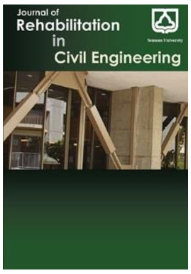

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Use of Ceramic-Industry Wastewater in Sandy Subgrade Stabilization by Deep Mixing Method

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ABSTRACT

Today, with the expansion of transportation, several road construction projects have been implemented in several parts of the world. The aim of this study is to stabilize and test sand using cement and drainage wastewater from the ceramic industry. Use of drained wastewater is to reduce the environmental pollution caused by drainage wastewater and reduced consumption of natural resources. In the first stage, the potential of off-site production by the factories and the advantages of using it were investigated. The optimal mixing plan was then obtained by performing a UCS test on samples that were made with different amounts of cement and wastewater. Other specifications of the desired mixture were: single gravity resistance, elasticity modulus, UCS, loss of resistance in saturation and microscopic structure of the particles. In the final stage, the efficiency of the mixture was studied using numerical modeling by finite element method. According to the results obtained from the experiments, it was found that adding 7.5% cement and 12.5% of dried wastewater, the UCS of sand increase from 0.005 MPa to 0.3 MPa and the sand elasticity modulus increase from MPa 5 to 65MPa. The specimen resistance did not increase significantly since the tenth day, and its saturation caused the resistance of the specimens to be reduced by 50%. The results of EDX and XRF tests revealed that the desired water included heavy metals. in addition use of wastewater reducing the consumption of natural resources, reduces the entry of heavy metals into the environment and urban environments. The level of surface treatment was obtained using sand-shaped modeling; which was considered as a substrate stabilizing element, and other pavement layers. The sum of the summands obtained from the modeling with the maximum allowed values was compared which provided satisfactory results. Finally, the processed sand could be used by deep mixing method to stabilize the subgrade of roads.

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1. Introduction

Large areas of the ground surface are covered by soft and problematic soils. Construction on this type of soils causes damages, due to unfavorable bearing capacity, settlement, water absorption, durability characteristics and shrink-swell. To improve soil characteristics, a number of stabilization methods are available to use including density treatments, pore pressure reduction techniques, the bonding of soil particles and use of reinforcing elements. In Europe, the issue of soil improvement also arises in the case of land roads with fixed soil, using so-called mechanical stabilization, when a layer of sandy gravel is mixed and compacted with poor-quality tied soil or the soil is changed by the addition of some kind of binder, typically lime or cement [1-3]. Geotextile reinforcement can be applied to several parts of the roadway structure, so the use of geotextiles can also help strengthen the soil. This paper focuses on reinforcing elements method with deep soil mixing (DSM) technique. In DSM soil mixed with binder material such as cement and lime. Now a days using soil-cement column are considered as an effective method to stabilize road and railroad subgrade[4]. previous studies have indicated that cement is used as a main additive for the enhancements of soils [5-7]. When binder materials are used for soil treatment, it can enhance the engineering properties of engineering materials. Studies have also determined that cement materials enhances soil strength compared to untreated soil [6].

Soil stanilaization will introduce bind structure with few void ratio and can improve the geotehnical properties such as unconfined compressive strength (UCS), angle friction, compaction, California bearing ratio (CBR), compaction, water absorption and cohesion [8-13]. The researchers indicate that in order to stabilize clay soil, the needed optimum percentage of cement and water is 10% and 70% (weight percentage); also they mention 28 days is suitable for curing time. Sunkontasukkul and Jamasawang (2012) studied bending behavior of deep soil-cement column. They added different percentage of the fiber (0.5, 0.75 and 1%) to the soil. It was observed that toughness and bending performance of the soil cement columns were improved by adding the fibers. The effect of propylene fibers was more better than steel fibers[14]. To improve soft soil subgrade of railroad using deep cement columns. It was found that cement columns increased bearing capacity and decreased settlement, also accelerated the stabilization process. The results showed that increasing the length of columns improved surface settlement [15]. In sandy soils, using deep soil mixing has been extensively considered in protection of environmental resources of soils [16]. Saberian, et al. (2018) added different weight percentages of cement (20, 30, 50 and 70%) and sodium bentonite (2, 3, 4 and 5%) to the sand (water/cement ratio of 0.5) to improve geotechnical properties of the sand. It was observed that while increasing the percentage of sodium bentonite and decreasing the partial replacements of cement, the UCS, E and Mr of sand increased. from UCS tests, it was observed that the specimens with 5% sodium bentonite and 20% cement after 28 curing days had the highest UCS value[17].

Also, in a research, Alipour and his colleagues discussed the effect of adding different amounts of cement on the settlement of clay soil. In this research, the physical and mechanical properties of clay soil in Bandar Imam, Iran, were determined with cement content of 4, 6, 8, and 10 percent and different amounts of water (30, 48, and 70 percent). Sample preparation was done using deep wet soil mixing (DSM) method, the settlement was investigated, and the results show that the settlement of the stabilized soil has improved [18].

Moreover, in recent years, many researchers have become more interested in the use of waste materials. In addition to land occupation, the storage of waste from various manufacturing industries has caused many environmental problems.[19, 20].

The influence of using glass powder on DSM was investigated in previous research; it was found that by increasing glass powder the setting times of mixture pastes increased and UCS improved[21]. Takahashi, et al. (2018) mentioned the use of sodium metasilicate alkaline waste as cement in deep soil mixing to stabilize and increase soil strength[22].

Sharma and Singh also investigated the effect of ash on soil strength in 2020. For this purpose, in this research, 21 samples were made and tested with different proportions of ash. Atterberg limit test, Proctor test and California load bearing ratio (CBR) test were performed to check the strength of different samples. The results show that ash as a waste material improves the strength of stabilized soil so that this increase in strength reaches 71% [23].

In another research conducted by Yorulmaz and Sivrikaya, pavement subsoils were stabilized with two different types of marble powder and California Bearing Ratio (CBR) tests were conducted to evaluate the improvement of their bearing capacity. According to the comparison based on CBR values, the inclusion of the appropriate amount and type of waste marble powder, regardless of the curing time and the number of freezing and thawing cycles, had a positive effect on the bearing capacity of the underlying soil samples[24]. In addition, Abdelkader and his colleagues investigated soil stabilization with granite waste powder. They found that the waste powder of granite stones can be effectively used to improve soil plasticity and control swelling behavior [25].

