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Shear behavior of EPS geofoam reinforced with polypropylene fiber

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Abstract. The EPS geofoam as a lightweight material has been widely used in recent years to boost the performance of geotechnical structures. Both the internal and external stability of the fills made by the EPS blocks should be met. Overlying concrete slabs and thick pavements or applying denser EPS blocks provide internal stability of EPS geofoam lightweight fills by reducing the internal vertical stress within the EPS blocks. As an alternative way, in this study, new composite material is introduced by using the polypropylene fiber to reinforce the EPS geofoam in the factory as an attempt to improve the mechanical properties of the EPS geofoam. The composite material was fabricated in different fiber contents by solidifying the mixture of fiber and geofoam beads using controlled heat and temperature. Then, the behavior of the composite was studied using a series of direct shear tests. The results show that including fiber leads to a rise in the shear strength and a significant decline in the compressibility of the reinforced EPS geofoam. For the geofoam reinforced with 80% fiber content, up to 23.3% increase in the shear strength and 57.6% reduction in the vertical displacement (Δz) were observed in the laboratory. In addition, while the change in the composite's cohesion is largely decreased, the friction angle of the composite shows an increasing trend with fiber content increase. A maximum of 12.6% reduction in the cohesion and 100% increase in the internal friction angle of the reinforced material were observed in the laboratory.

Keywords: EPS geofoam; polypropylene fiber; reinforcement; shear behavior; fiber content

1. Introduction

Expanded Polystyrene (EPS) geofoam as a lightweight material was applied for the first time under the foundation of a bridge deck in the early 1970s (Negussy 2007). Since then, they have been wildly utilized because of their outstanding features, primarily their highly light weight in comparison with other lightweight and conventional construction materials. EPS geofoam is known as a multifunctional material due to its high thermal resistance, inertness, high-energy absorption, low water absorption, recyclability and appropriate acoustical properties (Elragi 2000, Gao *et al.* 2011). In addition, they do not need special equipment for installation (Beju and Mandal 2017). The high compressibility properties of the EPS geofoam, when used as a backfill of retaining walls, helps reduce the imposed lateral pressure (Aytekin 1997, Ikizler *et al.* 2008, Ertugrul and Trandafir 2014, AbdelSalam and Azzam 2016, Wan *et al.* 2018, Kim *et al.* 2018, Dabiri and Notash 2020). In addition, the effect of using EPS geofoam blocks as lightweight fill to boost the stability of slopes (Negussey and Srirajan 2001, Stark and Mann 2006, Arellano *et al.* 2010, Arellano *et al.* 2011, Akay *et al.* 2013, Akay 2016) and mechanical behavior of embankments (Jutkofsky *et al.* 2000, Bartlett and Lawton 2008, Newman *et al.* 2010, Ruttanaporamakul *et al.* 2016, Srivastava *et al.* 2019, Puppala *et al.* 2019) have been the subject of some studies. Moreover, the enhancing effects of the EPS geofoam in buried pipes and structures (Meguid *et al.* 2017, Al-Naddaf *et al.* 2019, AbdelSalam *et al.* 2019), railway track structures (Esveld *et al.* 2001), bridge abutments (Vaslestad et al 2019), road pavements (Duškov and Scarpas 1997, Huang and Negussey 2011, Ghotbi Siabil *et al.* 2019), foundation (Ojima *et al.* 1996, Abdelrahman and Elragi 2006, Gendy *et al.* 2019) and as a seismic buffer (Zarnani *et al.* 2005, Bathurst *et al.* 2007, Zarnani *et al.* 2009) have been investigated so far.

