by 16% due to the addition of granite powder. The optimum ratio of granite powder was determined to be 8%, as it led to an increase in CBR value from 3.65% to 16.5%. Additionally, the shear strength was observed to increase by 2.8 times.

According to research by Eltwati and Saleh (2020), it was found that adding 5%, 10%, 15%, and 20% by weight of marble dust led to a significant increase in maximum dry density. The optimal ratio was 10% based on the experiments conducted. Subsequently, the authors conducted CBR experiments and found that the best result was achieved with a mixture ratio of 25%. These findings indicate that adding marble dust can improve the density and strength of the soil.

Abdelkader *et al.* (2021) studied the effects of adding varying percentages of marble dust to medium plasticity clay (CI) soil. The results showed that as the percentage of marble dust increased (from 5% to 25%), the liquid limit decreased from 42.12% to 29.5%, and the plastic limit decreased from 25.8% to 8%. Additionally, the clay soil changed from medium plasticity to low plasticity. The maximum dry density increased from 18.72 kN/m3 to 20.2 kN/m3, while the optimum water content decreased from 13.1% to 11.2%. The study also found a 47.48% improvement in bearing capacity during the 7-day curing period, with the best recovery at 20%. Overall, these findings provide valuable insights into the engineering properties of CI-type soil when mixed with marble dust.

Jassim *et al.* (2022) investigated the impact of marble dust on the bearing capacity of the soil by using the unconfined pressure test. The results indicated that the optimum ratio of marble powder was 3% out of the ratios tested (3%, 6%, 9%, 12%). Moreover, as the marble dust ratio increased, the maximum dry density and optimum water content decreased by 14% and 26%, respectively. The highest bearing capacity was observed with 3% marble powder. A finite element model was developed using the optimal ratios, which showed that stresses formed in the soil decreased by 38% and rutting by 55.3%."

1.1 Goals and objectives

Studies have been conducted on the individual utilization of granite and marble waste literature. However, these studies have primarily focused on the soil's index properties and stress-strain behavior obtained from laboratory tests like unconfined compression test, simple shear box test, or triaxial tests. Research on model laboratory experiments that explore the effects of combining granite and marble wastes has been limited in the literature. This study aims to determine the behavior of soil formed with cement (C), granite, and marble wastes (MGW) at different mixing ratios and curing times in terms of bearing capacity and time-dependent settlement through model laboratory experiments. This study sets itself apart by conducting loading experiments on a model foundation placed on soil treated with MGW, providing a distinctive perspective compared to prior research.

2. Material and methods

The clayey soil used in the experiments was gathered from Adana Province, situated in the southern region of Türkiye. The first step was to analyze the index properties of clayey soil using the standard geotechnical laboratory test procedure (ASTM D7263–09, ASTM D698, ASTM D4318, ASTM-6913-04, ASTM D2487) at Çukurova University Geotechnical Laboratory. Through conducting specific gravity tests on samples of clayey soil, it was discovered that the unit weight of grains was 27 kN/m^3. The maximum dry unit weight and optimum water content values were obtained at 17.40 kN/m^3 and 18%, respectively. The Atterberg Limits were determined to be as follows: the liquid limit was 42%, the plastic limit was 24%, and the plasticity index was 18%. The MGW sample was obtained from a factory located in Adana, Türkiye. In Fig. 1, the results of the sieve analysis for clayey soil and MGW are shown through gradation curves. Also, Table 1. indicates the chemical compositions of clayey soil and MGW, analyzed