There are many tile and ceramic industries in some parts of Iran (Yazd). The tile and ceramic industry generates large volume of waste and wastewater that leads to the landfill. Several papers were published on the feasible use of recycled material in DSM [17,21] and use of recycled aggregates and soils from ceramic waste in contraction of landfills, subgrade, concrete blocks and manufacture of concrete [26-29].

A review of the references showed that wastewater from tile and ceramic industry have been never used to stabilize a weak subgrade layer. According to the characteristics of dried ceramic may be the integration as substitute of cement in DSM which would result in a reduction on environmental impacts, and the manufacturing costs of waste management. The present research intends to investigate the feasibility of using wastewater from the local ceramic tile industry, as a potential raw material for DSM in sandy soil for sealing and increasing resistance. A technical methodology for mixture design and specific characterization tests will be developed. Also soil and mixture properties were determined for finite element modeling of road pavements and traffic loading. This would contribute to reducing both environmental effects of wastewater and demand for cement and water.

In general, regarding the innovation of this research, it can be said that the use of deep mixing in improvement projects for lands with low to medium resistance has been expanded in recent decades due to its easy and economical implementation. But the use of environmentally friendly waste resources has received less attention from the industry. Paying attention to microstructural issues and analysis of adhesion and interaction of environmental soil with treated soil is also one of the things that has been given special attention in this research. Although the type of environmental soil that is quick sand has covered large areas of the world, the increase in resistance and improvement of this type of soil by deep mixing method studied in this research shows the innovative aspect of this study.

2. Experimental investigation

2.1. Materials

Materials used in this research include natural sand, ceramic-industry wastewater, cement and water.

2.1.1. Sand

The soil used in this study for treatment via deep soil mixing was the desert sand from Yazd (Iran). Some geotechnical and chemical properties of sand are presented in Table 1, Table 2 and the particle size distribution of the soil is shown in Fig. 1 that it is classified as SP in accordance with the unified soil classification system (USCS).

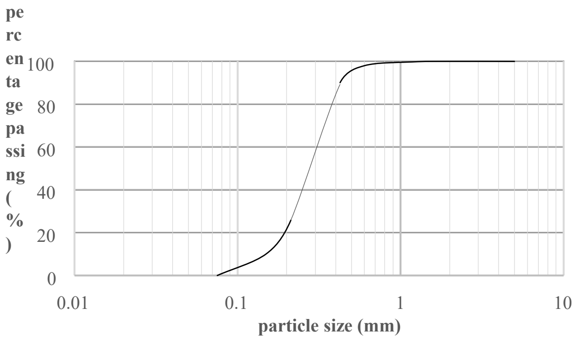


Fig 1. Particle size distribution of sand.

Table 1. Basic geotechnical properties of sand.

Soil properties	
Unified Soil /AASHTO Classification	Sand SW/A-3
Coefficient of uniformity, C_u	2.5
Coefficient of curvature, C_C	1.23
Specific gravity,	2.7
Dry density, γ_d max (kg/m^3)	1845
Optimum water content	16
Cohesion (kPa)	0.1
Angel of internal friction (°)	46
California bearing ratio (%)	28.5

Table 2. Heavy elements and other elements present in the CIWW (XRF test).

	Elements					
Proportion (p.p.m)	As	Ba	Cr	Pb	Rb	Sr
	18	450	1166	406	60	141

2.1.2. Cement

The cement used was ordinary Portland cement. The chemical properties of the cement are given in Table 3.

2.1.3. Ceramic-industry wastewater

The ceramic-industry wastewater (CIWW) used in this study is a mixture of unheated glaze that and water. The wastewater was removed from the production line and drained into the ponds and released into the environment after clotting and drying (see Fig. 2), that is harmful to the environment because it contained heavy metals; according X-ray fluorescence (XRF) test results (Table 3, Fig. 3). The CIWW studied in this paper was obtained from Dorsa Ceram tile industry in Meybod, Yazd, Iran, The chemical properties of the CIWW are given in Table 3.

Fig 2. clotting and drying CIWW.

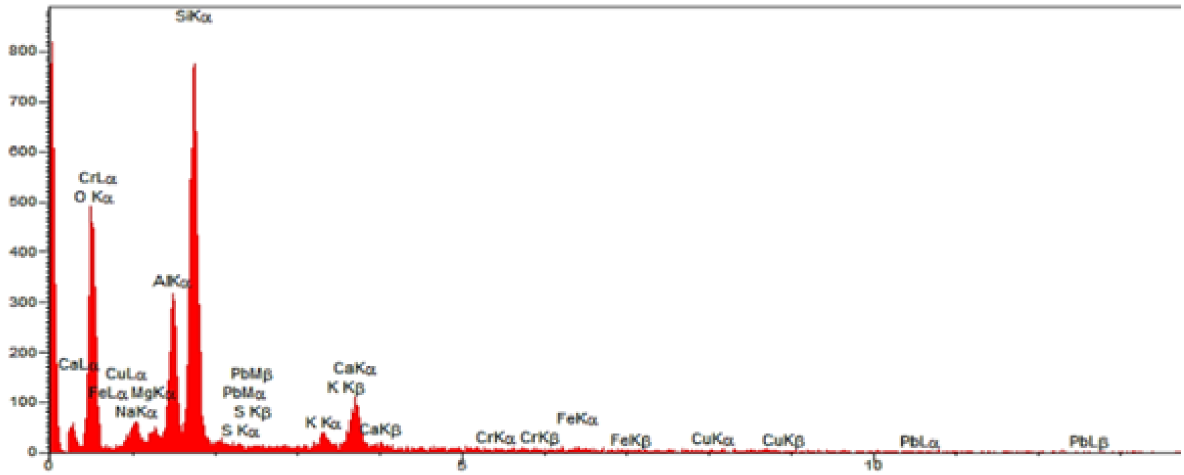


Fig 3. XRD test on the CIWW.

Table 3. Percentage of chemical composition in sand, Portland cement and CIWW, measured by XRF.

