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Evaluation of strength properties of cement stabilized sand mixed with EPS beads and fly ash

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Abstract. The importance of using materials cost effectively to enhance the strength and reduce the cost, and weight of earth fill materials in geotechnical engineering led researchers to seek for modifying the soil properties by adding proper additives. Lightweight fill materials made of soil, binder, water, and Expanded polystyrene (EPS) beads are increasingly being used in geotechnical practices. This paper primarily investigates the behavior of sandy soil, modified by EPS particles. Besides, the mechanical properties of blending sand, EPS and the binder material such as fly ash and cement were examined in different mixing ratios using a number of various laboratory studies including the Modified Standard Proctor (MSP) test, the Unconfined Compressive Strength (UCS) test, the California Bearing Ratio (CBR) test and the Direct Shear test (DST). According to the results, an increase of 0.1% of EPS results in a reduction of the density of the mixture for 10%, as well as making the mixture more ductile rather than brittle. Moreover, the compressive strength, CBR value and shear strength parameters of the mixture decreases by an increase of the EPS beads, a trend on the contrary to the increase of cement and fly ash content.

Keywords: sand; EPS; fly ash; cement; unconfined compression strength; California bearing ratio; direct shear test

1. Introduction

There are various physical or chemical techniques to improve properties of soil for construction (e.g., Parsa-Pajouh *et al.* 2016, Azari *et al.* 2016, Nguyen *et al.* 2017) while recently application of recycled materials for ground improvement has become more attractive (e.g., Nguyen and Fatahi 2017, Fatahi *et al.* 2013). For the past three decades, Expanded Polystyrene (EPS) has widely been used in many geotechnical applications including pavements, railways, retaining walls and slope stability purposes, as well as improving the seismic performance of granular fills, filling the embankment, solidification and stabilization of the soil, etc.

EPS beads and EPS blocks are various types of environmentally friendly Expanded PolyStyrene, which having them mixed with the soil is proved to be a viable alternative, especially when the installation of large geofoam blocks is not feasible. The addition of low-density EPS beads into the soil can dramatically affect the density and mechanical properties of the mixtures. Besides, mixing soil with cement or other pozzolanic materials such as fly ash or lime, for shallow fills or deep in-situ placements is common practice to improve the performance of the soil.

The first use of EPS geo-foam blocks was reported in Norway in 1965. Kaniraj *et al.* (2001) studied geotechnical characteristics of fly ash-soil mixtures with fiber inclusion and cement stabilization. Tsuchida *et al.* (2001) presented the results of engineering properties of a geomaterial, comprised of the Portland cement stabilized mud, dredged from Tokyo Bay and mixed with lightweight additives, such as foam or expanded polystyrene beads. Babu *et al.* (2006) covered the effect of EPS beads as lightweight aggregates on the mechanical properties of EPS concrete with fly ash, both in concrete and mortar. Finally, they compared their results with those found in the literature regarding concretes containing merely ordinary Portland cement (OPC) as the binder. Babu *et al.* (2005) also in another study, reported on the usage of expanded polystyrene (EPS) and un-expanded polystyrene (UEPS) beads as lightweight aggregates in concrete containing fly ash as a supplementary cementitious material. Deng and Xiao (2010) evaluated EPS-sand mixture specimens to observe their stress-strain characteristics using consolidated-drained (CD) triaxial compression tests and showed, increasing EPS content led to decreased shear strength and increased volumetric strain. Miao *et al.* (2010) discussed the geotechnical characteristics of the lightweight fill materials, using sand mixed with EPS beads and cement as a binder. Gao *et al.* (2011) provided a comprehensive review of geotechnical properties of EPS-soil mixtures, including the unit weight, the compressive strength, permeability, dynamic properties, creep properties, and water absorption characteristics. Kogbara *et al.* (2013) evaluated the mechanical and P^H-dependent leaching performance of a mixed contaminated soil, treated with a mixture of Portland cement (CEMI) and fuel ash (PFA). Miao *et al.* (2012) examined the effect of EPS beads and cement on the mechanical properties of lightweight

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materials. Herki *et al.* (2013) reported the effects of fly ash and a type of waste EPS-based lightweight aggregates, called Stabilized Polystyrene (SPS) in concrete. Deng and Feng (2013) carried out an experimental study to model the mechanical response of EPS-backfill regarding cemented structure of the material. Padade and Mandel (2014), carrying out an experimental laboratory study, investigated the mechanical properties of expanded polystyrene-based geomaterial (EPGM) with fly ash. Jamshidi *et al.* (2016) also evaluated the applicability of EPS beads mixed with sand in five different contents and measured some of their vital properties such as permeability, coefficient of earth pressure ‘‘at-rest” and the coefficient of volume compressibility. Marjive *et al.* (2016) presented the results of an experimental study carried out through compressive strength tests on materials made of stone dust and EPS beads. Marjive *et al.* (2016) also reported on a series of compressive strength tests; performed on newly developed construction materials (NDCM) made of stone dust, EPS beads plus binder materials such as cement.

Cement and fly ash have long been added to granular materials as binder agents to improve their strength and stiffness properties (Yilmaz *et al.* 2017, Shooshpasha and Alijani 2015, Karabash and Firat 2015, Azadegan *et al.* 2014, Frydman 2011 and Bera and Chakraborty 2015). However, no study has yet been reported to incorporate their mutual utilization into an EPS beads-sand mixture. This paper evaluates the engineering properties of sandy soil mixed with EPS, class *F* fly ash and cement in different mix ratios through laboratory studies. Modified Standard Proctor (MSP) test was carried out to examine the optimum moisture content and the maximum dry density of the mixtures. The unconfined compressive strength (UCS) and California bearing ratio (CBR) test were put into practice to gain an insight into the strength of materials. The effect of different additives on the friction angle and cohesion of the mixture was also appraised by direct shear test (DST). Moreover, comprehensive reviews of other studies were conducted for the sake of comparison and verification of the results.

2. Experimental programs

2.1 Materials

The sand used in this study was taken from Chamkhaleh beach in Guilan province, located in the north of Iran, for which Jamshidi *et al.* (2016) has also provided magnified photos of particles. Table 1 along with Fig. 1 present the physical properties and the particle-size distribution curve of this sand.