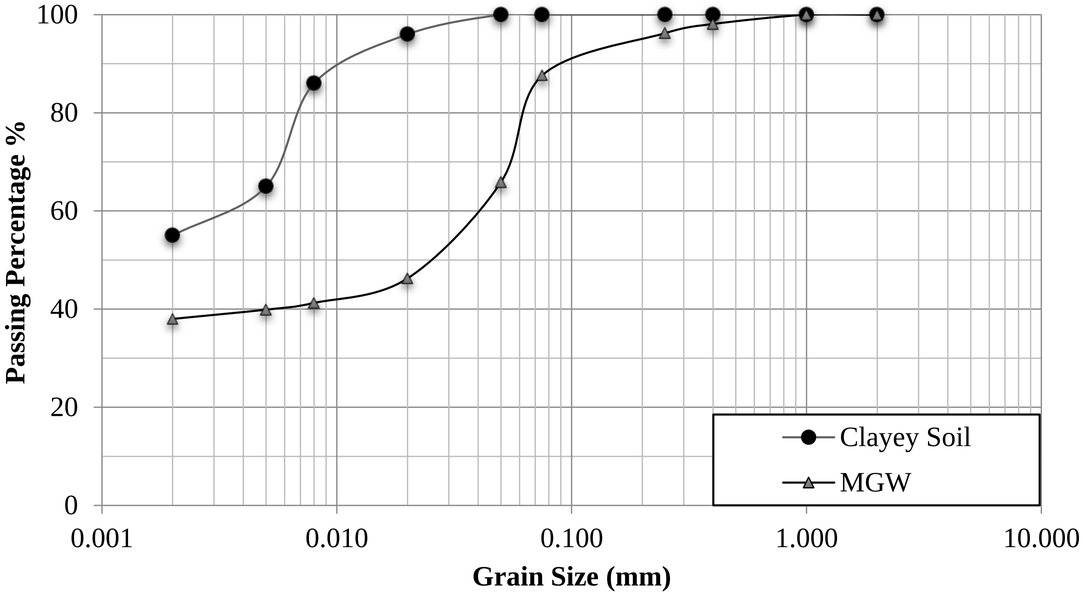

Fig. 1 Grain size distribution of clayey soil and MGW

Table 1 The chemical compositions of clayey soil and MGW

Content (%)	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	MnO	Fe_2O_3	Na_2O	TiO_2	LL
Clayey soil	6,1	18,4	50,6	0,65	3,10	3,20	3,10	8,70	2,50	1,65	3,15
MGW	2,51	0,41	44,5	-	-	49,2	-	1,38	-	-	-

through XRF (Minipal 4). Based on the tests conducted, the soil has been categorized as low plasticity clay (CL) in accordance with ASTM D 2487-06. Additionally, it has been observed that the clayey soil contains high ratios of alumina and silicate. Moreover, the soil contains calcite, quartz, and various clay mineral groups including smectite, kaolinite, and vermiculite.

Table 2 Outline of soil mixtures used in experiments

Additive (%)	Soil mixtures								
	Clayey Soil	MGWS				CMGWS			
	-	1	2	3	4	1	2	3	4
MGW (%)	0	5	10	15	20	5	10	15	20
C (%)	0	0	0	0	0	6	10	14	18

2.1 Preparation of mixtures

The MGW underwent a 24-hour drying process in an oven set at a constant temperature of 105±5°C and was subsequently ground in a grinding machine. The test medium in the cylindrical test tank was prepared by compacting a mixture of dry soil, MGW, and C at the optimum water content (OWC). To maintain consistent water distribution and prevent moisture loss, the test sample and the accompanying tank were bagged and placed in the curing room for a duration of 24 hours. Table 2 summarizes the portions and preparation of two soil mixtures: clayey soil with marble-granite waste (MGWS) and clayey soil with cement marble-granite waste (CMGWS). The portions of each mixture have also been documented in the table.

2.2 Experimental methodology

The model experiment setup consisted of a test tank, circular steel plate, electronic load cell, electronic displacement transducer, and computer. A circular steel plate with a thickness of 10 mm and a diameter of 600 mm was used for the test tank. The height of the test tank was also 600 mm (Fig. 2). During the experiments, the samples were arranged in layers that were 2 cm thick and placed inside the test tank. The compression process was carried out by applying a fixed standard energy using a specially prepared knob. The knob was dropped 80 times for every 30 layers to complete the compression process (Dash et al. 2003). The test samples were placed in the test tank, and then the model footing was positioned at the center. To measure the results, two vertical displacement gauges and a load cell were installed. During the experiment, the load was applied in a vertical and static manner to the center of the footing. The loading speed remained constant, and displacements were recorded at each load level until they reached their respective limits. At two separate points equidistant from the center of the footing, displacements were measured, and the average of these two readings determined the settlement value. To analyze the data, the DS7 program was utilized with the assistance of 32-channel input data collection devices known as ADU (Autonomous Data Acquisition Units). Equation 1. was used to calculate the Bearing Capacity Ratio (BCR) (Binquet and Lee 1975).

This ratio is commonly used to indicate the

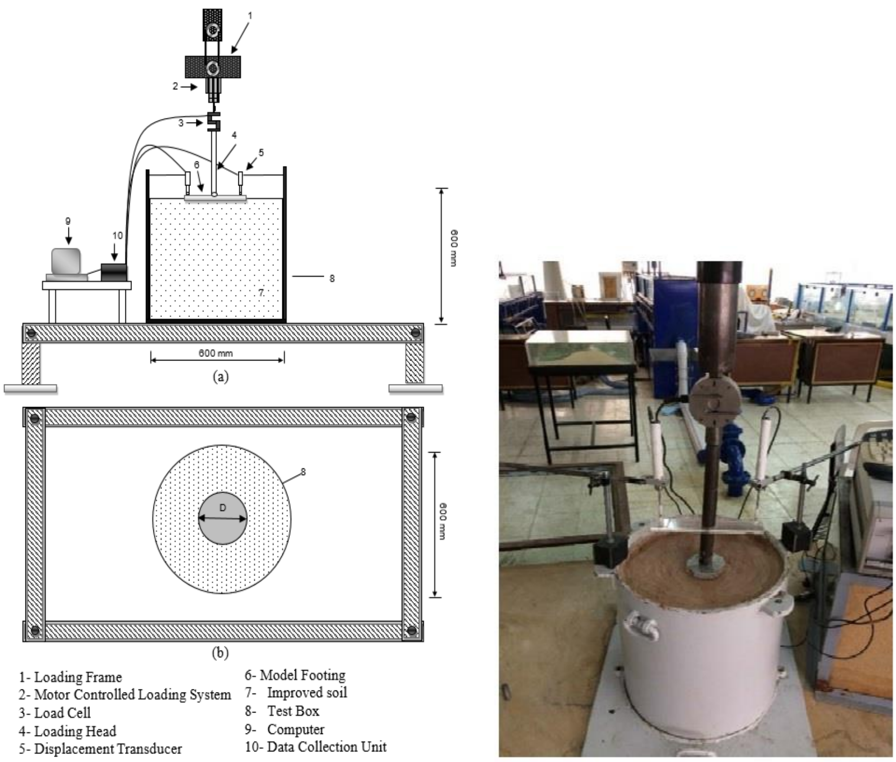

Fig. 2 Experimental Setup (a): plan, (b): section and (c): laboratory view)

improvement in the system's bearing capacity due to the additive used.