Chemical composition	Sand	Ordinary Portland cement	CIWW
SiO2	18.43	20.50	33.29
Al2O3	7.8	4.70	14.22
Fe2O3	7.65	3.50	1.09
CaO	53.89	67	39.24
Na2O3			0.61
MgO	.1.34	2.20	1.60
SO3	2.09		
K_2O	0.65		1.99
TiO2	0.87		0.11
SoO	0.089		
MnO	0.53		0.03
P2O5	0.13		0.14
Na_2O	0.08		
ZrO2			0.60
ZnO			2.5
LOI	3.87	1.5	4.33
Total (%)	96.08	99.40	99.75

2.2.Testing Program

2.2.1 Determining optimum mix proportion

In order to achieve a better understanding of the performance of grout mixing for DSM of sand in this study, a research program comprising some laboratory tests was conducted to assess the influence of the CIWW on the performance of sand. Sample mixtures were built by previous guides. Different percentage of cement and sand added to CIWW to build the samples. Samples were made in UCS molds. After curing the samples for 3 days, UCS test was performed on the samples and according to the required strength that was 2.5 MPa [30][31], the percentage of the binder was obtained, that according Fig. 4 in this study the optimum binder/soil ratio was 20%. The 20% binder/soil ratio is also in agreement with the previous efforts of deep mixing [21][31][30][32].

The sand was sieved (passing 4.75 mm) and then dried in the oven for 24 h to ensure an initial water content of zero. According to the required dried binder, the CIWW with different density was prepared and water, cement and sand added to it Table 4. The grout mixtures were mixed until they were uniform.

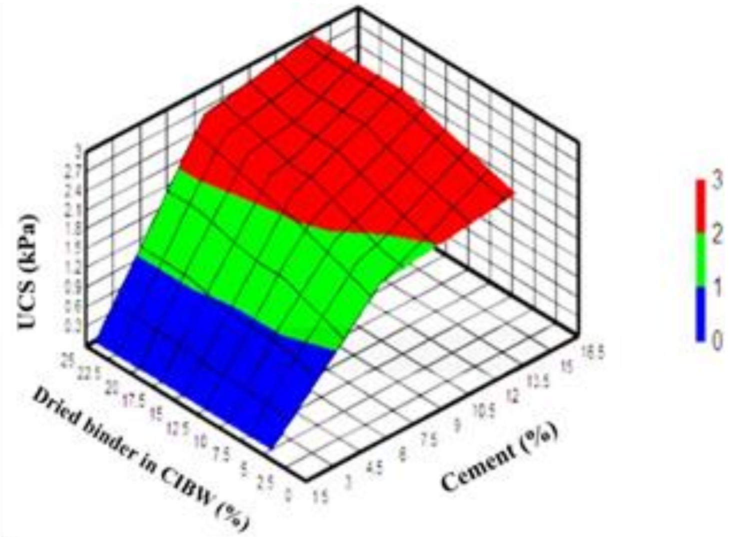


Fig 4. Determining optimum mix proportion of binders.

Table 4. Experimental program of the testing in the study.

Mix	Water/Binde	Cement (%)	Binder (%)	Wate (gr)	Cement (gr)	CBW quantity (Lit)	Dried binde inCBW (gr)	Sand(gr)
M1	2	95	5	341.4	166.3	0.2	43.8	8.8
M2	2	90	10	341.4	157.5	0.2	87.5	17.5
M3	2	85	15	341.4	148.8	0.2	131.3	26.3
M4	2	80	20	341.4	140.0	0.2	175.0	35.0
M5	2	75	25	341.4	131.3	0.2	218.8	43.8
M6	2	70	30	341.4	122.5	0.2	262.5	52.5
M7	2	65	35	341.4	113.8	0.2	306.3	61.3
M8	2	60	40	341.4	105.0	0.2	350.0	70.0
M9	2	50	50	341.4	87.5	0.2	437.5	87.5
M10	2	40	60	341.4	70.0	0.2	525.0	105.0

After preparing each material, the cemented material, which is a mixture of dried wastewater and cement, was first added to the sand. First, samples with different cement-dried wastewater ratio were prepared (three samples for each mix proportion). Water to cement ratio equals to 0.5 was considered [28]. In order to have a similar method for mixture preparation using deep mixing method, the cemented material was prepared as a grout and was added to the sand. The prepared materials were in cylinder-shaped with the diameter and height of 5cm and 10cm, respectively. Once the primary samples were settled, they were removed from the mold (after 24 hours); and then after two days, further studies were performed on them (The total curing period was 3days).

2.2.2. Uniaxial compression strength

The uniaxial compression strength is usually used in order to determine the compression and shear strengths of soil. This is the fastest and most straightforward way to determine the shear strength of the soil. Also, this method is widely used for in-situ tests in order to determine the strength of different types of soils. This test is known as ASTM D 2166-87 standard.

According to specify the unlimited compaction stability components of fix and unstable instances, according to ASTM at the rate of 1.2 mm/min, threads of unlimited compaction trails were done. The pivotal race and pivotal ordinary pressing pressure are given by the appendix terms:

$$\sigma = \frac{P}{A}$$

Which A0 is the primary cross-sectional area of the instance [mm^2], A is the corresponding cross-sectional area [mm2], L0 is the primary length of the trial instance [mm], P is the corresponding stability [kN], ΔL is the length change of sample [mm], σ is the components pressure [kPa], ε is the pivotal race for the given load.

$$\varepsilon = \frac{\Delta L}{L_0}$$

$$A = \frac{A_0}{(1-\varepsilon)}$$

In the present research, the Marshall device was used. By changing the device's jaw, its efficiency became similar to that of the uniaxial test device. First, the sample was placed under the loading jack so that its vertical axis coincided on the loading's center. For better contact, as shown in Fig. 5, an overload with a weight about 0.5kg was placed on the sample. In the next step, the load extent and vertical displacement in every time step were recorded. Generally, the readings should be continued until one of the following scenarios is reached:

1. Load reduced in the sample.

2. Load is the same for four consecutive readings.

3. Displacement continues until 15% .

The test method is shown in Figure 6.

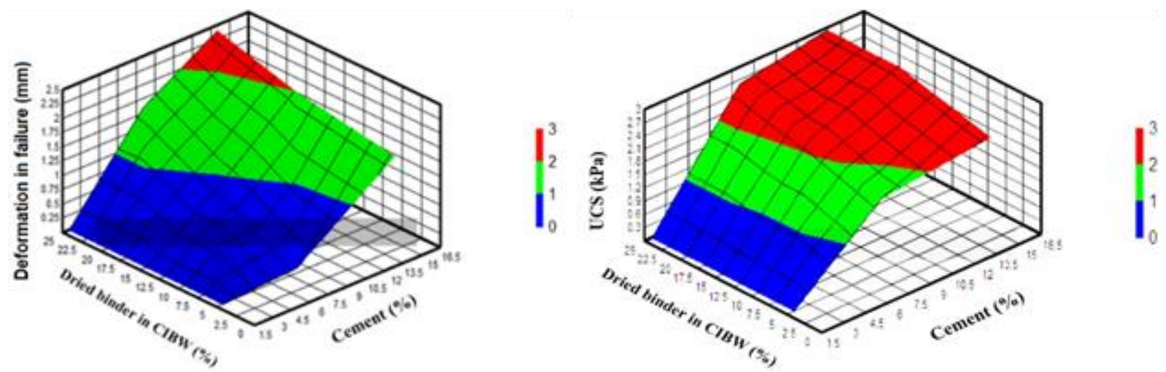


Fig 5. A 3D-curve showingUSC(above) and deformation(botom) at the failure's moment for a different proportion of additives.