Both the internal and external stability of slopes containing EPS blocks, as lightweight fill should be met (Arellano *et al.* 2011). The latter criterion concerns the shear strength of the individual EPS block, while the former is associated with the interfacial resistance between the EPS blocks with the surrounding similar or dissimilar materials. In practice, the EPS blocks may contact the adjoining EPS blocks or with construction materials such as concrete or soil. In this regard, the effects of the material type, the wet condition, the sample size, the normal stress, size of the geofoam beads, the EPS density and the surface roughness on the interfacial behavior have been investigated so far (Sheeley and Negussey 2001, Negussey *et al.* 2001, Xenaki 2001, Atmatzidis *et al.* 2001, Abdelrahman *et al.* 2010, Padade and Mandal 2014, Khan and Meguid 2018, Khalaj *et al.* 2020). Sheely and Negussey (2001) showed that the material density, sample size, stress level, and surface moisture do not significantly influence geofoam to geofoam

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interface strengths. In addition, to minimize the movement between the EPS blocks during construction and in particular, in case of an earthquake, the effects of applying the persistently-used barbed connector plates were studied as well (Barrett and Valsangkar 2009). An interlocking mechanism, polyurethane adhesive, and shear keys were introduced and their influence on the improvement of the EPS-EPS interfacial resistance was investigated (Ozer and Akay 2016, Barrett and Valsangkar 2009, Bartlett and Lawton 2008).

The internal stability of the EPS monoblocks is generally analyzed based on either their strength at low strain level within the elastic limit (usually 1%) or a proportion of the failure compressive resistance associated with the large strain of 5% or 10% obtained from unconfined compression (UC) tests on small samples (0.05 m cube) of the EPS geofoam (Negussy 2007, Elragi, 2000). Using the UC test to assess the strength of the EPS geofoam implies that the EPS geofoam is generally assumed as a purely cohesive material. However, the EPS geofoam shows some frictional resistance, though relatively small, as the results of the direct shear and triaxial tests confirm (Leo *et al*. 2008, Padade and Mandal 2012a, b, Beju and Mandal 2017, Khan and Meguid 2018). Moreover, UC tests on the large blocks (0.6 m cube) of the EPS geofoam showed that using conventional 0.05 m cube specimens, gives rise to substantial underestimation of the elastic modulus and Poisson's ratio of this material (Elragi *et al.* 2000). Furthermore, the rise in the density has been found to significantly increase the compressive strength and stiffness of the geofoam (Horvath 1994, Ossa and Romo 2009).

In order to boost the internal stability and behavior of the EPS geofoam lightweight fills, usually either the vertical stresses within the EPS blocks are reduced indirectly by distributing the applied load over a wider area using concrete slabs on and in between the blocks or a thicker overlying pavement layer is used. Alternatively, EPS geofoam with higher shear strength can be used. In this regard, at the moment, the only approach is to apply a denser EPS geofoam block. However, geofoam density is a restricted parameter, ranging from 10 kg/m^3 to 40 kg/m^3 (AbdelSalam and Azzam 2016). Because of this, the idea of boosting the mechanical behavior of the EPS geofoam by combining them with randomly distributed polypropylene (PP) fibers was considered being assessed in the present study. The same rationale was behind the research conducted by Arvin *et al.* (2021) on EPS geofoam reinforced with geocell using large-scale direct shear test. Their results show that the geocell-geofoam composite (GGC) is much stronger and less compressible than the EPS geofoam.