$$BCR = \frac{Bearing\ capacity\ for\ expansive\ soil\ with\ additive\ (q_r)}{\text{Bearing capacity for only expansive soil } (q_0)} \quad (1)$$

3. Results and discussion

This study aimed to explore the potential of using marble and granite waste (MGW) from the construction industry to improve clayey soil. To achieve this, firstly, standard soil mechanics tests were conducted to determine the physical and mechanical properties of clayey soil. The waste materials and clayey soil were then analyzed for their chemical components using XRF (Minipal 4). Finally, model plate loading tests were carried out by mixing the waste materials with the clayey soil in specific ratios. The results were analyzed to determine the extent to which the waste materials improved the clayey soil.

Through XRF (Minipal 4) analysis, it was discovered that the chemical composition of MGW waste materials has a significantly higher ratio of SiO_2 and CaO components compared to others. Specifically, the ratio of SiO_2 and CaO is 44.5% and 49.2%, respectively. This finding reinforces the known preference for marble powder due to its high calcium, silica, and alumina content, which helps stabilize weak natural clayey soils and improve their bearing capacity.

3.1 Determination of optimum water content

In Fig. 3, the optimum water contents (OWC) and maximum dry density (MDD) values obtained from the compaction test are shown for samples prepared by mixing MGW in varying proportions. It should be noted that the OWC values increase with increasing MGW additive rates. For instance, the OWC value for pure soil is 18.1%, while it is 20.65%, 22.46%, 23.65%, and 24.76% for soil samples with 5%, 10%, 15%, and 20% MGW additive, respectively. However, the MDD changes do not exhibit similar behavior. When the MGW additive exceeds a certain limit, it leads to a reduction in MDD beyond a specific point. The findings regarding the correlation between the rises in MDD of soils through an increase in additives were corroborated by Eltwati and Saleh (2020), as well as Abdelkader *et al.* (2020). Both studies concluded that an increase in the quantity of additives leads to an increase in the MDD of soils.

Fig. 4 presents the OWC and MDD values obtained from the compaction test of samples with cement (CMGWS) in varying proportions. Notably, the behavior of these samples differed from those with MGW. Upon adding cement, the OWC increased while the MDD decreased. Specifically, the OWC values for soil samples with 5%, 10%, 15%, and 20% cement added ranged from 23.65 to 27.86. In contrast, the MDD values of soils with CMGW significantly dropped from 19.2 to 17.73. This phenomenon can be attributed to the finer gradation of cement compared to clayey soils. The fact that the MDD decreases while OWC increases supports this explanation.

3.2 Effect of MGW on ultimate bearing capacity

The results on the model foundation resting on soil with varying rates of MGW are presented in Fig. 5. The graph illustrates the correlation between the load per unit area (q) and the foundation settlement (s) ratio to the foundation diameter (D), for different MGW additive rates. The bearing capacity

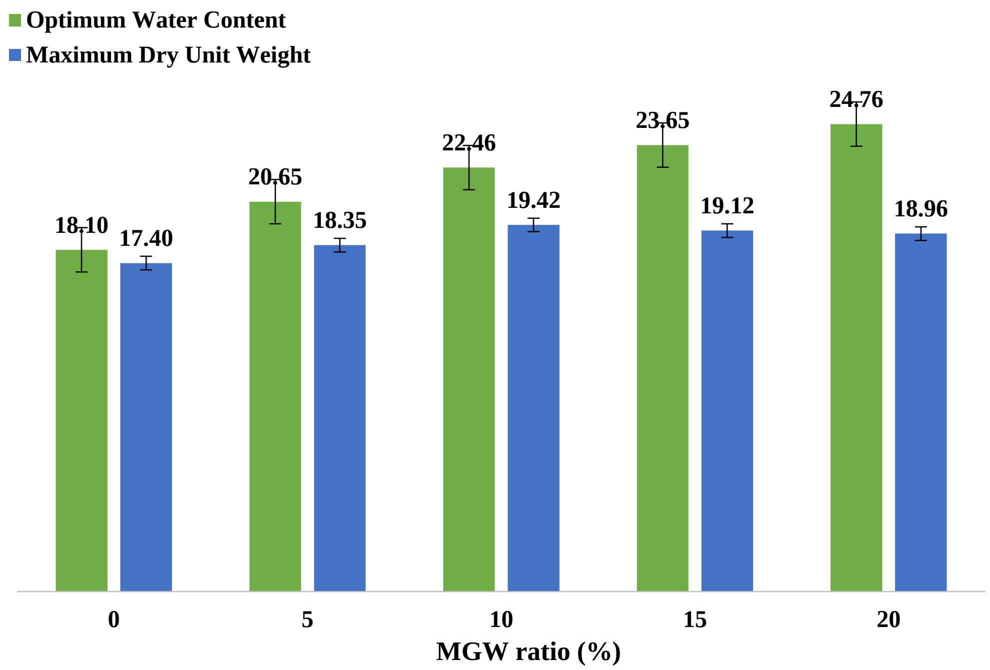

Fig. 3 The OWC and MDD values for MGWS (clayey soil with marble-granite waste) mixtures