Fig 6. The prepared grout sample to be placed under the loading device and an overburden of 0.5 kg.

As you see during unlimited compaction trial, Figure 7 indicates a generic race-softening curve, with the subordinate phrase of σ= σ($\boldsymbol{\varepsilon}$). many significant characteristic ingredients could be respectively obtain from the curve, inclusive peak power q_u, fracture race ε_u, primary springy factor E_0, and remaining stability q_c. of subordinate phrases of these ingredients in The appendix equations are fixed..

$$q_u = Max\ \sigma(\varepsilon)$$

$$q_u = \sigma(\varepsilon_u)$$

$$E_0 = \frac{d\sigma(\varepsilon)}{d\varepsilon}|\varepsilon{=}0$$

$$q_c = \lim_{\varepsilon\to\infty} \sigma(\varepsilon)$$

The loading procedure of unlimited compaction trial can be behaved as an action of energy condensation and liberation. According to the law of energy condensation, work done by pivotal force F while trialing can be used to specify energy waste while the loading procedure, as shown in Figure7.

$$W_S = \int_0^{S^*} Fds$$

Therefore F =σ (ε) A; s = εH; A and H are the cross section and elevation of the instance, respectively. A was 1200 mm2 and H was 80 mm, In this article. The appendix equation has been concluded. it is important to citation ε∗ = ε(u) + 5%[33].

$$W_S = \text{AH} \int_0^{\varepsilon^* H} \sigma\ (\varepsilon) d\varepsilon$$

As the proportion of cement and wastewater increases, the strain samples at the moment of failure increases. According to Fig. 7, for the samples in which the cement proportion was less than 7.5, the axial strain was more a function of the amount of dried wastewater, and the proportion of cement can be ignored in determining the strain samples. The relation between wastewater and strain samples for cement proportions less than 7.5 has been shown in Fig. 7. One reason for greater changes in strain for a different proportion of dried wastewater can be attributed to its higher proportion than the cement.

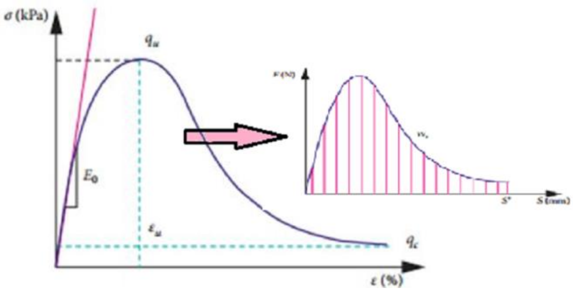


Fig 7.A- Typical stress-strain curve occurred and energy dissipation during unconfined compression test.

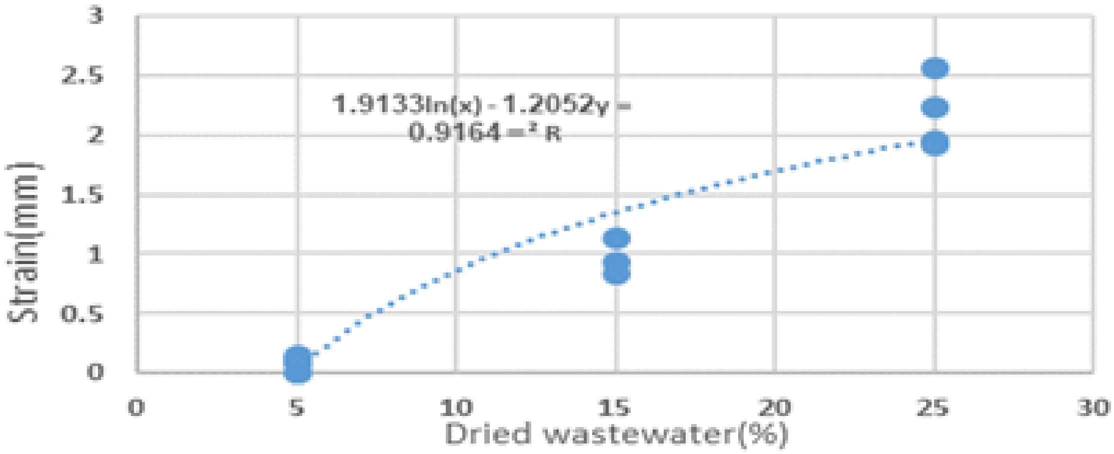
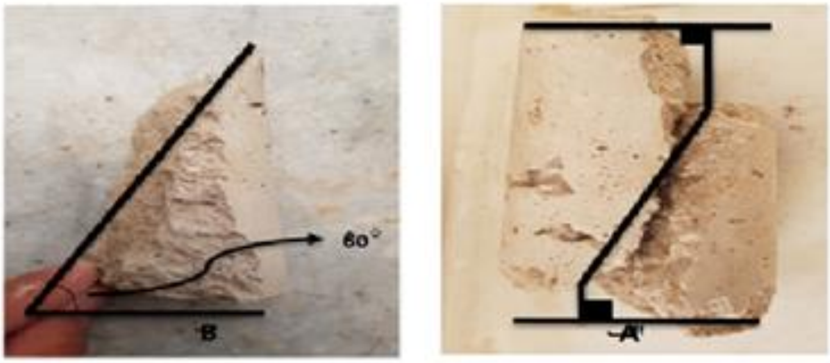
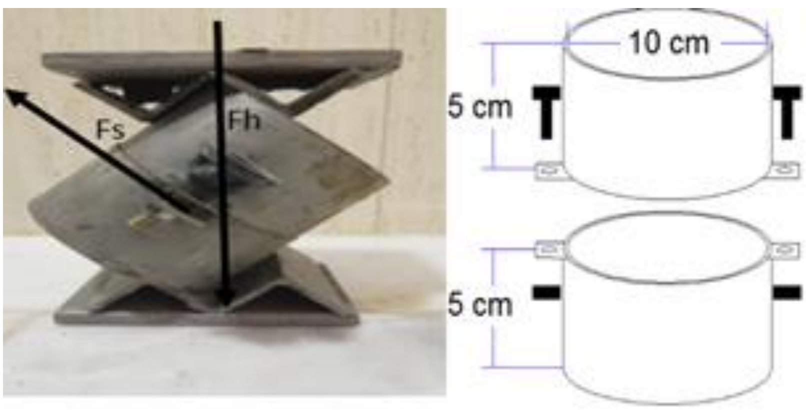


Fig 8. Strain curve against varying values of dried wastewater.