The EPS beads are white rounded particles with a diameter about 2 to 4 mm and density about 0.008 g/cm^3. In EPS geofoams, which undergo a manufacturing process, the resin beads are exposed to heat so that they steam at a temperature of 100-110℃. As the beads are expanded, the density decreases and the lighter particles are moved upward and discharged. The final product often called polystyrene pre-puffed (PSPP) beads, are expanded up to 40 times the original resin bead size after the pre-expansion process. After pre-expansion, the PSPP is transferred to the storage hoppers where the cell walls are cooled and hardened, and any remaining blowing agents are diffused through the cell walls and replaced by the ambient air (Rocco 2012).

Table 1 Properties of sand used in this study

UCSC (ASTM D2487-11)	Density (g/cm^3)	Specific gravity	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	C_u	C_c
SP	1.86	2.65	0.12	0.19	0.26	2.14	1.11

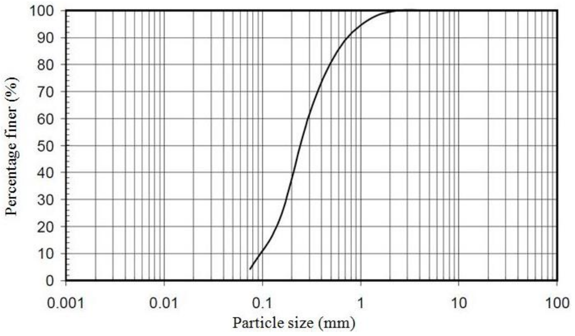


Fig. 1 Particle size distribution curve of the “Chamkhaleh” sand

Table 2 Chemical composition and physical properties of the fly ash used in this study

Composition or property	value
Chemical composition (%)	
Silica (SiO_2)	59.3
Alumina (Al_2O_3)	23.4
Iron oxide (Fe_2O_3)	4.8
Lime (CaO)	8.6
Magnesia (MgO)	0.6
Soda (Na_2O)	3.2
Potash (K_2O)	-
Sulfates (SO_3)	0.1
Physical property	
Specific gravity	2.54
Loss on ignition (LOI) (%)	1.4
Specific surface area (cm^2/g)	4100

Table 3 Mix proportions examined in this study

EPS (%)	Cement (%)	Fly Ash (%)
0.25, 0.35, 0.45	4, 6, 8	0, 6, 12

Fly ash, which is produced by coal-fired electric and steam generating plants, can be classified as either class *C* or class *F* ash according to ASTM C 618 (ASTM 1993). The class *C* fly ash can be used as a stand-alone material because of its self-cementitious properties. Class *F* fly ash can be used in geotechnical applications with the addition of a cementation agent (lime, lime kiln dust, CKD, and cement). In this study, the fly ash of class *F*, as well as the Portland cement of type-1, was put into practice as the binder to make bonding between the sand particles and EPS beads. Table 2 presents the chemical composition and physical properties of the used fly ash (Rossow 2003).

2.2 Mixing proportions

The specimen preparing procedure included mixing weight-based proportions of the sand, cement, fly ash and EPS beads together and then adding water to the mixture.

All specimens were prepared at the Optimum Moisture Content (OMC) and the Maximum Dry Density (MDD) so that the highest strength of materials could be achieved after compaction. Besides, samples were cured for 7 and 14 days to account for the effect of curing period on the mechanical properties of the mixture. Details of the mix proportions for the UCS, CBR and DST experiments carried out in this study are presented in Table 3. In the current study, the bulk density was maintained constant (γ=1.5 g/cm^3). This means that higher compaction efforts are required to achieve the same bulk density when the EPS content rises. This is reached by applying more compaction efforts and blows to contain a constant overall mixture weight in test mould. The reason is that more voluminous constituents should be contained in the mould with increasing the EPS content. Some researchers have achieved higher EPS contents by maintaining the compaction effort only. Obviously, the bulk density decreases with EPS content in such cases. Therefore, the mechanical parameters change is not solely due to EPS inclusion. It is the mutual effect of inclusion and density effect.

2.3 Modified standard proctor tests

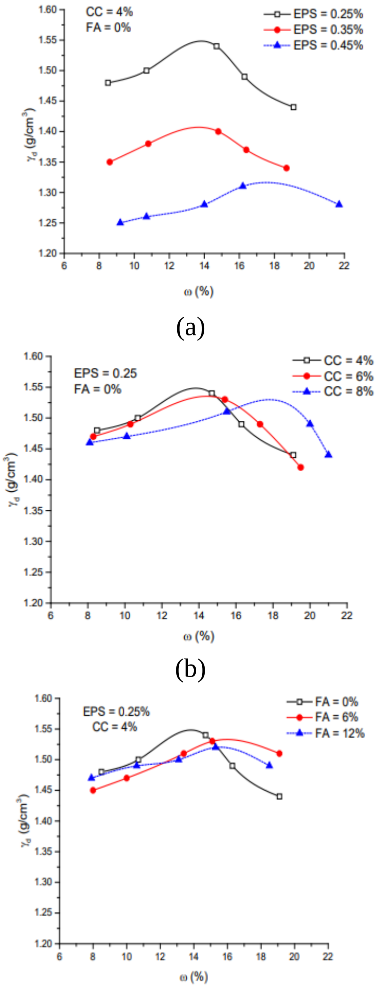
Modified standard Proctor (MSP) tests (ASTM D1557 - 12e1) were undertaken to obtain the OMC and the MDD of the mixture, as summarized in Table 4. Besides, carrying out the MSP test, made it feasible to appraise the effect of different materials including EPS, cement and fly ash content on the OMC and MDD of the mixture, presented as follows.

2.3.1 Effect of EPS

The compaction behavior of the mixture in Fig. 2, indicates that the OMC ranges between 14.7 to 16.2. Besides, increase in the EPS beads has no remarkable impact on the OMC, while it reduces the MDD of the samples. This is because firstly, the density of EPS is much less than the other materials and secondly, EPS beads are damping some of the compaction energy. Nevertheless, increasing the amount of fly ash and cement content decreases the MDD and increases the OMC of the samples.
Similar results were also obtained by other researchers. For instance, Marjive *et al.* (2016), Padade and Mandal (2014), Herki *et al.* (2013), Deng and Feng (2013), Edinçliler and Özer (2014), Rocco and Luna (2013) and Babu *et al.* (2006) demonstrated that increase of EPS beads results in a reduction of the MDD of the mixture, as illustrated in Fig. 3.