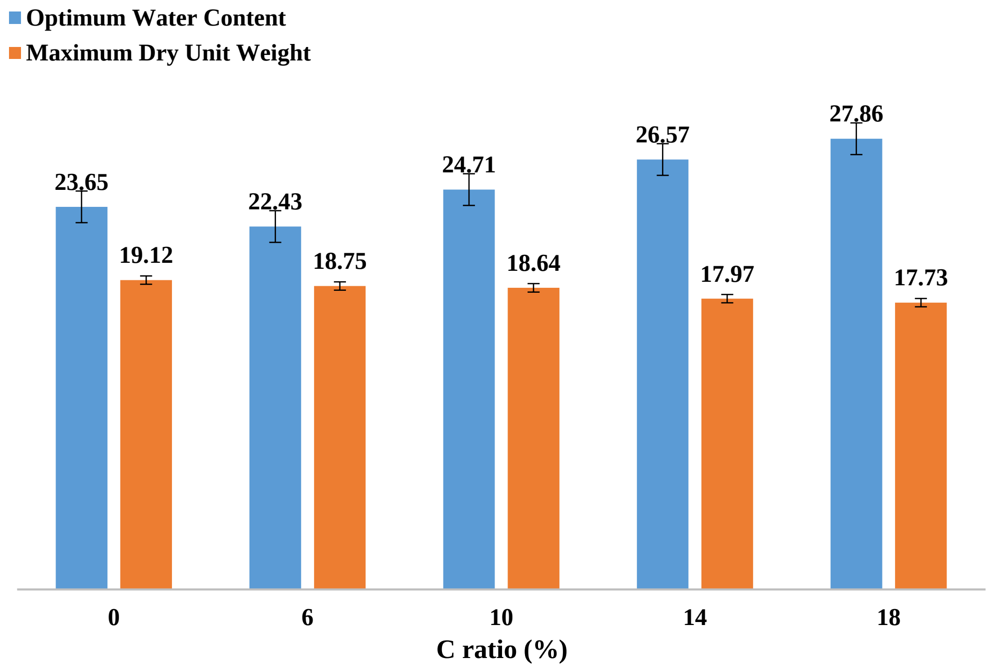

Fig. 4 The OWC and MDD values for CMGWS (clayey soil with cement and marble-granite waste) mixtures

test results indicate a general shear failure point, which signifies the total failure stress of the soil. The settlement curves for unreinforced (UR) cases display local failure types, whereas the addition of MGW provides rigidity to the soil, making it more brittle. It is noteworthy that the settlements at ultimate load are around 17% for the UR case and approximately 10-15% for the MGW addition case.

Fig. 6 displays the ultimate bearing capacity (qu) for different MGW ratios obtained from all tests. When MGW is zero, qu is approximately 175 kPa, while soils with MGW range from 200 kPa to 310 kPa. Interestingly, the qu value for soils with 15% MGW is similar to those with 20% MGW added. Fig. 7 illustrates this finding more clearly, showing the BCR versus MGW ratio variation. The curve reveals that a 15% MGW additive rate is optimum for bearing capacity, as BCR values range from 1.12 to 1.7 for soils with 5-20% MGW added. Additionally, 15% MGW increased qu value by about 70%. This study's findings on BCR are consistent with those of Jassim *et al.* (2022). When Jassim *et al.* added a 15% additive to the soil, they observed an increase of around 70% in the soil's unconfined compressive strength. Similarly, in this study, adding a 15% additive resulted in an increase of approximately