The samples are mainly a failure, according to Fig. 8, and a few numbers of samples had different failure surface, which were irregular and fragmented. By checking how the samples were a failure, it was found that failure and fracture of samples have occurred in shear form.



A



B

Fig 9. A-(a) The failure shape of the sample, and (b) failure angle of samples.B- Forces applied to the samples' surface- preparing the sample for loading.

2.2.3. Inter-layer bonding test

One of the essential parameters used in designing rigid and flexible pavement and also designing micro-piles is the extent of shear strength between the involved surfaces. Determining the amount of inter-layer bonding of the pavement, especially pavement-subgrade soil bonding, is one of the most critical parameters in designing the pavements. Most of the pavement failures occur due to the lack of appropriate amount of inter-layer bonding; which has become an essential issue in this field. All forces applied to the sample's surface are shown in Fig. 9-B.

$$F_s = F_h \times Sin\theta$$
$$F_h = (w_1 + w_2 + w_3)g + F_w$$

where,

F_s is the maximum adhesion force between two surfaces (N).

F_h is all forces normal to the surface of two samples (N).

F_w is the force applied by the device (N).

w_1 is the weight of the upper jaw (kg).

w_2 is the weight of lower mold (kg).

w_3 is the weight of the sample inside the upper mold (kg).

The lower mold was stabilized with sand, while the upper side was prepared with the subbase stabilized with cement. In fact, the purpose of this test was to investigate the amount of adhering of subbase stabilized with cement and was for constructing the road.

3. Results and discussion

In this section, the results obtained from the investigation of bonding between different surfaces are discussed. The obtained results were used to determine the adhesion between surfaces in the model.

To investigate the effect of different conditions on samples, their strengths at two different conditions i.e. saturated and dried after being saturated, have been investigated, shown in Fig. 11. As the samples saturated, they lose nearly 50% of their strength. Fig. 12, shows the stress-ultimate strain plot for a sample built with optimal mix design; also, the sample was investigated for unidirectional strength of saturated condition. The elasticity module obtained from Fig. 11, was used for modeling. Besides, the elasticity module obtained from Fig. 12, was used to model the sand cushion soil.

3.1. Variations of the strength of sand treated with different curing time

Different proportions of additives to be added to sand were determined in the previous section. The proportion for cement was 7.5%, and for dried wastewater is 12.5% by the weight of dried materials. The dried materials include sand, cement and wastewater. According to Fig. 10, with the addition of cement, the soil strength increases; but the research aimed to obtain a mixture despite having proper strength, its cement proportion was minimum. According to the investigations, in the beginning, the uniaxial strength of sand was negligible and nearly zero; with some modifications, this value reached to about 5 kg/cm^2. It should be noted that the consumables include 7.5% of cement and the remaining additives were prepared from the waste materials available in the ceramic-industry backwater.

According to Fig. 10, it was found that, after 10 days, the samples achieved 80% of their ultimate strength. Given the chemical compounds of dried wastewater, including high amounts of SiO_2 ، Fe_2O_3 و Al_2O_3, it can be used as Pozzolanic material. According to standard ASTM C 618, if the sum of the Pozzolanic oxygenated materials is more than 70%, it is regarded as a Pozzolanic material. The corresponding value for dried wastewater is approximately 80%. Therefore, it was observed from the curing curve that rapid hydration and Pozzolanic reactions were initially performed and gradually deaccelerated with the time. Despite the strength, the settling at the failure-time was also investigated for every sample. Generally, the variation of samples' settling at the failure-time was insignificant, such that it can be considered to be constant over time (Fig. 11).

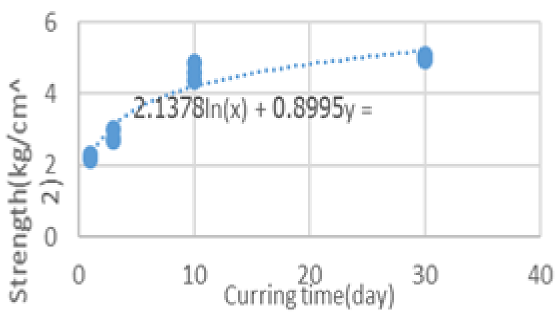


Fig 10. Strength variation of sample built with optimal mix design over time.

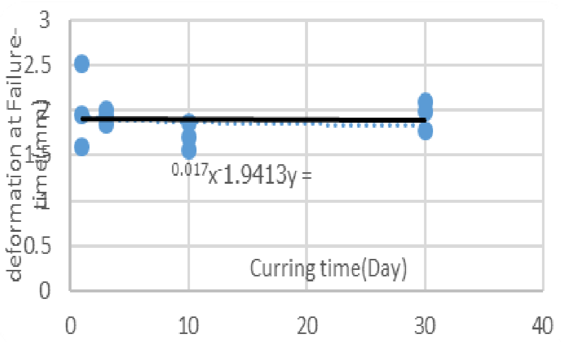


Fig 11. The relation between deformation at failure-time of sample built with optimal mix design over time.

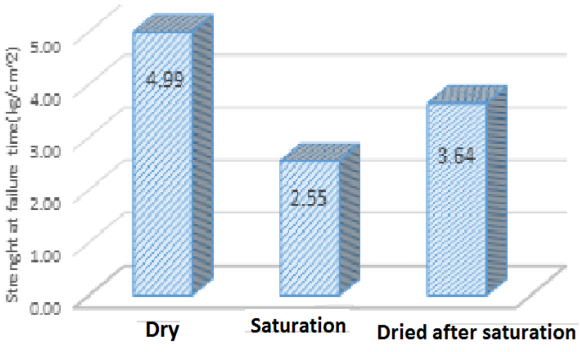


Fig 12. Strength variations of sample built with optimal mix design at different conditions.