Natural and synthetic fibers have been used for decades to improve the mechanical behavior of soils. Fiber-reinforcement can potentially boost the performance of highway and railway embankments, pavements, foundation, retaining walls, and slope stability (Arenicz and Chowdhury 1988, Park and Tan 2005, Kaur and Kumar 2016, Johari and Kalantari 2016, Sridhar and Prathap Kumar 2018, Gong *et al.* 2019, Li *et al.* 2019). Mechanical properties of fiber-reinforced soil are affected by soil properties (e.g., particle size, gradation, particle shape, and soil density), characteristics of fiber (Length, diameter, aspect ratio, orientation, fiber content, fiber stiffness, fiber extension, and fiber tensile strength) and soil-fiber interface resistance. Peak and post-peak strength of soils are increased by adding randomly distributed fibers (Maher and Gray 1990, Al-Refeai 1991, Maher and Ho 1994, Yetimoglu and Salbas 2003, Michalowski and Čermák 2003, Heineck *et al.* 2005, Consoli *et al.* 2007a, Ple and Le 2012, Diab *et al.* 2018, Liu *et al.* 2019). The significant effect of fiber on the residual strength of soil continues even at large strain levels (Heineck *et al.* 2005, Consoli *et al.* 2007a). Researches indicate that while clayey soil loses ductility when combined with fibers in drained condition (Maher and Ho 1994, Ple and Le 2012, Diab *et al.* 2018), fiber inclusion results in a rise in the ductility of sand (Al-Refeai 1991, Yetimoglu and Salbas 2003, Heineck *et al.* 2005, Consoli *et al.* 2007a). Furthermore, generally, fiber-reinforced sand is less stiff than the unreinforced ones (Maher and Gray 1990, Al-Refeai 1991, Yetimoglu and Salbas 2003, Ple and Le 2012, Güllü and Fedakar 2017, Li *et al.* 2019). Moreover, the addition of fiber increases the hydraulic conductivity of soil (Maher and Ho 1994, Ple and Le 2012). In addition, dilation of soil declines with an increase in the fiber content (Heineck *et al.* 2005, Kong *et al.* 2019). Denser sand samples are shown to be more effective in increasing and maintaining the residual shear strength of fiber-reinforced soils (Consoli *et al.* 2007a). Laboratory observations suggest that the failure envelope of the fiber-reinforced soils is either nonlinear or bilinear and is not affected by the stress path (Maher and Gray 1990, Consoli *et al.* 2007b).

The effect of fiber content on the behavior of reinforced soil has been investigated by some researches (Maher and Gray 1990, Al-Refeai 1991, Maher and Ho 1994, Yetimoglu and Salbas 2003, Michalowski and Čermák 2003, Diambra *et al.* 2007, Ple and Le 2012, Li *et al.* 2019). In addition, fiber length influence on the behavior of soil has been the subject of some studies (Michalowski and Čermák 2003, Consoli *et al.* 2007a, Diambra and Ibraim 2015, Li *et al.* 2019). Furthermore, many researches are devoted to the effect of fiber inclusion on the behavior of cemented soil by different cementing agents such as Portland cement, bio cementation, and calcium carbonate (Consoli *et al.* 1998, Tang *et al.* 2007, Hamidi and Hooresfand 2013, Ghoi *et al.* 2016, Cristelo *et al.* 2017, Lin *et al.* 2019, Arabani and Haghsheno 2020). Addition of fiber results in a higher peak and post-peak strength and a decline in the stiffness and permeability of the cemented soils. Fiber reinforcement's influence on reducing the liquefaction potential of soils has been investigated through some studies (Krishnaswamy and Isaac 1994, Maheshwari *et al.* 2012, Ye *et al.* 2017, Sonmezer 2019, Zhang *et al.* 2020).

Based on the literature review, it is noted that the properties of reinforced EPS have not been addressed so far. In the present study, the effects of fiber inclusion on the shear behavior of reinforced EPS geofoam are investigated using a series of direct shear tests. Samples of fiber-reinforced geofoam with different weight fraction of polypropylene fiber were fabricated in the factory. Then, the influence of the fiber content on the shear strength, volumetric behavior and shear strength parameters of fiber-reinforced geofoam has been investigated and discussed.

2. Materials and methods

2.1 Materials

2.1.1 PP fiber

The polypropylene (PP) fibers used in this study were relatively short with an average length of 12 mm. A photographic view of the fiber is shown in Fig.1. The fibers were deliberately chosen orange in color to make them recognizable inside the fiber-geofoam composite (FGC). The index and mechanical properties of the fibers used in the present study were provided by the manufacture as illustrated in Table 1.