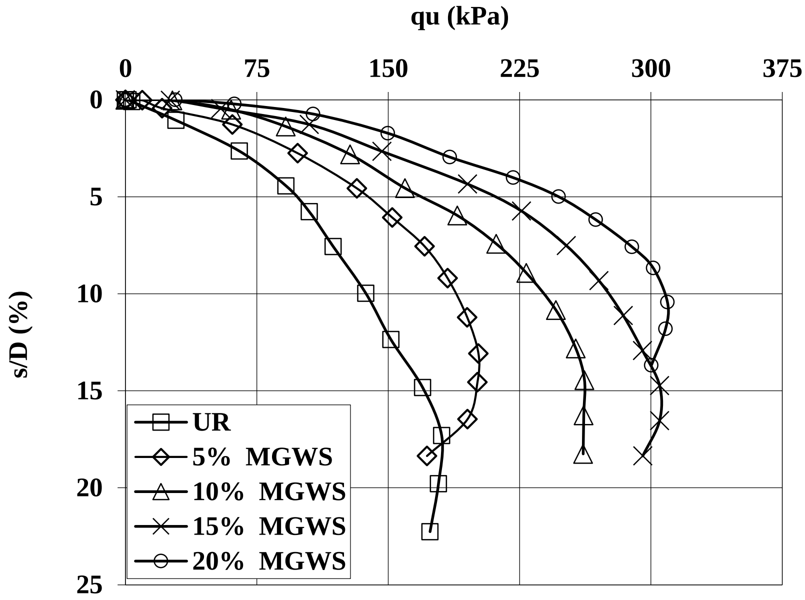

Fig. 5 Effect of MGW addition on clayey soil in terms of ultimate load capacity

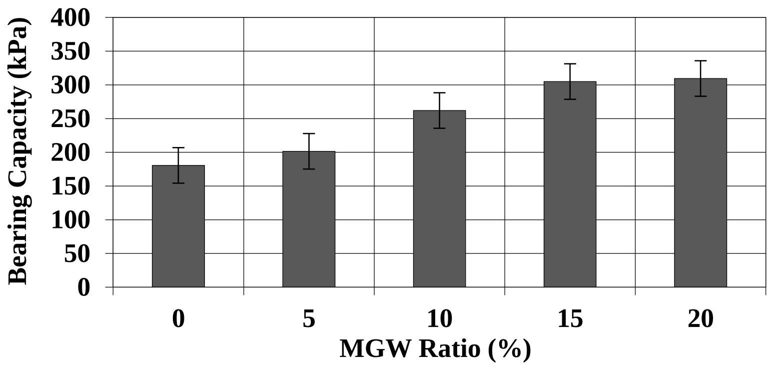

Fig. 6 Effect of MGW addition on clayey soil in terms of bearing capacity

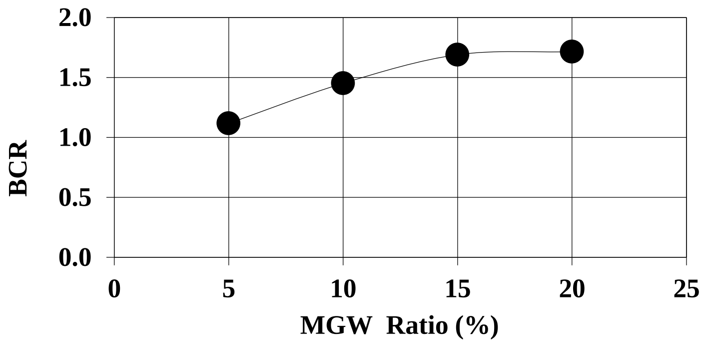

Fig. 7 Variation of bearing capacity ratio of MGW ratio for MGWS (clayey soil with marble-granite waste) mixtures

70% in the soil's bearing capacity. Both studies found that the strength of the soil increases as the amount of additives is added to the soil, which can be attributed to the cementation effects of additives like marble granite waste and marble dust.

3.3 Effect of C+MGW on ultimate bearing capacity

The previous section noted that a 15% MGW addition rate to improve soil is the most effective value. Using this value as a reference, various quantities of cement were added to the clayey soil with a 15% MGW addition to create the CMGWS mixture. The mixture was then compacted in the test tank. Fig. 8 displays the test results for the CMGWS mixture. The load-settlement behavior observed in CMGWS was similar to that of MGWS mixtures. However, the general shear failure point was more prominent in CMGWS than in MGWS. This indicates that adding cement to soil with MGW additive made the clayey soil more brittle due to the cement's binder properties. This feature gives rise to stronger cementation, particularly between MGW particles.

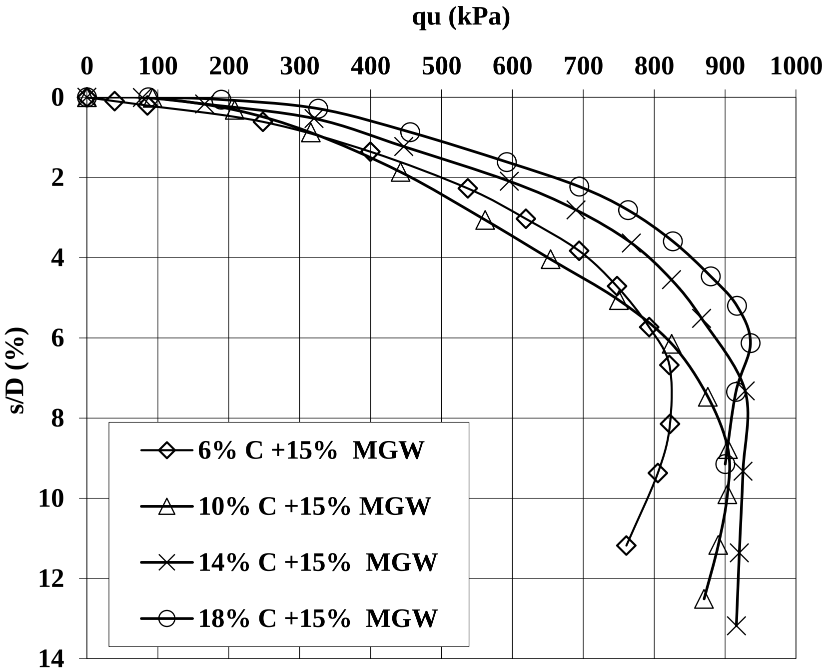

Fig. 8 qu vs s/D curves of clayey soil with added different rates of C when MGW is 15%