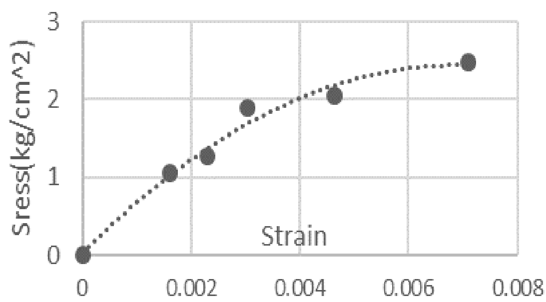


Fig 13. Stress-strain curve of the sample at the saturated condition.

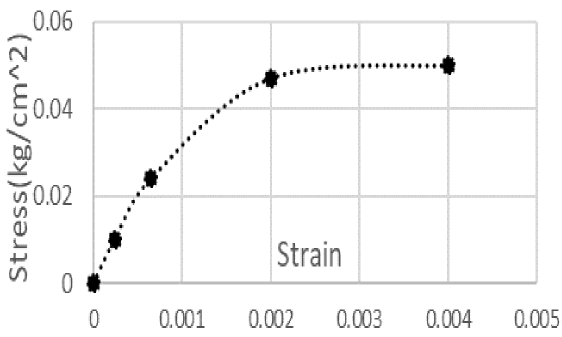


Fig 14. Stress-strain curve of sand.

Table 5. Results obtained from uniaxial tests for samples with optimal mix design at different co nditions.

Sample	Curing condition	Curing period (day)	Ultimate strength (kg)	Pressure (kg/cm^2)	Deformation at failure-time (mm)
1-1	Dried	1	45	2.31	2.51
1-2	Dried	1	43	2.19	1.60
1-3	Dried	1	42	2.15	1.95
2-1	Dried	3	54	2.75	1.94
2-2	Dried	3	53	2.7	2.00
2-3	Dried	3	59	3	1.84
3-1	Dried	10	90	4.6	1.56
3-2	Dried	10	86	4.37	1.70
3-3	Dried	10	96	4.87	1.87
4-1	Dried	30	100	5.09	1.98
4-2	Dried	30	97	4.94	2.10
4-3	Dried	30	99	5.04	1.77
5-1	Dried-Saturated	30 <	56	2.85	1.17
5-2	Dried-Saturated	30 <	44	2.24	1.85
6-1	Dried-Saturated-Dried	30 <	70	3.57	1.93
6-2	Dried-Saturated-Dried	30 <	73	3.72	0.97

3.2. The shear force created between sand and cured sand (Treated with cement and dried wastewater)

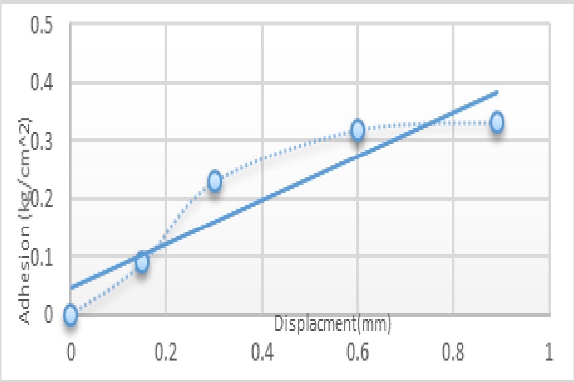
To determine the shear force created between the sand and cured sand, the shear force was investigated using the built mold. According to Fig. 8, in the beginning, the force has an ascending trend, and eventually remains constant until the sample is fractured.

The similar results with the previous case were obtained for the surface of cured sand and cement-stabilized subgrade. On the contact surface of the cement layer and cured sand, the shear force had a higher amount. The reason for this higher amount, than the previous case, can be attributed to the following factors:

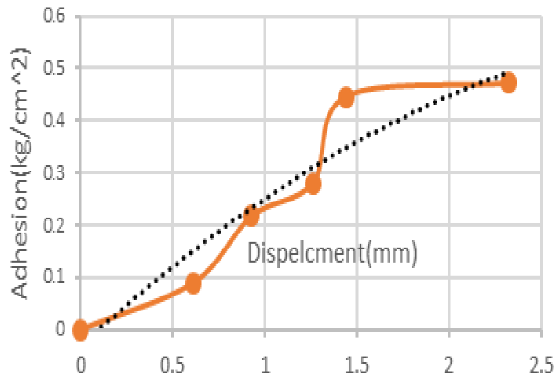
-Penetration of slurry water of both mixtures into each other.

-The more contact surface of two layers due to penetration of coarse-grain particles of subgrade into fine-grain mix surface (cured sand).

According to Fig. 15, the adhesion of sand ,0.35 kg/cm2 and adhesion of subgrade stabilized with the cement of 0.45kg/cm^2 were obtained.



A



B

Fig 15. A-Adhesion and corresponded deformation in measuring the shear force between sand and cured sand B- Adhesion and corresponded deformation in measuring the shear force between d cured sand and cement-stabilized subgrade.

3.3. Analysis of scanning electron microscopy (SEM)

In order to investigate and analyze the microstructure of cured sand soil, the SEM test was performed in the sand and cured samples(Table.6). The cured samples which have been investigated in this section, have a different proportion of cement and wastewater. Sample 1 has 14% of cement and 25% of dried wastewater; sample 2 has 14% of cement and 15% of dried wastewater; sample 3 has 7.5% of cement and 12.5% of wastewater. The samples 1 to 3 have been shown in Figs. 16, 17, 18 and 19, respectively.

Table 6. Samples checked with SEM.

Sample	Cement (%)	Dried wastewater (%)	Sum of cemented materials (%)	Figure
1	0	0	0	17
2	7.5	12.5	20	18
3	14	15	29	19
4	14	25	39	20

As it is clear from Fig. 16, desired sand has particles with uniform sizes. The additives have cemented property which caused the sand grains adhered to each other during the Pozzolanic process, indicated in Figs. 17, 18, and 19. Also, these figures show how the sand grains adhere to each other. By increasing the cemented materials, the strength of samples increases. The reason for increased adhesion can be attributed to filling the empty space between sand grains with cemented materials and the formation of a stronger adhesion between the soil grains. By adding too much cemented materials to sand, it is predicted that their compression strength decreases, because, with an increase in cemented materials, the empty space between the sand is first filled and keeps the sand grains together (Fig. 19); however, as the addition of cemented materials exceeds a specific limit, the empty space between the sand grains increases and the grains are spaced apart. This is similar to a scenario in which, adding too much bitumen to asphalt mixture, exceeding an optimal limit, causes a reduced interaction of mixture aggregates.