2.3.2 Effect of cement content

Miao *et al.* (2010), Padade and Mandal (2014), Gao *et al.* (2011), Miao *et al.* (2012) and Kogbara *et al.* (2013), expressed that cement content has no significant effect on the MDD and the OMC of the samples. Although Brooks *et al.* (2010) showed that the MDD and the OMC of the sample could be decreased and increased, respectively, when the amount of pozzolanic material is increased. However, bearing in mind that the compaction behavior of the mixture depends on different factors including the material type and composition, a slight discrepancy might be found between the results of this study and that of other researches.



(a)

(b)

(c)

Fig. 2 Effect of different compositions on OMC and MDD (CC: Cement Content, FA: Fly Ash), (a) EPS, (b) cement content and (c) fly ash

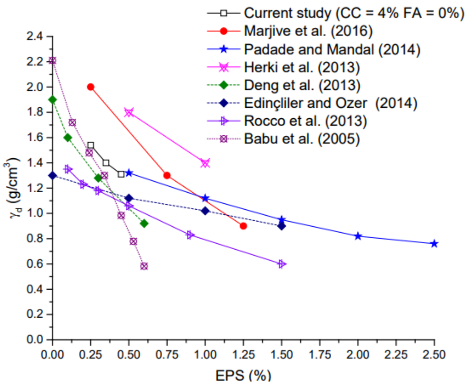
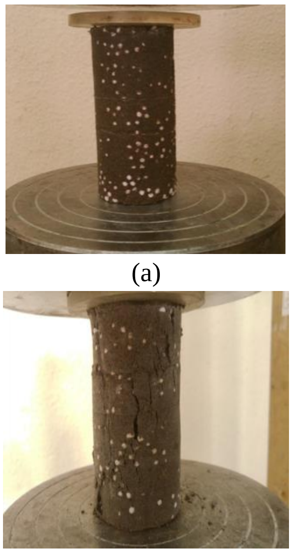


Fig. 3 Effect of EPS beads on MDD in comparison with different results

2.3.3 Effect of fly ash

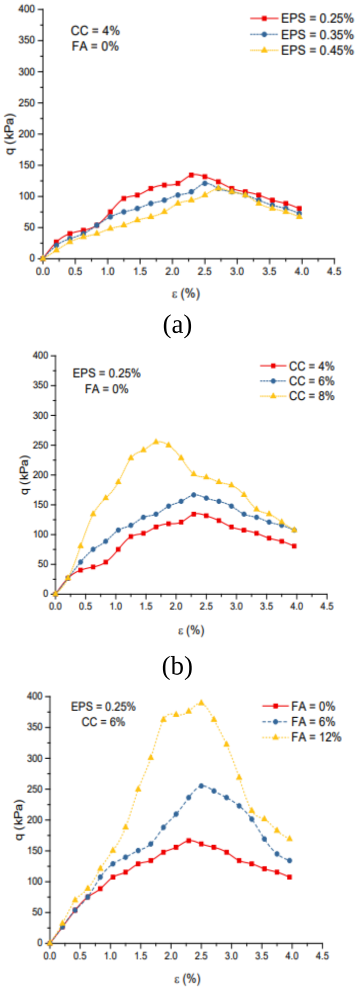
In the samples including fly ash, because fly ash is typically finer than other materials, bleeding was observed at the surface by increasing the amount of water in compaction test, which apparently acts like air-entraining admixtures. Fly ash is placed between the other particles and closes water passes through the pores, so appears on the surface of the samples (Archuleta *et al.* 1986).



(a)

(b)

Fig. 4 Unconfined compression tests, (a) before loading and (b) after loading



(a)

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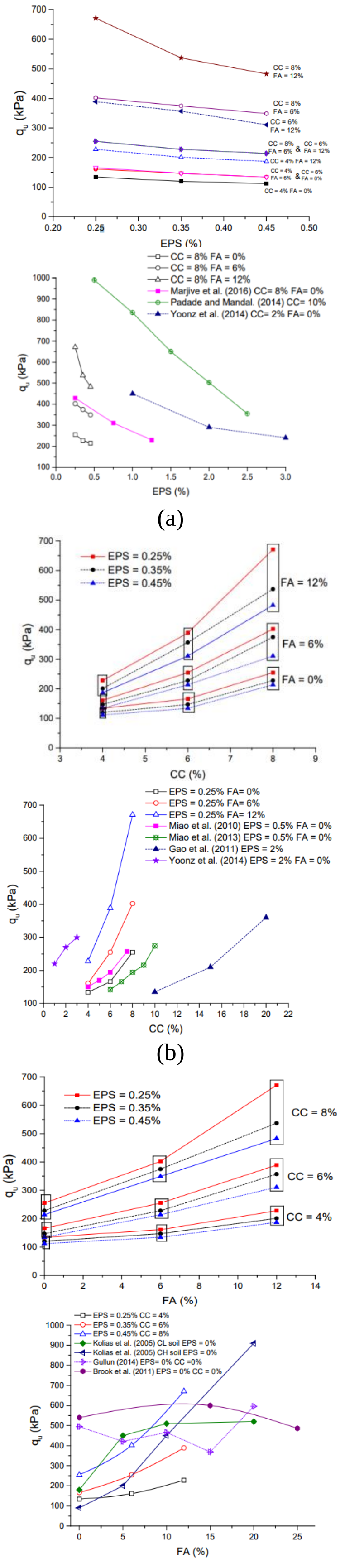
Fig. 5 Stress-strain curves of the specimens, (a) EPS, (b) cement content and (c) fly ash (curing period = 7 days)

