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Behaviour of a Foam Mixture as a Lightweight Construction Material

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Abstract

Building on weak soils is very challenging in engineering projects, especially highway and railway projects. In order to overcome these problems, especially in the construction of embankments and abutments, it is necessary to reduce the settlement of soil and increase the bearing capacity. This paper investigates the characteristics of expanded polystyrene (EPS) foam beads mixture as a lightweight construction material. EPS foam is characterized as a lightweight, economic and environmentally friendly material. Samples of different mixtures were prepared using EPS foam beads with sand, cement and water at different ratios. A series of rigorous tests were carried out to evaluate density, shear strength parameter, compressibility, and crushing strength of the prepared mixtures. The mixture of foam beads and sand was mixed in ratios 1:1, 1.5:1 and 1:2 by volume and mixed with cement content of 7%, 8%, 9% and 10% of sand weight using the optimum water content. From the results it was found that the best ratio between sand and foam beads by volume was 1:1, and high cement ratio of 10% formed lightweight mass with acceptable crushing strength, CBR and compressibility characteristics. The results proved that, the characteristics of the mixture are linearly proportional with cement content and curing time. Practically, the mixture can be used as a subgrade material to overcome the problems of weak soils especially in highway construction.

Keywords EPS foam beads, cement, sand, subgrade, lightweight mixture, highways.

Introduction

Increase in world populations has led governments to build infrastructures, such as highways and roads, on weak soils. This leads to a number of problems, namely high settlements and low bearing capacity. Such problems are often addressed by placing lightweight material on the soft soil in order to allow it carry higher stresses [1-3]. The application of geofoam as a construction material goes back to 1972 in Norway for constructing a road on a weak soil [4]. Recently, geofoam was used in different applications all over the world. Stark et al. [2] classified the EPS blocks in two branches, first according to geofoam function such as: lightweight fill, slope of stability, returning structure, thermal isolation, basement structure and underground utilities. The second according to geofoam properties which are: low density, low compressibility, high thermal resistance, adsorbed vibration and self-supporting natural [2, 5]. There are two techniques for using geofoam as a construction material. The first is to use layers of foam blocks. The second technique is to use a lightweight mixture of air-foam, west tier chips and EPS beads with sand and ponded material. The unit weight of the mixture ranges from 6 to 15 kN/m^3, which has a unit weight of about 50% of the soil weight.

The EPS geofoam blocks are used to reduce the different stresses, static and dynamic, on the road subgrade and underground utilities. Tarek et al. [6] used different cover systems of EPS geofoam as lightweight material to protect utilities under roadway and railway from deformations or ruptures. The results obtained showed that EPS reduced stress by percentages ranging between 60% and 99% depending on the cover method and EPS density. Khalaj et al. [3] used laboratory testing to investigate the reduction of dynamics stress on buried pipes in case of ultra-lightweight expanded polystyrene (EPS) geofoam block layer, with varying EPS block thickness and density. The results indicated that, with increase in the thickness of EPS block from 30 mm to 100 mm, the VDS value had an 83% reduction.

Ashna and Chandrakaran [7] studied the EPS beads mixture with sand by 0.25, 0.5 and 0.75% of weight. The results illustrated that, when increasing the beads content, the deviator stress and shear parameters are decreased, However, the mixture will be more lightweight which can be used in several applications. The main factors affecting the stress-strain behaviour of the mixture were the size and the percentage of foam beads. Wang and Miao [8] and Miao et al. [9] prepared a lightweight mixture from dredged sand and foam beads with different percentage of cement. This mixture was successfully used to overcome the soft or weak soil. Reza et al. [10] used a large odometer to study the properties of foam bead mixture. The Results showed that permeability, shear parameters and linear elastic modulus decrease with increasing inclusion content, while the compressibility coefficient and the K_o coefficient give opposite trends.

This paper aims to manufacture a lightweight mixture consisting of sand, cement and water EPS foam beads, which can be used as a lightweight base layer of roadways, fill or embankment on weak soils, thus saving time, cost and soil improvement. Aseries of laboratory tests are carried out to investigate the physical and mechanical properties of new mixture to identify how this mixture could be used as a lightweight base and sub-base for highway applications.

Experimental Study

Properties of Materials

Three materials were used in this research: sand, cement and EPS foam beads. Sand was taken from the eastern desert of Egypt; it passes through sieve No 7 (2.8 mm). Fig. 1 shows the grading of used sand, the properties of sand from the grading curve are D_{10} = 0.06mm, C_U = 4.9 and C_C = 1.34. According to AASHTO [11] sand is classified as A-3, while, according to USCS it is graded as sand *SP* [12].