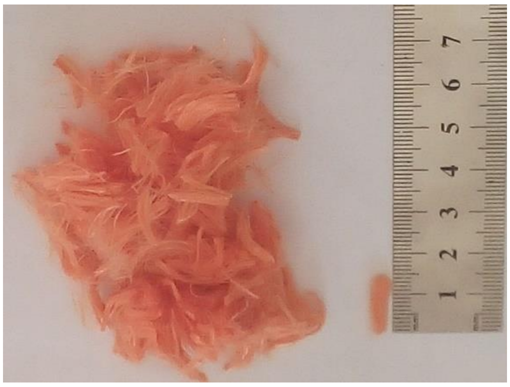

Fig. 1 A photographic view of the polypropylene fiber used in this study

Fig. 2 Adding PP fibers to the geofoam beads fiber used in this study

Table 1 Properties of PP-fiber used in this study

Parameters	Unit	Values
Fiber type		Single fiber
Color		Orange
Unit weight	g/cm^3	0.91
Average diameter	mm	0.018
Average length	mm	12
Breaking tensile strength	MPa	350
Modulus of elasticity	MPa	3500

2.1.2 EPS geofoam

EPS geofoam is usually manufactured as large blocks and is cut into desired shapes using hot wires. EPS blocks are fabricated by solidifying a large mass of pre-puffed polystyrene resin beads molded in a large container by blowing heat and steam through the walls of the mold. The level of the applied pressure can be arranged to achieve a predefined unit weight. In this study, the heat and pressure were adjusted to produce samples of FGC whose EPS proportion had a unit weight of 18.6 kN/m^3.

2.2 Preparation of EPS geofoam and FGC

To investigate the effect of PP fiber as a reinforcing agent, four different fiber contents by weight (χ_F = weight of PP fiber×100/weight of geofoam), χ_F =20%, 40%, 60% and 80% were considered and the behavior of the corresponding produced composites were compared with that of the pure geofoam (χ_F = 0%,). In order to make FGC samples, masses of geofoam beads and PP fibers weighed corresponding to the desired fiber content and transferred into a plastic container (Fig. 2). To make the mixture uniform, it was stirred manually with a metal stick for at least 5 minutes. Subsequently, the content of the container was moved inside the mold to change it to a solidified fiber-geofoam composite. The produced small block then was cut into 10 cm ×10 cm ×5 cm slices before the direct shear testing. The same approach, excluding the fiber inclusion, was followed to make the pure EPS specimens.

3. Test program

As explained earlier different fiber content (χF = 0%, 20%, 40%, 60%, and 80%) were considered to evaluate the effect of PP fiber content on shear behavior of reinforced EPS geofoam. All samples were tested using a 10 cm×10 cm×5 cm direct shear test (DST) apparatus. Figure.3 illustrates a view of typical EPS-PP fiber specimens in different fiber content considered in this study. In performing DST, three different normal stresses 50 kPa, 75 kPa and 100 kPa were applied to the specimens. All tests were carried out at a horizontal displacement rate of 1 mm/min. In total, 15 tests were performed. Each test was replicated at least twice to ensure the accuracy of the results.