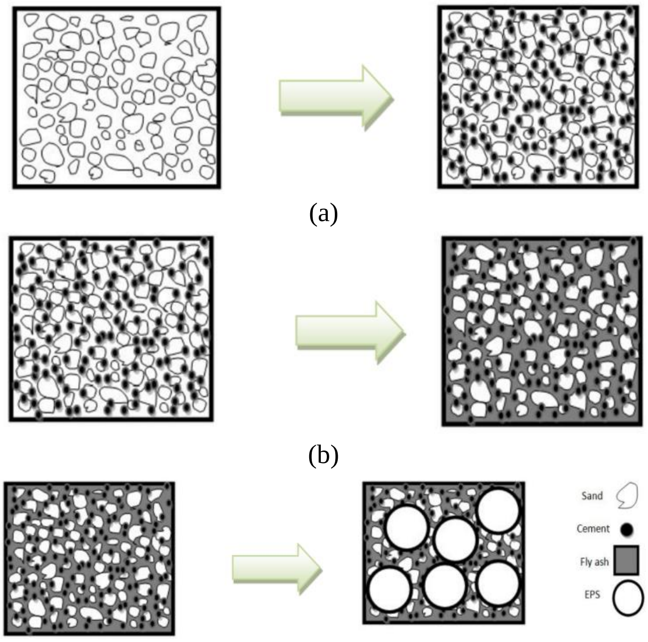


(a)

(b)

(c)

Fig. 6 Effect of different constituents on UCS value (CC : Cement Content, FA : Fly Ash), (a) EPS, (b) cement content and (c) fly ash (curing time=7 days)



(a)

(b)

(c)

Fig. 7 Schematic illustration of different constituents in the mixture, (a) cement effect, (b) fly ash effect and (c) EPS effect

Fig. 8 Formation of local failure with increase of EPS content

2.4 Unconfined compression tests

The unconfined compressive strength (UCS) test (ASTM D2166/D2166M) were conducted on cylindrical specimens with a diameter of 48 mm and height of 96 mm at the OMC and MDD condition. Specimens, with the mix proportions presented in Table 3, were cured for two different curing times of 7 and 14 days and the load was then applied at 1 mm/min rate for all tests. Fig. 4 demonstrates a typical specimen of UCT before and after loading. The stress-strain curves of the specimens at different mix proportions are given in Fig. 5.

2.4.1 Effect of EPS

According to the results, the peak compressive stress representing the compressive strength, q_u of all samples showed a decreasing trend with increasing the amount of EPS beads (Fig. 6(a)). This can be simply because the compressibility of EPS is much higher than the other constituents of the mixture. Besides, EPS beads do not absorb water and make a separation between sand grains and binders, hindering to bond with each other (Fig. 7(c)).

On the other hand, Fig. 5(a) shows that increasing the EPS beads increases the failure strain of the samples, implying a more ductile behavior. Furthermore, in some cases, an increase of EPS content caused the length of propagation of cracks to be shortened, represented by local failure (Fig. 8). It is worth mentioning that Marjive *et al.* (2016), Padade and Mandal (2014) and Yoonz *et al.* (2004) also reported on the reduction of UCS value with increasing EPS content. (Fig. 6(a)).

2.4.2 Effect of cement content

On the contrary, it can be concluded from Fig. 6(b) that increasing cement content (CC) increases UCS value, mainly due to the pozzolanic reactions made between lime, silica and aluminum, present in cement, which leads to the production of hydrated calcium silicate (C-S-H) and hydrated calcium aluminate (C-A-H). The following reactions cause hardening of the mixture through hydration process: (Kim and Do 2013 and Brooks *et al.* 2011).

$$6\,(3CaO.SiO_2) + 18H_2O \longrightarrow 5Cao.6\ SiO_2 + 13\ Ca(OH) \quad (1)$$

$$3\ CaO.\ Al_2O_3 + 6\ H_2O \longrightarrow 3\ Cao.\ Al_2O_3\ .\ 6\ H_2O \quad (2)$$

These chemical reactions increase the P^H of the mixture, produce C-S-H and C-A-H cementations gels and increase the strength of the mixture, after setting and hardening stage (Fig. 7(a)).

All in all, the results showed that increasing the cement content (CC) increases the rate of increase in the UCS, increases hardness, reduces compressibility and finally increases the slope of the stress-strain curves both before and after reaching the peak compressive stress value. This means increasing CC results in a more brittle behavior by decreasing the failure strain of the material, although no sudden failure was observed (Fig 5(b)). Padade and Mandal (2014), Gao *et al.* (2011), Yoonz *et al.* (2004), Miao *et al.* (2010), and Miao *et al.* (2012) also demonstrated that cement increases the UCS value, as shown by Fig. 6(b).

2.4.3 Effect of fly ash

Taking into consideration Fig. 6(c), the effect of fly ash (FA) on the UCS value, it can be inferred that the compressive strength increases with increasing amount of fly ash (FA), which can be explained by two mechanisms. Firstly, fly ash consists of silica that reacts with the lime and alkali found in the mixture and produces additional cementation compounds. The following equations elaborate the pozzolanic reaction of fly ash with lime to produce additional calcium silicate hydrate (C-S-H) binder as illustrated schematically in Fig. 7(b) (Rossow 2003).

$$\text{cement reaction (1)} \quad C_3S + H \longrightarrow \text{C-S-H} + CaOH \quad \text{(hydration)} \quad (3)$$

$$\text{pozzolanic reaction} \quad CaOH + S \longrightarrow \text{C-S-H} \quad \text{(S is silica from fly ash)} \quad (4)$$

Fly ash produces an additional amount of silica for the pozzolanic reaction, therefore the compressive strength of sand and the hydrated lime increases by pozzolanic reaction between the alumina and silica content of the mixture. Secondly, fly ash is typically finer than other materials in the mixture that can fill the empty spaces, so reduce the movement between particles with increasing interlocking reaction.