EPS foam beads are rounded white beads with a diameter range from 2mm to 4mm, depending on manufacture, the density is about 0.01 kN/m^3 and yield stress of a round 7.5 kPa. The cement used is normal Portland cement, with practical size of which range from 0.5 to 3.2 µm and specific gravity *Gs* of particles ranges from 31 to 32. The particle size of Portland cement (fineness) is 3050 cm^2/g, and the retained weight on sieve No. 200 was not more than 10% by dry weight of the cement. The compression strength after 2, 7 and 28 days is 14, 24 and 33 MPa, respectively. Tables 1 and 2 show the chemical properties of the cement. It was used as a bond material between two materials, sand and foam beads to make the mix stable, cohesive and stronger. Cement was mixed with sand in percentages of 7%, 8%, 9%, and 10% of sand weight.

Mixture Preparation

The cement was mixed with sand as a percentage of sand-weight using the AASHTO classification of sand [11]. In the present study, the sand used is classified as A-3, where the cement content is mixed with sand following the Portland Cement Association guidance as 7% to 10% % of sand weight [13]. In order to obtain the optimum water content, a 10% cement of the sand weight was mixed with EPS foam beads by volume ratio of 1:1. This ratio is the best of ratios among the possible ratios 1:1, 1.5:1 and 2:1. The 10% ratio was decided based on the result of a proctor test that was carried out according to ASTM D558 [14]. The highest quantity of fine materials, additionally the cement used in this study is only used as bond material between sand and foam beads. Fig.2 shows the optimum sand to foam mixture, and the optimum water content used. The result of compaction test shows that the best ratio between the foam beads and sand with cement is 1:1 by volume because of the lightweight and optimum water content compared with other two ratios. The optimum water content from the proctor test is 17% of weight.

Materials Mixing

The specimens consisted of mixing sand with cement percentages of 7%, 8%, 9% and 10% of sand weight with EPS foam beads with a ratio of 1:1 of sand volume, the volume of water added is approximately 17% of the dry density (see Table 3). All these materials are well mixed together manually in a box of dimension 1m×1m×0.25m. The specimens were prepared in cubes of 50x50x50 mm and cylinders of 150mm height x 75mm diameter and were well compacted before being placed in a curing base at 25°C for 7, 14, 28 days.

Methodology

The testing programme used to investigate of the mechanical behaviour of the mixture in cubes and cylinders, consisting of sand mixed with Portland cement percentages from 7% to 10% of sand weight and EPS foam beads and water content 17% of dry unit weight. The tests used to investigate the physical and mechanical properties of the mixture are as follows: (i) The unit weights of the specimens according to ASTM D2166 [14]; (ii) The percentage of water absorption of prepared mixture material according to ASTM D 2216 [15] after 28 days with cement contents 7%, 8%, 9% and 10%; (iii) the unconfined compressive (q_u) test according to ASTM D2166 [16-17], used to test the cube and the cylinder samples, which were cured for 7, 14 and 28 days to investigate the crushing strength of mixture; (iv) the direct shear box test carried out according to ASTM-D6528 [18] to measure the shear strength parameters (C, Φ) of the mixture, using two specimens 50mm×50mm×25mm. The test was carried out under plain strain consolidated undrained conditions, as the mixture is used as a subgrade layer for roads or embankments; (v) California Bearing Ratio (CBR) test was carried in accordance with ASTM D1883 [19] on mixture with different cement contents for curing time at 7, 14, and 28 days; (vi) the oedometer test was carried out in accordance with ASTM- D2435 [20] to measure the volumetric strain and compressibility of samples from the foam beads, sand and the mixture with cement ratios of 7, 8, 9 and 10% after curing for 28 days.

Experimental Results

Properties of Mixture

The unit weights of the specimens are shown in Table 4. From the Table it can be observed that the unit weight ranged from 10.35 to 10.30 kN/m^3 depending on the cement content.