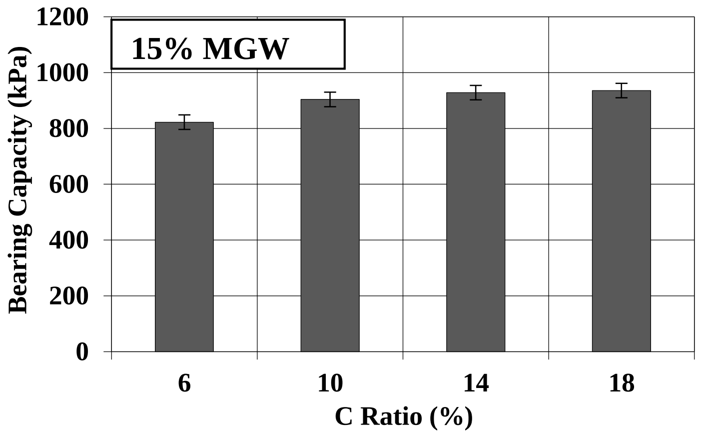

Fig. 9 Variation of bearing capacity of clayey soil with different C ratios when MGW is 15%

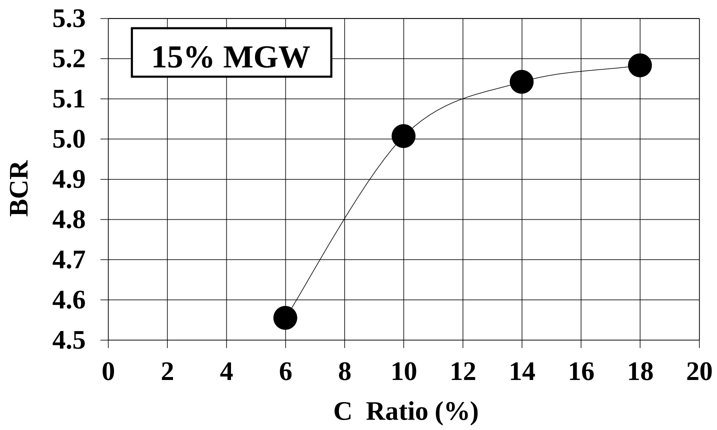

Fig. 10 Variation of bearing capacity ratio of clayey soil with different C ratios when MGW is 15%

The results clearly indicate a significant drop in settlement values corresponding to maximum qu values. It's important to note that settlements at ultimate load vary between 6% and 8% for all CMGWS mixtures. A crucial discovery in Fig. 8 is the

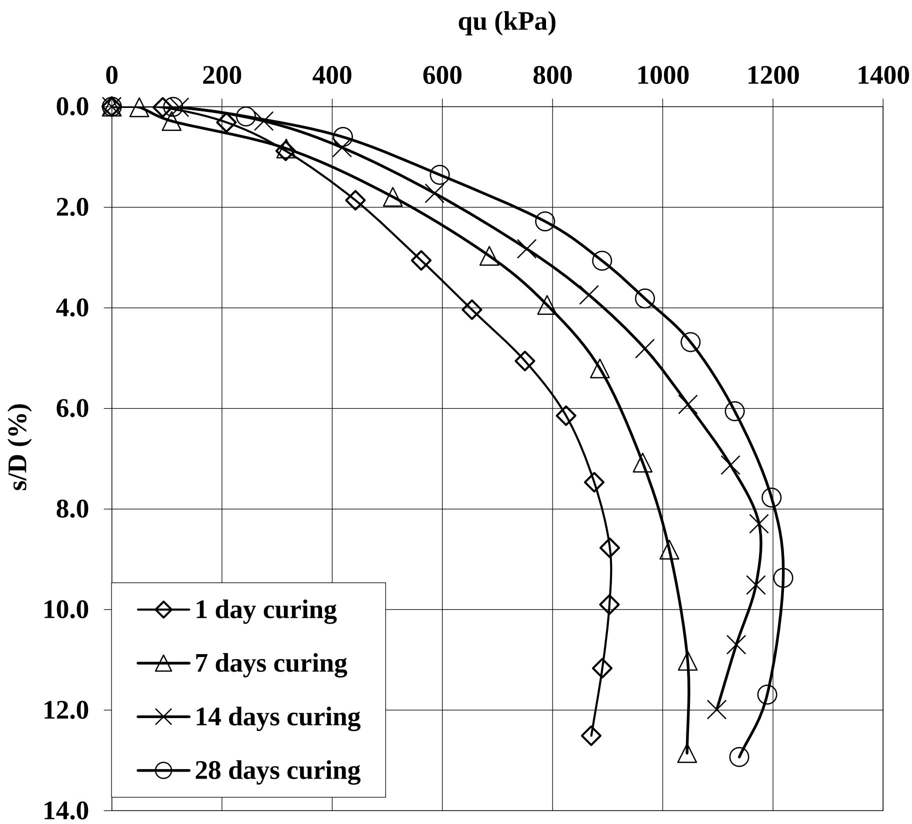

Fig. 11 Effect of curing time on CMGWS mixtures (14% C, 15% MGW, and 71% clayey soil)