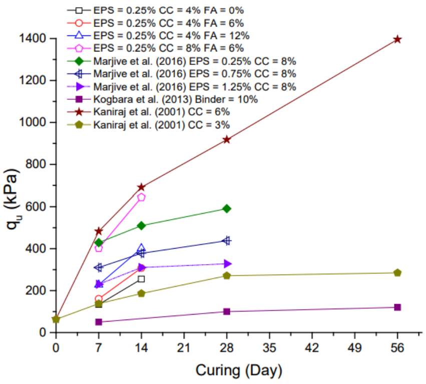


Fig. 9 Effect of curing on the UCS value

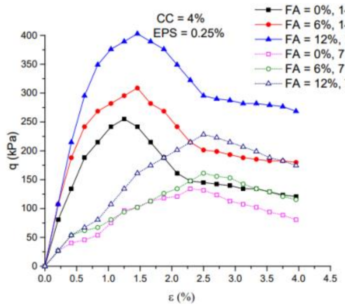


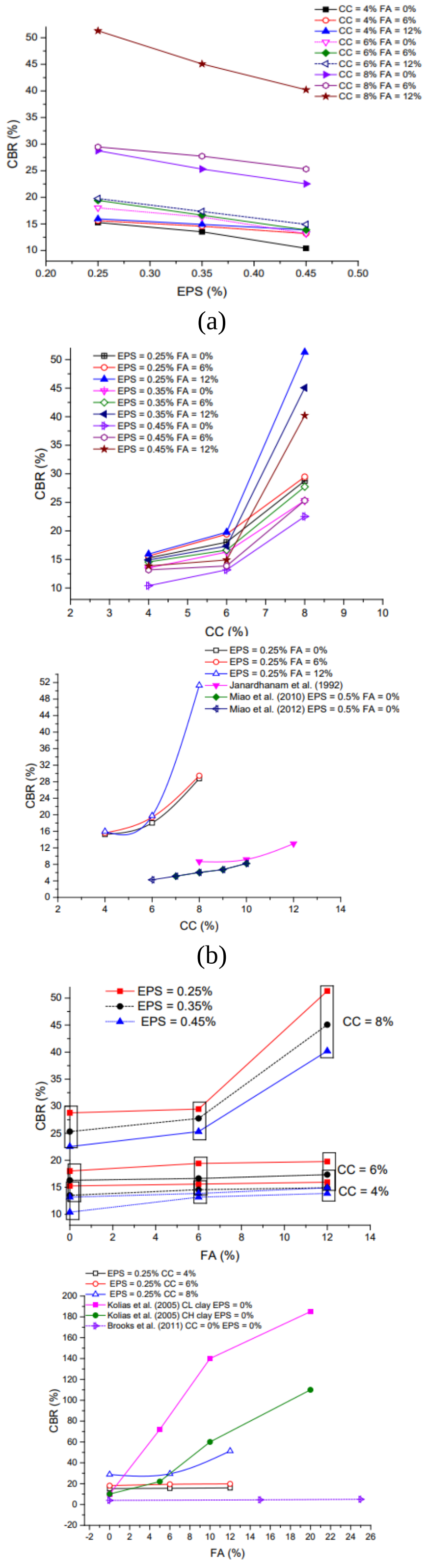
Fig. 10 Stress-strain curves of the specimens at different curing times

Moreover, there is a high amount of silica, alumina, and calcium in fly ash. Silica reacts with calcium and decreases the SiO_2/Al_2O_3 ratio of the mixtures. This reaction consequently increases the compressive strength of the mixture by producing C-S-H gel.

Fig. 6(c), demonstrating the effect of fly ash on the UCS, shows that the rate of increase in the UCS increases at specimens with 8% of cement compared to that of 4% and 6%, primarily because increase in the amount of lime found in cement gives rise to the chemical reactions of fly ash in the mixture. Also, the rate of increase of the UCS at the same cement content increases with increasing of fly ash content, noticeably identified in samples with 8% of cement and 12% of fly ash. Nevertheless, despite the increase in the compressive strength, the failure strain is not remarkably changed compared to that of cement increase. Similarly, Kolias *et al.* (2005) reported on the increase of compressive strength by increase of fly ash content.

All in all, comparing the effect of cement content on the UCS value with that of fly ash, shows that the UCS is more sensitive to the variation of cement content. Besides, considering Fig. 6(a), it can be inferred that adding 6% of fly ash is roughly equivalent to a cement increase of 2% regarding enhancing the compressive strength.

On the other hand, taking into account the curing period, for each mixing ratio, the compressive strength of 14 days is higher than that of 7 days, as expected, because of increase of pozzolanic reactions as well as producing additional cementation compounds in more curing time. For example, as demonstrated by Fig. 9, the samples cured for 14 days, with the fly ash content of 0%, 6% and 12% show an increase of UCS for 90%, 91% and 75%, respectively, in comparison to the samples with 7 days of curing period. It is also worth mentioning that Marjive *et al.* (2016), Kogbara *et al.* (2013) and Kaniraj *et al.* (2001) similarly



(a)

(b)

(c)

Fig. 11 Effect of different parameters on E_{50} value, (a) EPS, (b) cement content and (c) fly ash (curing time=7 days) stated that increasing the curing period leads to an increase in the compressive strength, as declared by Fig. 9.

It can be said that lengthening the curing period increases stiffness, reduces compressibility and increases the slope of stress-strain curves both before and after the peak compressive stress value, which consequently decreases the failure strain of samples to result in a more brittle behavior of the mixture, as depicted in Fig. 10.

Moreover, E_{50}, or the tangent Young`s modulus at 50% of UCS, can be obtained based on the compressive strength equal to 50% and its corresponding strain, ε_{cor} (Miao *et al.* 2012).

$$E_{50} = \frac{q_u}{2\,\varepsilon_{cor}} \tag{5}$$

Table 4 presents values of E_{50} obtained in this study and Fig. 11 manifests the effect of different materials on the value of E_{50}. According to Fig. 11a, an increase of EPS beads reduces the compressive strength and increases the corresponding strain, which means the reduction of E_{50}. Jamshidi *et al.* (2016) using large oedometer apparatus and Edinçliler and Ö zer (2014) with triaxial test showed that increase of EPS content reduces the drained and undrained elasticity modulus of sand mixtures.

As depicted in Fig. 11(b) and 11(c), increasing cement and fly ash content leads to increase of E_{50}, as a result of the rise in the compressive strength and drop in the corresponding strain. It should be noted that E_{50} is not only dependent on the compressive strength, but it also depends on ε_{cor}, as a key parameter. For instance, in samples with 8% of cement content and 0.25% of EPS, E_{50} reduces to 18% by rising of the fly ash content from 0% to 6%.