The percentage of water absorption of prepared mixture results are shown in Table 5. From the Table it can be observed that the mixture has an adsorption of water just less than 5%.

$$\text{Water absorption (\%)} = \frac{W_1 - W_2}{W_1} \tag{1}$$

where, W_1 is the dry weight of the cube and W_2 is the wet weight of the cube

Crushing Strength of Mixture

Effect of Curing Time

Figs. 3-6 show the stress-strain relationships for different cement contents of 7, 8, 9 and 10% depending on curing times for 7, 14 and 28 days. The results shown in Fig. 3 indicate that at 7% cement contents compression resistance increase with increase of curing time, Curves show that, the maximum crushing strength ranging from 170 kPa at the strain of about 4% after 7 days curing to 300 kPa after 28 days curing at the strain of about 8%. In the case of 8% cement content, Fig. 4 illustrates that, the compression resistance affected by curing time, curves show that, the maximum peak crushing strength ranging from 200 kPa at the strain of about 3% to 330 kPa at the strain and 6%, after 7 and 28 days of curing, respectively. Fig. 5 shows that, at 9% cement content, the compression resistance is proportional with curing time, and the crushing strength increases from 220 kPa to 390 kPa after curing time 7 and 28 days at the strain of about 4% to 6%, respectively. Fig. 6 illustrates that, the maximum crushing strength increasing from 270 kPa after curing 7 days at the strain of about 3% to be 470 kPa after curing 28 days at the strain of about 8%. The results shown in the Figs. 3-6 indicate that all curves reach the peak resistance at the strain of about 3% to 8%. Crushing resistance increases with an increase of curing time. All curves started without strain control (stress proportional with strain) with the hardening trend until they reached to the peak resistance and then yield gradual failure.

The graphs show that the curing time and cement content has a positive effect on the crushing strength and tangent modulus values. The strain at failure also increases because the cement is used as a bond material in low percentage, and as a result, the foam is the one governing the specimen behaviour. Additionally, the presence of micro-cracks in the specimen would increase the specimen strain. These reasons are responsible for the high settlement of specimens at failure [10, 21-23]. When the cement content increases to 10%, the failure strain reduces to the minimum Increase in cement content alters the properties of mixture making it brittle, and the failure settlement reduced.

Fig. 7 shows the shape of failure of the mixture cube at the end of the unconfined compression test. Fig. 8 illustrates the relationship between unconfined compression stress and curing time for all cement contents. For the same cement content, the crushing strength increases with the curing time. It also shows the change of strength depending on the relationship between curing time and cement content.

Effect of Cement Content

Fig. 9 shows that all stress-strain curves start with a linear trend until they reach the peak resistance and then decrease gradually. The failure of the mixture is brittle. On the other hand, the compression resistance of the samples after curing for 28 days, increased with increase in cement content. The peak crushing strength is 300 kPa at a strain of about 6% for cement content of 7%, then increased to 470 kPa for a strain of about 9% and a cement content of 10% as shown in Fig. 9.

Effect of Specimen Geometry

In this test the effects of samples grouping, and geometry were tested using groups of three cubes and a cylinder with a height equivalent to that of three cubes according to ASTM- D1633 [17] for 10% cement content after a curing 28 days.

Three cubes with a 10% cement ratio and curing time 28 days were tested to calculate the crushing strength in the unconfined compression. The results shown in Fig.10 indicate that after a curing time of 28 days, the maximum peak crushing strength was 365 kPa for a cement content of 10% and with a strain of about 4.5%. The cylinder used was 80 mm in diameter and 150 mm height. The specimens tested were 10% cement content after curing of 28 days. The results indicated that the maximum peak crushing strength is 400 kPa for a strain of about 6 % after curing for 28 days as shown in shown in Fig. 10.

The effect of bedding on the crushing strength for two and three cubs, compared with the cylinder sample as a unit mass, is shown in Fig. 10. It can be observed that the stress-strain relationships of samples of three cubes and cylinder follow almost the same trend. On the other hand, the sample of one cube showed the same stress strain relationship, but with higher crushing strength and strain at the peak. This may be attributed to the bedding effect on the cube group samples, and the resulting non-homogeneity of the cylinder sample as a one-unit mass. The results shown in Fig.11 indicate that, the three cubes as well as the cylinder sample, reached the crushing strength at values ranging from 365 to 400 kPa (3.6 to 4.0 kg/cm^2), for a strain ranging between 4.5% and 6%. The difference in the results may be attributed to the effect of bedding between the cube surfaces. There is no effect of the geometry on the results.

Shear Strength Characteristics

Effect of Curing Time

The results listed in Table 6 indicate that the shear strength parameters affected by cement ratio and curing time. The rate of increase in the mixture cohesion is relatively higher than that of the angle of friction. The cohesion has values ranging from 35 to 45.8 kPa, while the angle of shear resistance has values ranging from 10° to 14° as illustrated in Table 6.