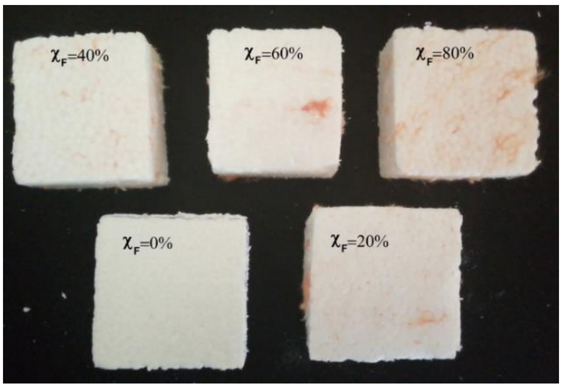

Fig. 3 Samples with different fiber contents

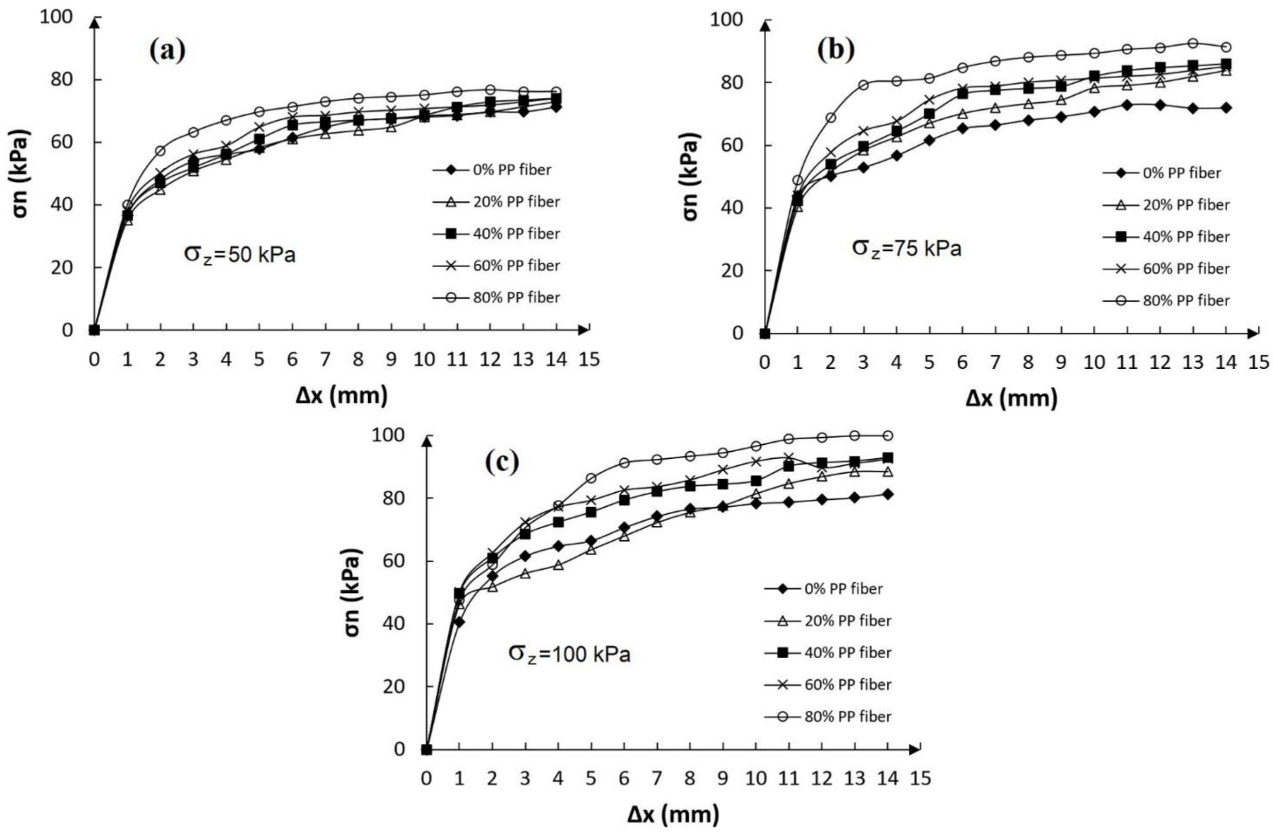

Fig. 4 Effect of the fiber content on the shearing behavior of the EPS geofoam at: (a) σ_z=50 kPa, (b) σ_z=75 kPa and (c) σ_z=100 kPa