2.5 California bearing ratio

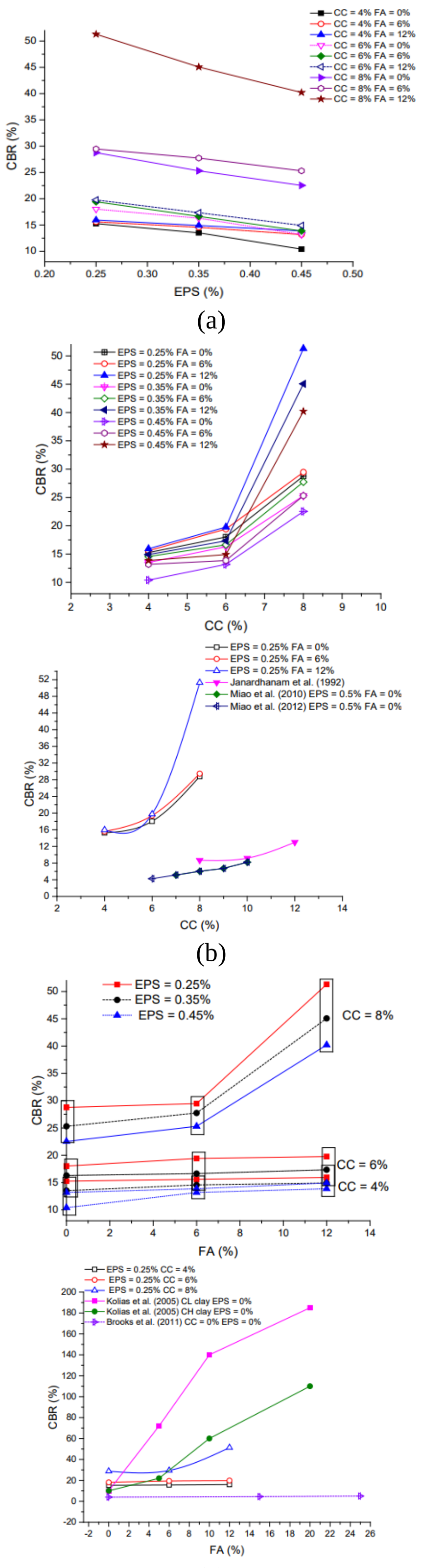
California Bearing Ratio (CBR) test is usually used to determine the strength of subgrade, subbase, and base materials for use in road and airfield pavements. CBR value (ASTM D1883), by definition, is the ratio of the pressure required to penetrate a piston with the specific area as much as a specific value (P) to a standard pressure value (P_s). The standard penetration is usually considered as 1 or 2 inches.

$$\text{CBR}\ (\%) = \frac{P}{P_s} \times 100 \tag{6}$$

In this study, the samples were prepared in a rigid metal cylinder with an inside diameter of 6 inches (152.4 mm) and height of 7 inches (177.8 mm) at the OMC and MDD, cured at 7 days, with the mix proportions presented in Table 3. Loading rate was 0.05 in/min (1.27 mm/min) for all tests.

Fig. 12 demonstrates the effect of EPS, cement and fly ash contents on the CBR value of the mixture. According to Fig. 12(a), the CBR value of samples decreased within a range of 6% to 23% by increasing of EPS beads for 0.1%.

Besides, the addition of cement content increases the CBR value, as shown in Fig. 12(b). Similar results were also obtained by Miao *et al.* (2005 and 2012), stating that the mechanical properties of the mixed lightweight materials increase by an increase of cement content, in terms of the CBR value.



(a)
(b)
(c)

Fig. 12 Effect of different parameters on CBR value, (a) EPS, (b) cement content and (c) fly ash (curing time=7 days)

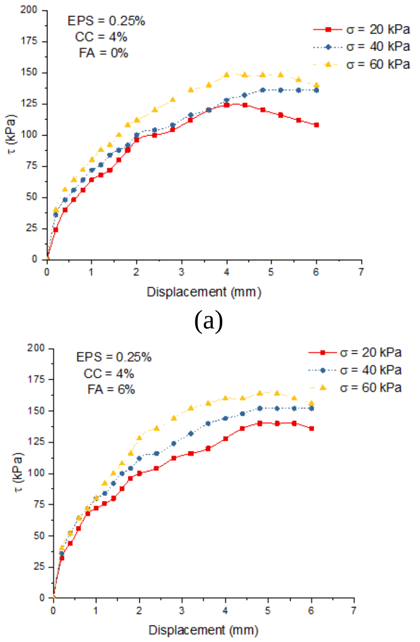
Fig. 12(c) presents the effect of fly ash content on the CBR value. It is observed that in the samples with 4% and 6% of cement, adding 6% and 12% fly ash, do not significantly influence the CBR value. This was also the case for samples with 8% cement and the addition of 6% fly ash, which could happen because no primary reactions happen on these mix ratios. Nevertheless, this neutral attitude changes when considering the respective results for samples with higher cement contents. To be more specific, in the samples with cement content of 8%, rising fly ash to 12% dramatically enhanced the CBR value, suggesting promotion in geotechnical practices and introducing an optimum ratio to achieve sufficient strength and appropriate performance, cost-effectively. Kolias *et al.* (2005) also studied *CH* and *CL* mixed with fly ash and demonstrated that increasing fly ash content can lead to increasing the CBR value. This means that fly ash inclusion is more effective when higher cement content is utilized.

2.6 Direct shear test (DST)

In the present study, direct shear tests were conducted following the procedure outlined by ASTM D3080. The experiments were carried out on samples with a dimension of 50×50×25 mm, at the OMC and MDD condition, and performed by deforming a specimen at a controlled strain rate of 1 mm/min. The three specimens were cured for 7 days, with the mix proportions specified in Table 3. The specimens were examined under various normal stresses including 20 kPa, 40 kPa and 60 kPa to determine the shear resistance, displacement and strength properties such as Mohr strength envelopes.

Fig. 13 typically presents the shear stress-displacement curves of some samples obtained in this study.