The effect of curing time on the internal friction angle (*Φ*) as shown in Fig. 11(a) the internal friction angle of the same cement content increases with increasing curing time. At 7% cement content, the internal friction angle starts at 10.5° after 7 days of curing and increases gradually to 12° after 28 days of curing. While for 8% cement content the internal friction angle starts as 10.8°, then increases gradually to 11.8° after curing for 28 days. In the case of 9% cement content, the internal friction angle increases from 12° to 14° at 7 days and 28 days, respectively. In the case of 10% cement content, the internal friction angle increases from 12° at 7 days to 14° at 28 days. It is evident that the mixture with the higher cement content was more affected by the curing time than that with the small cement content. Fig. 11(b) shows the effect of curing time on cohesion (*C*), after 7 days and cement contents 7, 8, 9 and 10%, the cohesion is at 35, 37.2, 39.2 and 40.6 kPa, respectively. These values increase gradually after curing for 28 days to be 39.2, 41.1, 43.5 and 45.8 kPa, respectively.

Effect of Cement Ratio on Shear Strength Parameters

Figs. 12 (a-b) represent the effect of cement content on the shear parameters: angle of internal friction *Φ* and the cohesion (*C*). Fig. 13(a) shows how the internal friction angle is affected by cement ratio especially for the 10% cement content, the behaviour is approximately linearly proportional after 8% cement content. The internal friction angle of the mixture reduces for 7% and 8% cement ratio by about 2.5%, this is due to water and voids inside the specimen. These results mean that the internal friction angle is not affected by cement content only, but also by the presence of the voids and microcracks inside the mixture. This was also confirmed by similar work carried out by Wang and Miao [8-9]. Fig. 12(b) shows that the cohesion C is linearly proportional with increasing cement content for all curves.

Effect of Foam Beads on the Shear Strength Parameters

The main purpose of EPS foam beads is to reduce the weight of the mixture. Figs. 11 and 12 show that there is no effect of foam beads on the cohesion (*C*) results, all results are proportional to the percentage of cement content and then curing time. On the other hand, the effect of EPS foam beads on the internal friction angle (*Φ*) is variable in the case of low cement contents. This influence is the result of the EPS foam beads inside the non-homogenous mixture (sand, cement, foam), which make the friction between two layers occurred variable. As the percentage of cement increases, the internal friction angle becomes stable.

California Bearing Ratio (CBR) of Prepared Mixture

The CBR test of the foam mixture was conducted to investigate the strength when used it as a subgrade. The CBR test was carried out on the prepared mixture according to ASTM- D1883 [19]. Table 7 shows the results of the CBR. All CBR values of the mixture increase with cement content for the same curing time.

Compressibility of Prepared Mixture

The results are presented in Fig. 13 which shows that under stress of 200kPa the strain of the mixture was about 0.05, 0.055, 0.065 and 0.075% for 10, 9, 8 and 7% cement content, respectively. The strain of foam beads was about 0.3%. While, the strain of sand was 0.03%. The prepared mixture reduced the compressibility of the foam beads by about 6 times.

Conclusions

In this study, a new type of lightweight material using EPS foam beads is proposed. The mixture, used as subgrade lightweight layer over weak soil, consisted of geofoam in the form of beads mix with sand and a percentage of cement. Shear strength, bearing stress, water absorption, CBR and compressibility of the prepared mixture were investigated. The results from this study could be demonstrated as follow:

1. The prepared mixture has created a lightweight material with a unit weigh of 10.30 kN/m^3, and a water absorption of less than 4.5%.

2. The crushing strength of the mixture increased with increasing cement ratio and curing time. The maximum crushing strength of the prepared cube mixture ranged from 365 to 470 kPa, the higher value corresponding to the high cement content, long curing time and is dependent of shape (cubic or cylinder). The cylindrical shape sample has indicted the possibility of non-homogeneity of the mixture.

3. The shear parameters (C and Φ) for 7, 8, 9 and 10% cement content increased with the increase of curing time. After curing for 28 days, the friction angle increased by 11% to 14% for curing for 7 days, and the cohesion increased between 11 % and 15% for a curing of 7 days.

4. The largest value of shear parameters *C, Φ* are 45.8 kPa and 13.9˚for mixture prepared with 10% cement and after curing of 28 days.
5. The compressibility of the prepared mixture with cement ratio of 10% was very low compared to foam beads only.
6. The increase in cement content leads to a decrease in the strain after 28 days.

Based on these findings, it can be concluded that the mixture is acceptable to be used as a subgrade for highways.