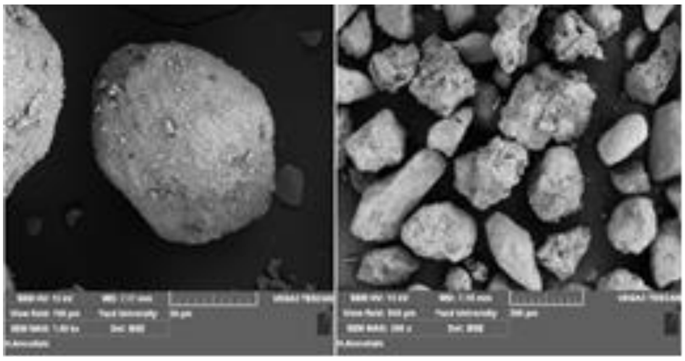


Fig 16. Magnified images of sand soil surface.

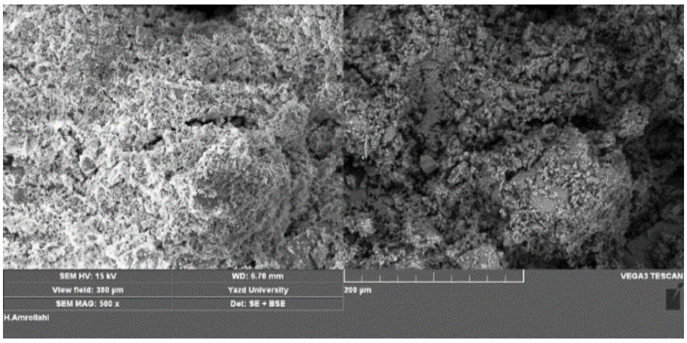


Fig 17. Magnified images of surface sample with 14% cement and 25% wastewater.

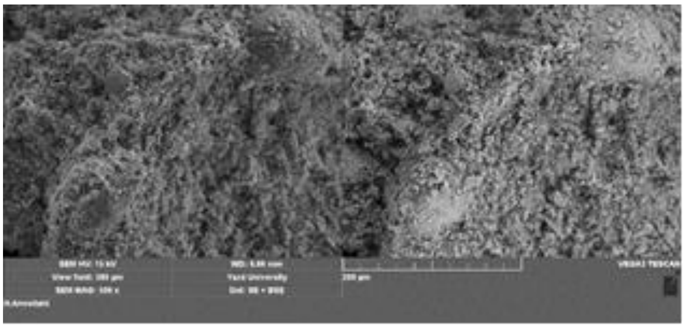


Fig 18. Magnified images of surface sample with 14% cement and 15% wastewater.

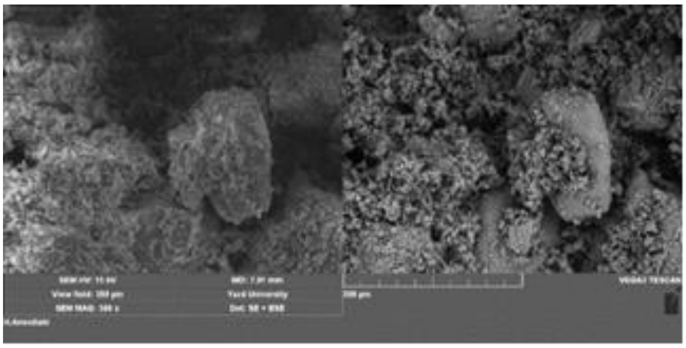


Fig 19. Magnified images of surface sample with 7.5% cement and 12.5% wastewater.

4. Conclusions

Dealing with weak soils is a major problem in road construction projects. The construction of any structure on such types of soil might result in a lot of damages. One way to stabilize these types of soil is to use the deep mix method. In this research, the steps for building mixtures used for executive operations were investigated.

• Given the investigations performed, the soil was of type A-7-5. the initial soil had a density of 2.43 , a liquid limit of 75, and a construction limit of 42%. By investigating the results obtained from XRF and EXD tests, it was found that the soil is composed of oxygen, aluminum, silicon and calcium oxides, so the material was of the Pozzolanic type. Besides, some quantity of heavy metals was found in the soil compound, which alleviated its harmful effects on the environment.

• After preparation of sand, its different parameters were evaluated. The investigation of the soil gradation showed that the soil falls in the A-3 category. The properties of the soil were determined as follows: density: 2.7, California bearing ratio (CBR): 28.5, adhesion: zero, internal friction angle: 46, optimum moisture content: 46%, and maximum dry density: 1845 kg/m3. Based on the stress-strain plot for sand, its maximum uniaxial strength was 0.05 kg/cm2 and its elasticity module was 5.1 MPa.

• The proper weight content for cement and dried wastewater was 7.5 and 12.5, respectively; then, the microstructure and density of the samples built with different contents of cement and wastewater were compared.

• By investigating different curing time, it was found that the mixture obtained its maximum ultimate strength on Day 10. However, the increase in strength continued until Day 30. The maximum strength on day 30 was 5.04 kg/cm^2. The uniaxial strength for the saturated sample was 2.5 kg/cm2 indicating a 50% reduction in strength for the saturated condition. Moreover, the elasticity modulus for the sand in the saturated condition was 66MPa.

• After building the mold, the adhesion strength between the cured sand and sandy soil, as well as between the cured sand and cement-stabilized subgrade, was 35 MPa and 45 MPa, respectively.

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References

[1] J. Huang, R. B. Kogbara, N. Hariharan, E. A. Masad, and D. N. Little, “A state-of-the-art review of polymers used in soil stabilization,” *Constr. Build. Mater.*, vol. 305, p. 124685, 2021.

[2] T. Harianto, “Performance of Subbase Layer with Geogrid Reinforcement and Zeolite-Waterglass Stabilization,” *Civ. Eng. J.*, vol. 8, no. 2, pp. 251–262, 2022.

[3] S. Ghareh, F. Akhlaghi, and K. Yazdani, “A Study on the Effects of Waste Rubber Tire Dimensions on Fine-Grained Soil Behavior,” *J. Rehabil. Civ. Eng.*, vol. 8, no. 3, pp. 15–33, 2020.

[4] N. Tiwari, N. Satyam, and A. J. Puppala, “Effect of synthetic geotextile on stabilization of expansive subgrades: experimental study,” *J. Mater. Civ. Eng.*, vol. 33, no. 10, p. 4021273, 2021.

[5] A. J. Puppala, R. S. Madhyannapu, S. Nazarian, D. Yuan, and L. R. Hoyos, “Deep soil mixing technology for mitigation of pavement roughness,” 2008.