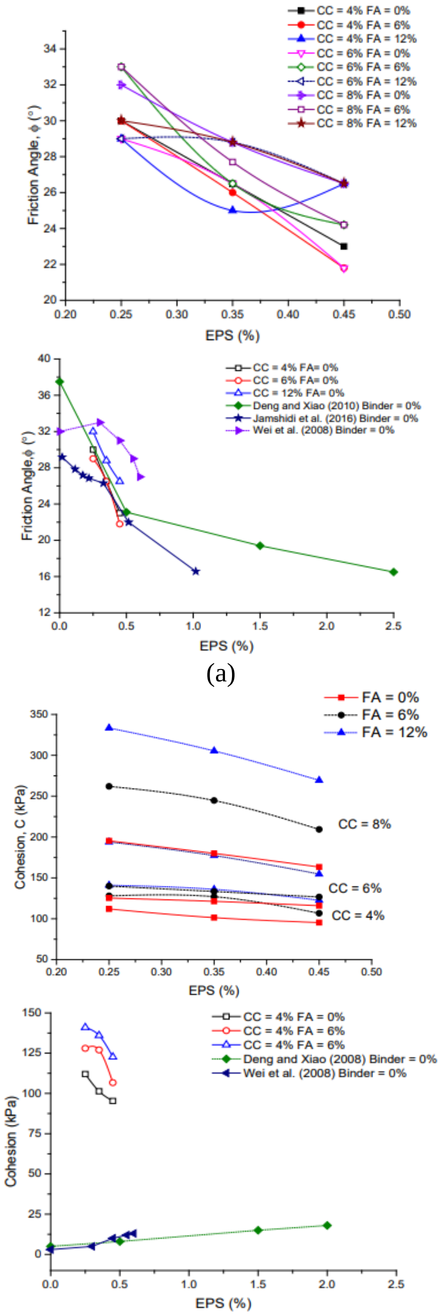
According to the results presented in Fig. 14, EPS beads reduce friction angle because they hinder sand-sand interaction mechanism and reduce the interlocking between particles. This is also true for cohesion as EPS beads prevent sand grains and binder to make bonding to each other. In this regard, Jamshidi *et al.* (2016) also expressed



(a)

(b)

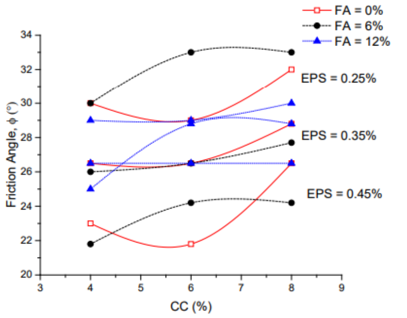
Fig. 13 Shear stress-displacement curves, (a) FA= 0% and (b) FA= 6%



(a)

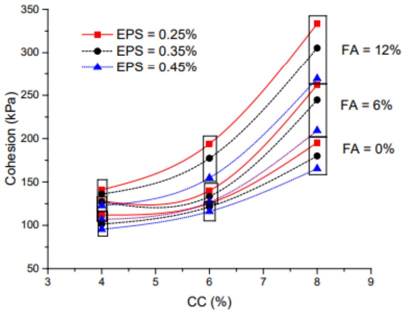
(b)

Fig. 14 Effect of EPS beads on shear strength parameters, (a) friction angle and (b) cohesion



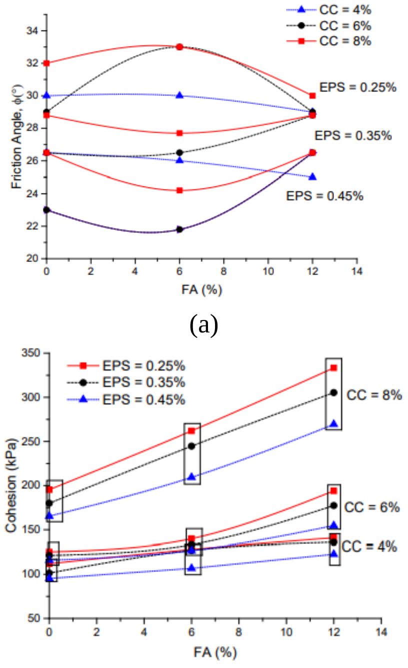
(a)

Fig. 15 Effect of cement content on shear strength parameters, (a) friction angle and (b) cohesion



(b)

Fig. 15 Continued



(a)

(b)

Fig. 16 Effect of fly ash on shear strength parameters, (a) friction angle and (b) cohesion

that the difference between the rigidity of sand and EPS beads decreases friction angle.

Besides, cement content and fly ash as illustrated in Figs. 15 and 16, respectively, increase the cohesion of the sample by making pozzolanic reactions and producing cementation gel, yet have no significant effect on friction angle. This is probably because cement and fly ash cannot influence the interlocking stress between particles. Thus, it can be concluded that the friction angle and cohesion are controlled by EPS beads and the binder material, respectively.

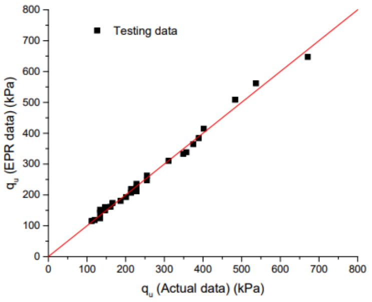
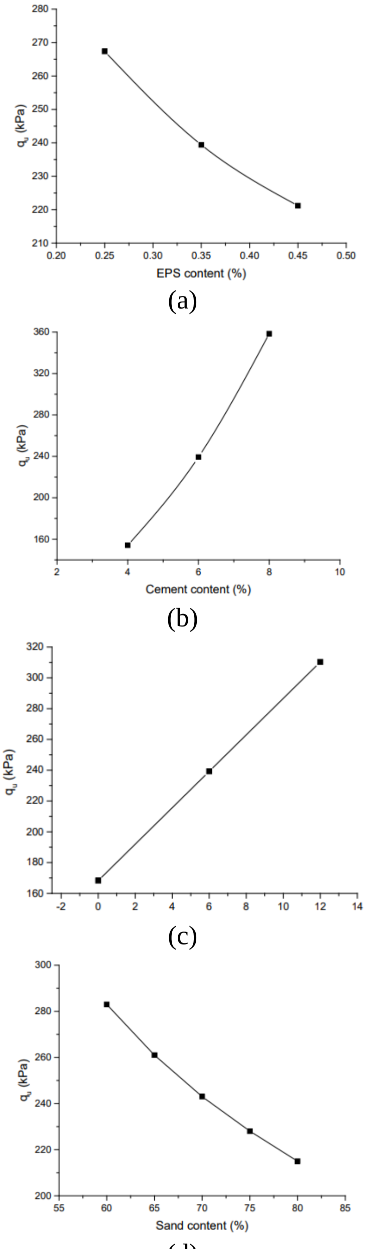


Fig. 17 Comparison between the predicted and measured UCS values



(a)

(b)

(c)

(d)

Fig. 18 Results of parametric study for the UCS value, a) EPS, (b) cement content, (c) fly ash and (d) sand