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Authors Contribution:

Conceptualization: D. Hassan and M. Saidani and A. Shibani
Formal analysis: D. Hassan and M. Saidani.
Investigation: D. Hassan and M. Saidani
Methodology: D. Hassan, M. Saidani
Writing – review & editing: D. Hassan. M. Saidani and A. Shibani

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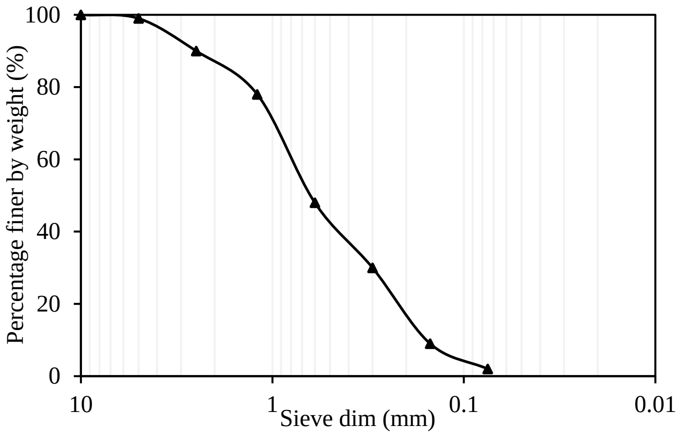


Fig. 1 Particle size distribution of sand

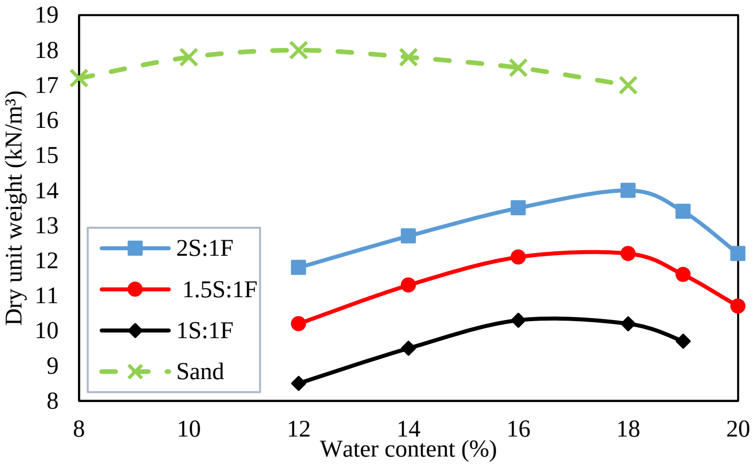


Fig. 2 Compaction test of different mixtures of sand with 10% cement and foam beads by volume