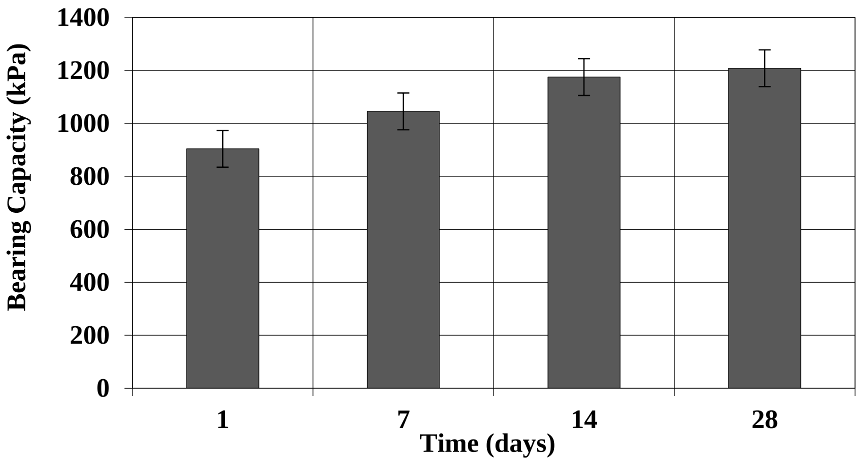

Fig. 12 Effect of curing time on bearing capacity of CMGWS mixtures (14% C, 15% MGW, and 71% clayey soil)

substantial increase in ultimate bearing capacity (qu) values. Specifically, when 18% C+15% MGW is added, it rises to approximately 950 kPa, representing an impressive 52% increase relative to the qu value of the clayey soil. This increase is more clearly demonstrated in Figs. 9 and 10. Moreover, ultimate bearing capacity (qu) values for the other CMGWS mixtures are also high, ranging from 825 kPa to 950 kPa. Despite the test results showing the same ultimate bearing capacity (qu) value as the 18% C+15% MGW mixture, it's important to note that 14% C+15% MGW is considered the optimum rates for mixtures.

3.4 Effect of curing time on bearing capacity

In order to investigate the impact of curing on bearing capacity, the clayey soil sample was placed in the test tank and subjected to varying durations of 1, 7, 14, and 28 days. The study centered on CMGWS mixtures blended with 14% C and 15% MGW with clayey soil. Once the mixtures were prepared at an optimum water content, they were carefully bagged and placed in a humidity and temperature-controlled curing room.

As illustrated in Fig. 11, longer curing times increased bearing capacity. The bearing capacity for 1-, 7-, 14-, and 28-

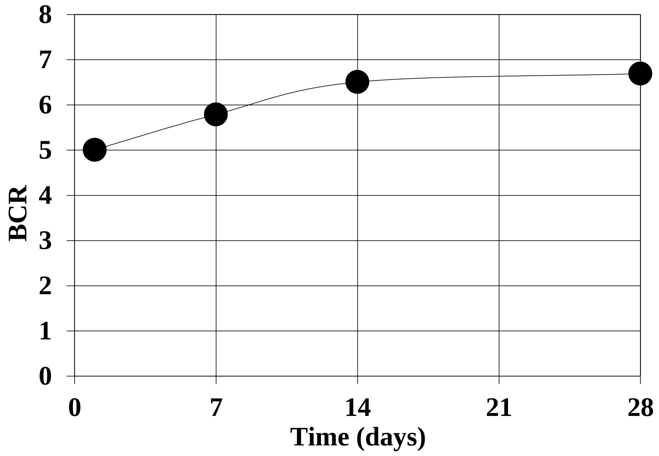

Fig. 13 Effect of curing time on bearing capacity ratio of CMGWS mixtures (14% C, 15% MGW, and 71% clayey soil)