2.7 EPR model for UCS value

Evolutionary polynomial regression (EPR) has been used to evaluate the relationship between the values of UCS and CBR, and the content of sand, EPS, fly ash and cement. This method of numerical analysis can be used to predict experimental results and models of lightweight materials as well as to provide polynomial structures that express the system (Rezania 2008). For this purpose, the four input parameters consisting the content ratio of sand, EPS, fly ash

Table 4 MDD, OMC, UCS, CBR and shear strength parameters of samples

Sample	EPS (%)	Fly ash F Class (%)	Cement (%)	OMC (%)	MDD (g/cm^3)	q_u (kPa) 7 days	q_u (kPa) 14 days	E_{50} (MPa) 7 days	CBR (%)	φ (degree)	c (kPa)
1	0.25	0	4	14.7	1.54	134	255	7.44	15.25	30	112
2	0.25	6	4	15.1	1.53	161	308	7.74	15.6	30	128
3	0.25	12	4	15.3	1.52	228	402	10.36	15.95	29	141
4	0.25	0	6	14.9	1.53	166	-	11.36	18.02	29	125.33
5	0.25	6	6	-	-	255	-	12.37	19.4	33	140
6	0.25	12	6	-	-	389	-	15.31	19.76	29	194
7	0.25	0	8	15.5	1.51	255	644	21.25	28.7	32	195.33
8	0.25	6	8	15.4	1.5	402	-	17.47	29.47	33	262
9	0.25	12	8	15.6	1.49	671	-	23.46	51.3	30	333.33
10	0.35	0	4	14.8	1.4	120	-	6.45	13.52	26.5	101.33
11	0.35	6	4	-	-	147	-	5.44	14.56	26	127
12	0.35	12	4	-	-	201	-	8.73	14.9	25	136
13	0.35	0	6	-	-	147	-	11.30	16.3	26.5	121.33
14	0.35	6	6	-	-	228	-	9.74	16.64	26.5	133.33
15	0.35	12	6	-	-	357	-	13.0	17.3	28.8	177.33
16	0.35	0	8	-	-	228	-	11.75	25.3	28.8	180
17	0.35	6	8	-	-	375	-	15	27.7	27.7	244.67
18	0.35	12	8	-	-	537	-	18.51	45	28.8	305.33
19	0.45	0	4	16.2	1.31	112	-	4.17	10.4	23	95.33
20	0.45	6	4	-	-	134	-	5.36	13.17	21.8	106.67
21	0.45	12	4	-	-	187	-	8.42	13.87	26.5	122.67
22	0.45	0	6	-	-	134	-	7.44	13.17	21.8	116
23	0.45	6	6	-	-	214	-	10.28	13.87	24.2	126.67
24	0.45	12	6	-	-	311	-	11.87	14.9	26.5	154.67
25	0.45	0	8	-	-	214	-	10.7	22.5	26.5	165.33
26	0.45	6	8	-	-	349	-	12.03	25.3	24.2	209.33
27	0.45	12	8	-	-	483		14.54	40.2	26.5	269.33

and cement, expressed by percentage, were considered for the EPR model for the UCS value. The following equation presents the EPR model for the UCS parameter.

$$q_u = 988.2613\frac{fc^2}{s^2\sqrt{e}} + 96.3194\frac{c^2}{s\sqrt{e}} + 86.0583 \qquad (7)$$

where s is sand content, e is EPS content, f is fly ash content, and c is cement content.

The coefficient of determination (*COD*) of the model can be defined to evaluate the accuracy level of modeling, as the following equation (Rezania *et al.* 2008).

$$COD = 1 - \frac{\sum_{i=1}^{N}(Y_a - Y_p)^2}{\sum_{i=1}^{N}(Y_a - \bar{Y}_a)^2} \qquad (8)$$

where Y_a is the actual output value, $\bar{Y}_a$ is the mean of actual output value, Y_p is the *EPR* predicted value, and N is the number of data points on which *COD* is computed. Calculations give the *COD* of the model as 99.01% for the UCS value. Fig. 17 provides a comparison of the results of prediction by the *EPR* model and those obtained by experimental tests, manifesting a favorable consistency between the predicted and the actual data.

On the other hand, carrying out a parametric study can reveal beneficial results regarding the effect of different materials on the UCS value, in the absence of other materials. Fig. 18 shows that the UCS increases by an increase of the cement and fly ash content, while it is declined by an increase of EPS beads and sand content.

3. Conclusions

This study proposed lightweight fill materials for pavements, railway, slope stability, retaining walls backfill, embankment fills, solidification and stabilization of soil, etc., which consists of sand, EPS, fly ash and cement. Mechanical properties of these lightweight materials were evaluated with laboratory tests including the modified standard proctor test, unconfined compression (UCS) test, California Bearing Ratio (CBR) test and large-scale direct shear test. The main findings of this study are as follows:

- Increasing the amount of EPS beads leads to the decline of the MDD while has no remarkable effect on the OMC of the samples. Also, fly ash and cement content decrease the MDD and increase the OMC.
- In the samples including fly ash, with increasing the amount of water in compaction test, bleeding was observed at the surface.
- Increasing the amount of EPS beads decreased the compressive strength, E_{50}, CBR value, friction angle and cohesion while increased the failure strain of samples, suggesting a more ductile behavior. It also decreased the propagation length of cracks and caused local failure in some cases.
- Increasing the amount of cement increased the compressive strength, E_{50}, CBR value and cohesion by producing cementation gel, yet had no significant effect on friction angle. On the other hand, increasing cement content resulted in a decrease of the failure strain of the samples, as a sign of brittle behavior.
- Increasing the amount of fly ash increased the compressive strength, CBR value and cohesion by producing additional cementation compounds, but failed to have a remarkable impact on the friction angle. Besides, such increase mostly resulted in an increase of $E_{50,}$ although a few records of decline was observed in some cases. Interestingly, the failure strain was not changed that much by an increase of fly ash, to be accounted as an advantage, compared to that of cement.
- Increasing of the curing period, increases the UCS value, decreases the failure strain of samples and causes brittle behavior.
- With the cement and fly ash content of 8% and 12%, respectively, a remarkable enhancement was observed in the mechanical properties of the samples, suggesting to be used in geotechnical practices to achieve the desired strength and performance, cost-effectively.

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