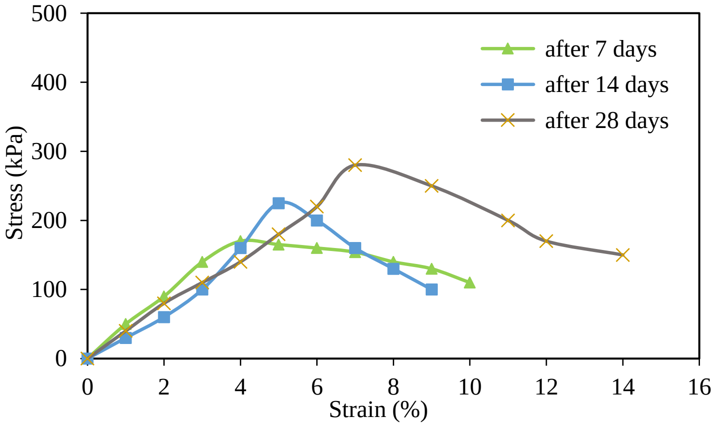


Fig. 3 Stress strain relationship of cement content 7% after 7, 14 and 28 days

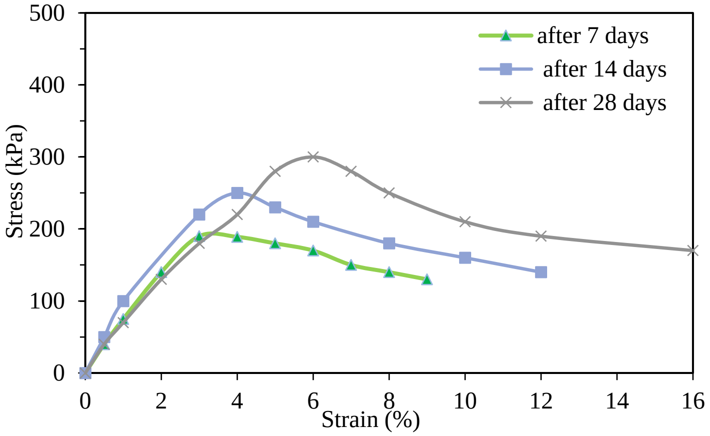


Fig. 4 Stress strain relationship of cement content 8% after 7, 14 and 28 days

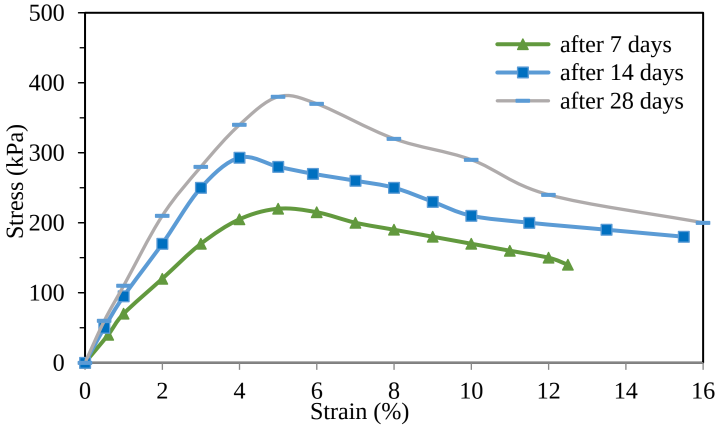


Fig. 5 Stress strain relationship of cement content 9% after 7, 14 and 28 days

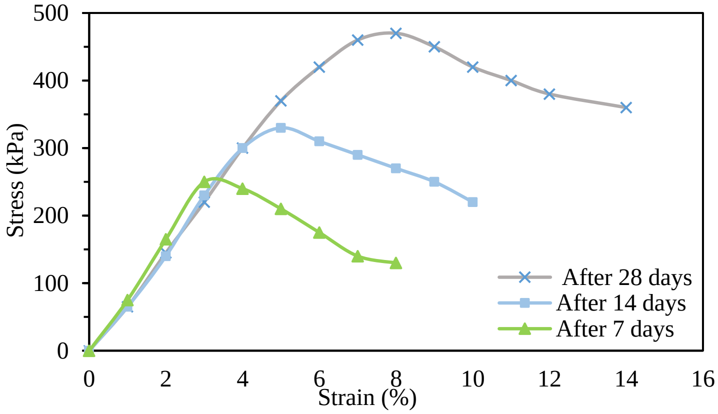


Fig. 6 Stress strain relationship of cement content 10% after 7, 14 and, 28 days