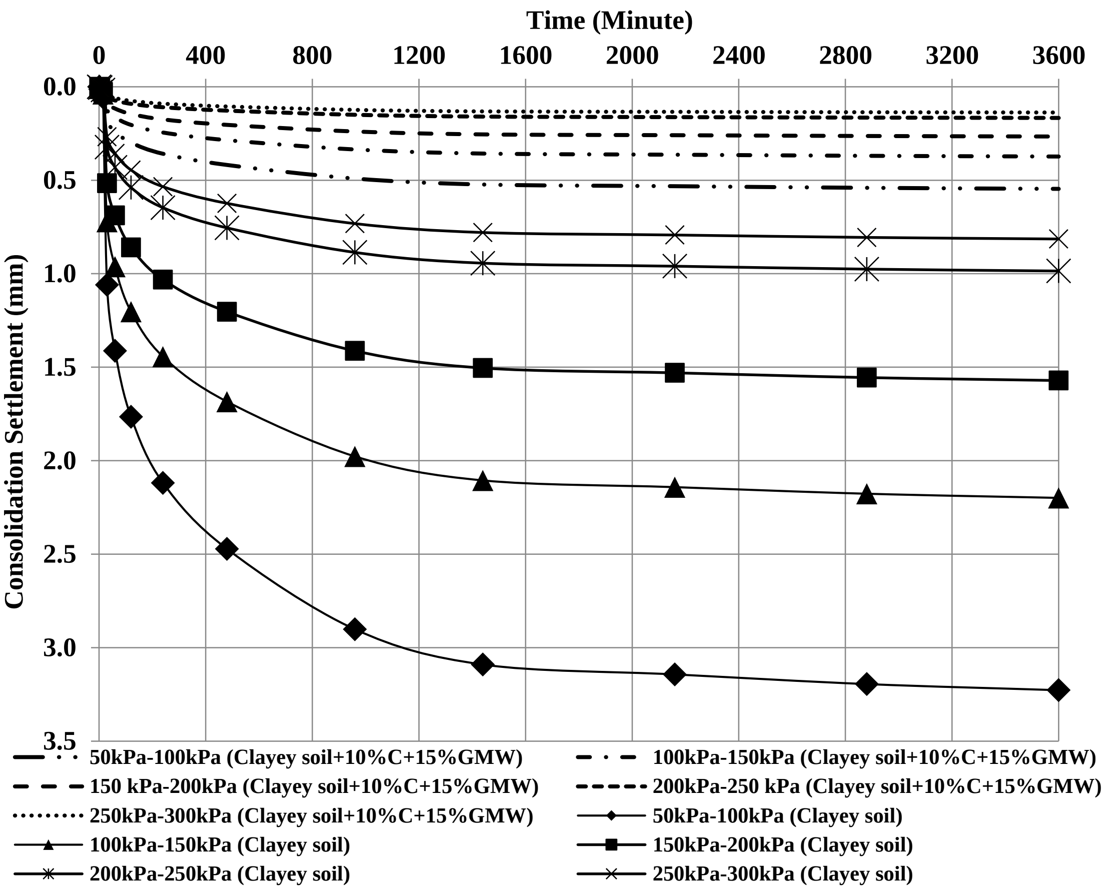

Fig. 14 Comparison of settlement behavior of pure clayey soil and CMGWS mixtures

day curing was approximately 900, 1050, 1170, and 1200 kPa, respectively (Fig. 12). The rate of increase between 1 day and 28 days was approximately 33%, emphasizing the critical role of curing time in determining bearing capacity. Fig. 13 depicts how the ultimate bearing ratio varies with curing time. At 14 and 28 days of curing, the bearing ratio curve appears to reach a certain asymptote value. The BCR values are approximately 6.5 and 6.8 for 14-day and 28-day curing times, signifying that the optimum curing time may be around 14 days.

3.5 Settlement behavior of CMGWS mixtures

The consolidation tests aimed to compare the settlement behavior of clayey soil and and CMGWS (clayey soil+%14 C+%15 MGW) mixture. The experiments started with 50 kPa as the first loading. Then, at the end of each loading, 300 kPa was reached by continuing with 50 kPa increments. Figure 14 shows settlement-time curves for each load increment, revealing typical settlement-time behaviors. Notably, the

CMGWS mixture exhibited significantly smaller settlement values than the clayey soil. At 300 kPa vertical load, the asymptotic settlement values of the clayey soil and CMGWS mixture were approximately 3.2 mm and 0.5 mm, respectively, indicating a settlement ratio of approximately 6 times. The remarkable finding is that the clayey soil and CMGWS mixture reached their asymptote settlement values around the same time, which was approximately 1200 minutes, suggesting similar permeability values for both materials.

4. Conclusions

In this study it is aimed simply to explore the usability of MGW, which is a waste of the construction industry and C for stabilization of clayey soil. Standard soil mechanic laboratory tests and model plate loading tests in special circular test tank were performed to obtain the physical and mechanical properties of the samples obtained by mixing the waste materials into the soil in certain proportions. The following findings were reached at the end of the studies.

- The addition of MGW to clayey soil resulted in a significant enhancement of the ultimate bearing capacity. The optimal rate of application was found to be 15% MGW, which led to an impressive increase of 70% in the ultimate bearing capacity of the clayey soil.
- The addition of cement (C) to the mixture of MGW and soil significantly increases the ultimate bearing capacity through cementation between the cement and MGW particles. Our tests reveal that the optimum cement ratio for the C+MGW+soil mixture (CMGWS) is 14%, resulting in a remarkable 52% increase in ultimate bearing capacity compared to clayey soil. Therefore, we conclude that the optimum mixing ratios for the CMGWS mixture are C=14%, MGW=15%, and Clayey soil=71%.
- The ultimate bearing capacity of the mixture is greatly affected by the curing process. Through experimentation, it has been determined that the best curing time for achieving the highest ultimate bearing capacity is around 14 days.
- It has been observed that mixing MGW and C with clayey soil reduces consolidation settlements. The combination of CMGWS has been found to generate settlement values six times lower than pure clayey soil under the same load.
- Based on the findings, it appears that using MGW with clay soils is a viable option for enhancing the mechanical properties of the soil and yielding economic advantages.

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