[6] E. A. Basha, R. Hashim, H. B. Mahmud, and A. S. Muntohar, “Stabilization of residual soil with rice husk ash and cement,” *Constr. Build. Mater.*, vol. 19, no. 6, pp. 448–453, 2005.

[7] S. H. Bahmani, B. B. K. Huat, A. Asadi, and N. Farzadnia, "Stabilization of residual soil using SiO2 nanoparticles and cement," *Constr. Build. Mater.*, vol. 64, pp. 350–359, 2014.

[8] S. F. Su, "Anisotropic strength evaluation of clay reinforced with grout piles," *J. Geotech. geoenvironmental Eng.*, vol. 135, no. 10, pp. 1529–1537, 2009.

[9] M. M. Khabiri, "The effect of stabilized subbase containing waste construction materials on reduction of pavement rutting depth," *Electron. J. Geotech. Eng.*, vol. 15, pp. 1211–1219, 2010.

[10] M. Saberian and M. M. Khabiri, "Experimental and numerical study of the effects of coal on pavement performance in mine haul road," *Geotech. Geol. Eng.*, vol. 35, no. 5, pp. 2467–2478, 2017.

[11] S. Bressi, M. Primavera, and J. Santos, "A comparative life cycle assessment study with uncertainty analysis of cement treated base (CTB) pavement layers containing recycled asphalt pavement (RAP) materials," *Resour. Conserv. Recycl.*, vol. 180, p. 106160, 2022.

[12] L. S. Wong, S. Mousavi, S. Sobhani, S. Y. Kong, A. H. Birima, and N. I. M. Pauzi, "Comparative measurement of compaction impact of clay stabilized with cement, peat ash and silica sand," *Measurement*, vol. 94, pp. 498–504, 2016.

[13] A. Sukpunya and A. Jotisankasa, "Large simple shear testing of soft Bangkok clay stabilized with soil--cement-columns and its application," *Soils Found.*, vol. 56, no. 4, pp. 640–651, 2016.

[14] P. Sukontasukkul and P. Jamsawang, "Use of steel and polypropylene fibers to improve flexural performance of deep soil--cement column," *Constr. Build. Mater.*, vol. 29, pp. 201–205, 2012.

[15] Y. Zhuang and K. Wang, "Numerical simulation of high-speed railway foundation improved by PVD-DCM method and compared with field measurements," *Eur. J. Environ. Civ. Eng.*, vol. 21, no. 11, pp. 1363–1383, 2017.

[16] C. A. Scanlan and S. L. Davies, "Soil mixing and redistribution by strategic deep tillage in a sandy soil," *Soil Tillage Res.*, vol. 185, pp. 139–145, 2019.

[17] M. Saberian, M. Moradi, R. Vali, and J. Li, "Stabilized marine and desert sands with deep mixing of cement and sodium bentonite. Geomech. Eng. 14 (6), 553--562 (2018)." .

[18] R. Alipour, J. Khazaei, M. S. Pakbaz, and A. Ghalandarzadeh, "Settlement control by deep and mass soil mixing in clayey soil," *Proc. Inst. Civ. Eng. Eng.*, vol. 170, no. 1, pp. 27–37, 2017.

[19] R. C. Karra and B. C. Gayana, *Mine Waste Utilization*. CRC Press, 2022.

[20] G. O. Akintola, "Evaluation of major clay deposits for potential industrial utilization in Vhembe District Municipality," *Limpopo Prov. South Africa (Doctoral Diss.*, 2018.

[21] H. Güllü, H. Canakci, and I. F. Al Zangana, "Use of cement based grout with glass powder for deep mixing," *Constr. Build. Mater.*, vol. 137, pp. 12–20, 2017.

[22] H. Takahashi, Y. Morikawa, N. Fujii, and M. Kitazume, "Thirty-seven-year investigation of quicklime-treated soil produced by deep mixing method," *Proc. Inst. Civ. Eng. Improv.*, vol. 171, no. 3, pp. 135–147, 2018.

[23] V. Sharma and S. Singh, "Modeling for the use of waste materials (Bottom ash and fly ash) in soil stabilization," *Mater. Today Proc.*, vol. 33, pp. 1610–1614, 2020.

[24] A. Yorulmaz, O. Sivrikaya, and F. Uysal, "Evaluation of the bearing capacity of poor subgrade soils stabilized with waste marble powder according to curing time and freeze-thaw cycles.," *Arab. J. Geosci.*, vol. 14, no. 5, pp. 1–10, 2021.

[25] H. A. Abdelkader, A. S. Ahmed, M. M. Hussein, H. Ye, and J. Zhang, "An Experimental Study on Geotechnical Properties and Micro-Structure of Expansive Soil Stabilized with Waste Granite Dust," *Sustainability*, vol. 14, no. 10, p. 6218, 2022.

[26] B. Huang, Q. Dong, and E. G. Burdette, "Laboratory evaluation of incorporating waste ceramic materials into Portland cement and asphaltic concrete," *Constr. Build. Mater.*, vol. 23, no. 12, pp. 3451–3456, 2009.

[27] J. Pooni, F. Giustozzi, D. Robert, S. Setunge, and B. O'Donnell, "Durability of

enzyme stabilized expansive soil in road pavements subjected to moisture degradation," *Transp. Geotech.*, vol. 21, p. 100255, 2019.

[28] H. Koyuncu, Y. Guney, G. Y\ilmaz, S. Koyuncu, and R. Bakis, "Utilization of ceramic wastes in the construction sector," in *Key Engineering Materials*, 2004, vol. 264, pp. 2509–2512.

[29] F. Pacheco-Torgal and S. Jalali, "RETRACTED ARTICLE: Compressive strength and durability properties of ceramic wastes based concrete," *Mater. Struct.*, vol. 44, no. 1, pp. 155–167, 2011.

[30] D. A. Bruce and E. C. O. Geosystems, "An introduction to the deep soil mixing methods as used in geotechnical applications," 2000.

[31] "FHWA, Federal Highway Administration Design Manual: Deep Mixing for Embankment and Foundation, Deep Mix. Embankment Found. Support. (2013) 228."

[32] A. Farouk and M. M. Shahien, "Ground improvement using soil--cement columns: Experimental investigation," *Alexandria Eng. J.*, vol. 52, no. 4, pp. 733–740, 2013.

[33] P. Jiang, T. Mao, N. Li, L. Jia, F. Zhang, and W. Wang, "Characterization of short-term strength properties of fiber/cement-modified slurry," *Adv. Civ. Eng.*, 2019.