Fig. 7 Failure shape of the cube after unconfined compression test

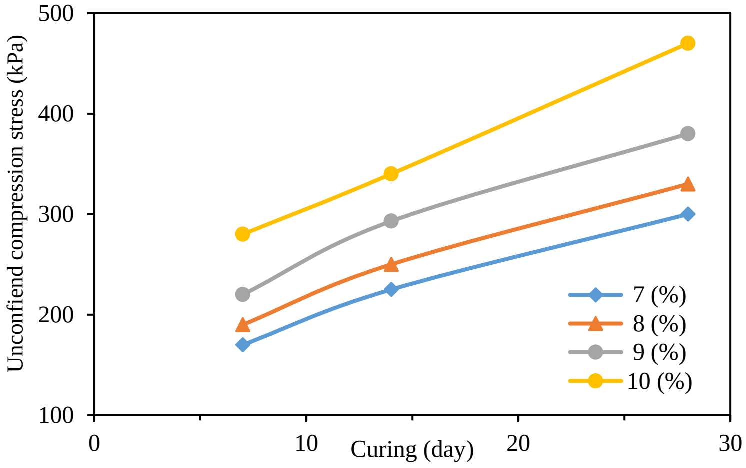


Fig. 8 Relationship between stress and curing time

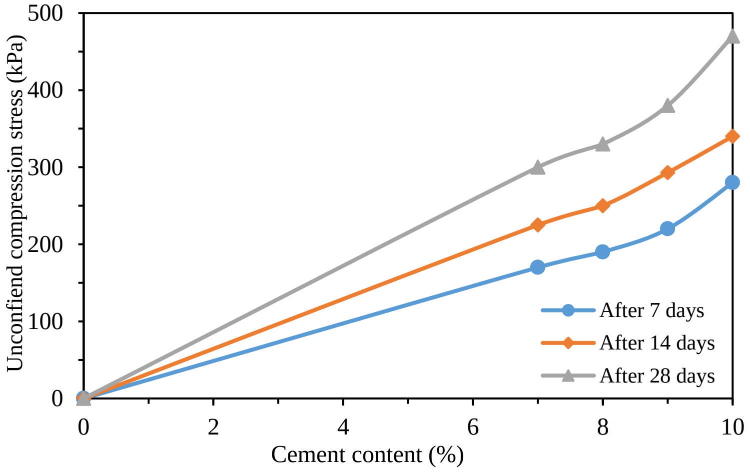


Fig. 9 Relationship between stress and cement contents

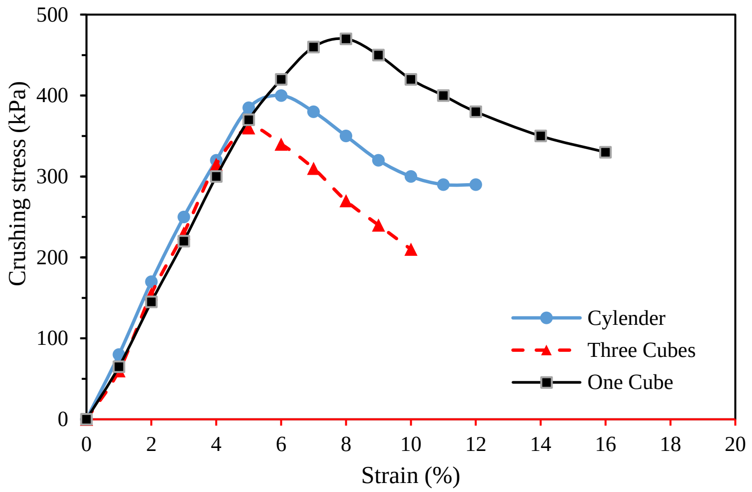
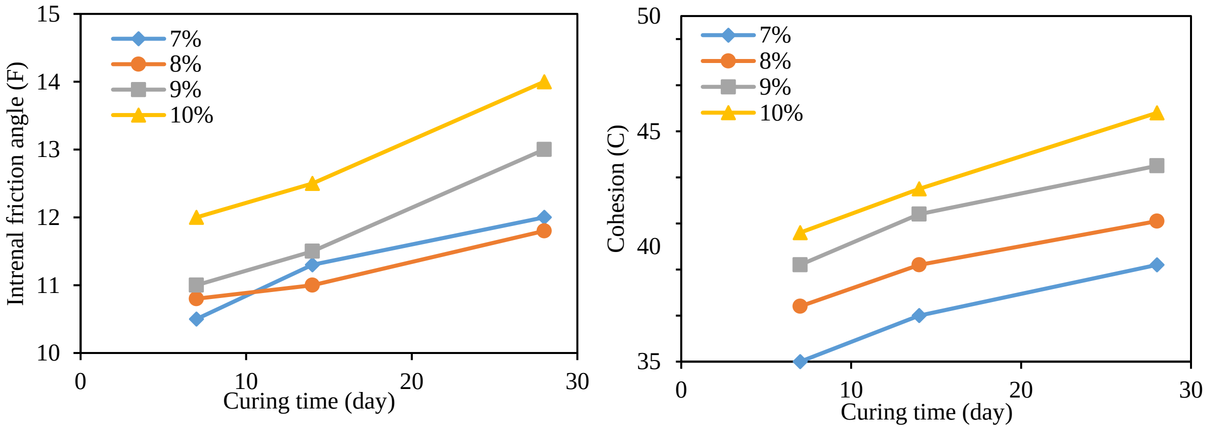


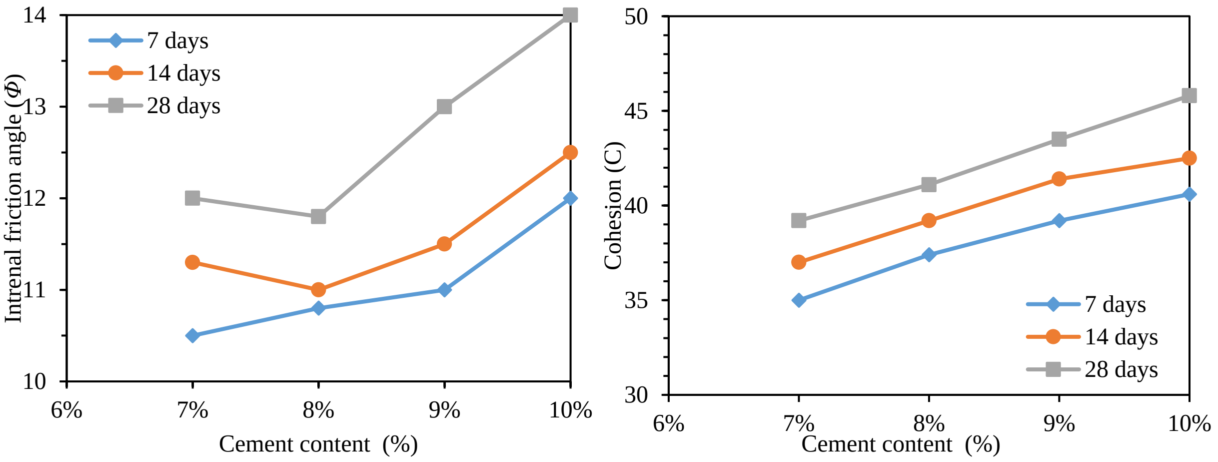
Fig. 10 Stress-strain Relationship of 10% cement content after 28 days of different geometry



(a)

(b)

Fig. 11 Effect of curing time on shear parameters of the mixture; a) internal friction angle (□); b) cohesion (*c*)



(a)

(b)

Fig. 12 Relationship between cement contents and shear parameters; a) internal friction angle (*Φ*); b) cohesion (*C*)

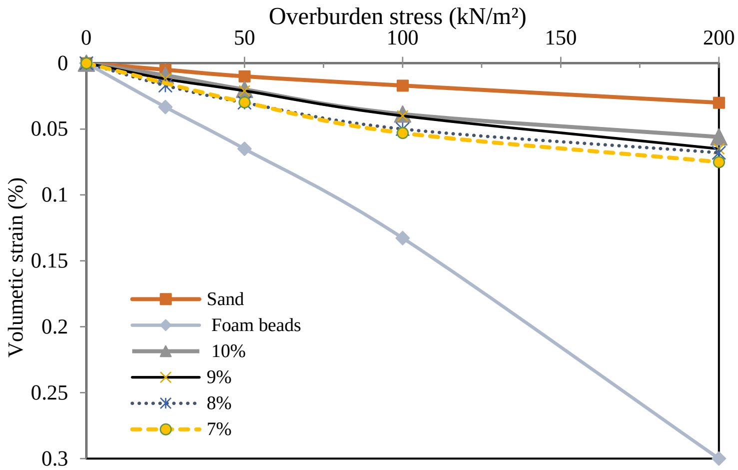


Fig. 13 Strain of foam beads, sand and prepared mixture after 28 days in oedometer test

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Table 1 Chemical properties of used Portland cement (%) of weight

SiO_2	SO_3	$Al_2 O_3$	Fe_2O_3	CaO	MgO
19	2.6	4.0	4.8	62	1

Table 2 Chemical properties of used Portland cement clinker contents (%)

C_3S	C_2S	C_3A	C_4AF	Lim Saturation Factor
55	23.5	7.2	13	0.95

Table 3 Experimental tests carried out on mixture samples with sand: foam beads ratio 1:1

Tests	No. of Samples	Cement Contents %				Dimensions
		7	8	9	10	
Unconfined Compressive stress after 7 days	12	3	3	3	3	12 cubes 50mm×50mm×50mm
Unconfined Compressive stress after 14 days	12	3	3	3	3	12 cubes 50mm×50mm×50mm
Unconfined Compressive stress after 28 days	24	3	3	3	15	21 cubes 50mm + 3 cylinders 75mm×150mm
Direct Shear Box 7 days	12	3	3	3	3	50mm×50mm×25mm
Direct Shear Box 14 days	12	3	3	3	3	50mm×50mm×25mm
Direct Shear Box 28 days	12	3	3	3	3	50mm×50mm×25mm
California Bearing Ratio (CBR) 28 days	12	3	3	3	3	Stander cylindrical metal mold
Oedometer test 28 days	12	3	3	3	3	Oedometer cell (D×H) 50mm×25mm

Table 4 Unit weight of mixture 1:1 with different cement contents

Cement content (%)	Max dry unit weight (kN/m^3)	Optimum water content (%)
7	10.35	16
8	10.32	16.40
9	10.30	16.80
10	10.30	17.00

Table 5 Relationship between cement contents and water absorption

Cement content (%)	7	8	9	10
Water absorption (%)	4.4	4.32	4.20	3.92

Table 6   Relationship of shear parameters and cement ratio at different curing times

Curing time	7 days		14 days		28 days	
Shear parameters	*Φ*°	*C* (kPa)	*Φ*°	*C* (kPa)	*Φ*°	*C* (kPa)
7%	10.5	35	11.3	37	12	39.2
8 %	10.8	37.4	11	39.2	11.8	41.1
9 %	11	39	11.5	41.4	13	43.5
10%	12	40.6	12.5	42.5	14	45.8

Table 7 CBR values of prepared mixture after curing 28 days

Cement content (%)	CBR (%)
7	6.20
8	7.10
9	8.38
10	9.50