4. Results and discussions

4.1 Shearing behaviour

Shear stress versus horizontal displacement curves associated with the composites containing different percentages of PP fibers (χ_F =0%, 20%, 40%, 60% and 80%) are shown in Figs. 4(a), 4(b) and 4(c) for σz=50 kPa, 75 kPa, and 100 kPa respectively. As these figures show, irrespective of the normal stress value, shear strength of the EPS geofoam goes up with the increase in the fiber content. For instance, in comparison with pure EPS geofoam, at σz=100 kPa and Δx=10 mm, an increase of 4%, 9.1%, 17.1% and 23.3% in shear strength was observed for samples reinforced with the fiber content of 20%, 40%, 60% and 80% respectively. One reason for the improvement in the shear strength might be the difference in the total unit weight between the composite and the pure EPS geofoam. The total unit weight of the composite (γ_{comp}) fabricated by combining the EPS geofoam and the PP fiber weighing W_G and $W_f=\chi_F\times W_G$ respectively, would be:

$$\gamma_{comp}=\frac{1+\frac{\chi_F}{100}}{\frac{1}{\gamma_G}+\frac{\chi_F}{100}\times\frac{1}{\gamma_F}} \tag{1}$$

In Eq. (1), γ_G and γ_F denote the unit weight of the geofoam and fiber respectively. Introducing the unit weight of the EPS geofoam and PP fiber used in this study into the Eq. (1), γ_{comp} will be determined 18.6, 22.2, 25.8, 29.4 and 32.9 kg/m^3 corresponding to χ_F =0%, 20%, 40%, 60% and 80% respectively. Almost the same values of γ_{comp} were measured in the laboratory with a maximum discrepancy of 3%. Since including the PP fiber results in a material with a higher density and the strength of materials grows proportionally with the unit weight, it can be argued that as well as the effect of the tensile strength of the PP fibers, the rise in the density contributes to the shear strength improvement of the developed material.

Furthermore, as Fig.4 indicates, there is no pronounced peak in the stress bearing of the fiber reinforced samples as shear strength continues to grow with Δx, though with a low rate in particular at large values of horizontal displacement. Accordingly, laboratory observations confirmed that no apparent failure plane was formed in any of the tested samples as the photos before and after the test on a typical specimen with χ_F = 60% indicates (Fig. 5). This might be due to the resilient behavior of EPS geofoam and FGC.

The volumetric behavior of the composites is depicted through Δz-Δx graphs in Fig.6(a), 6(b) and 6(c) corresponding to σ_z=50 kPa, 75 kPa and 100 kPa respectively. Regardless of the normal stress, as expected, higher fiber content leads to a lower level of compressibility in the composites. For instance, at Δx=10 mm and under σ_z=100 kPa, in comparison with pure geofoam, fiber contents of 20%, 40%, 60% and 80% have led to 3.4%, 19.2%, 46.3% and 57.6% fall in the vertical displacement (Δz) respectively. Moreover, the compressibility of FGC

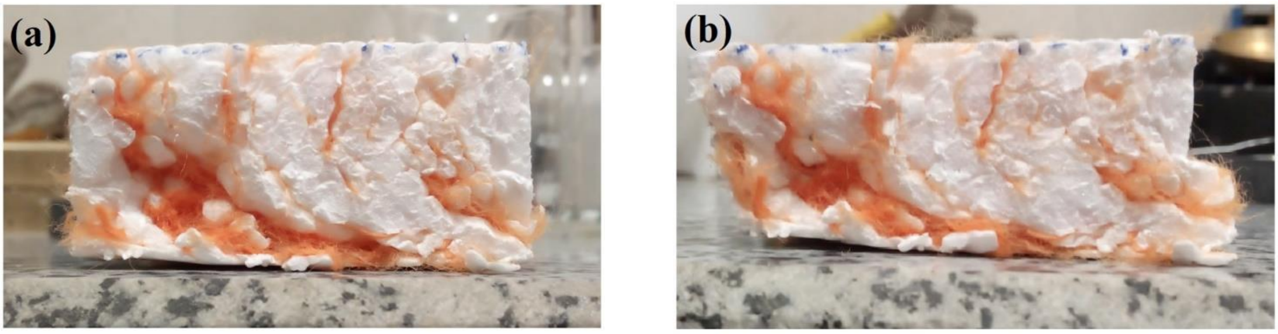

Fig. 5 A photographic view of a specimen with 60% fiber content, (a) before test and (b) after test

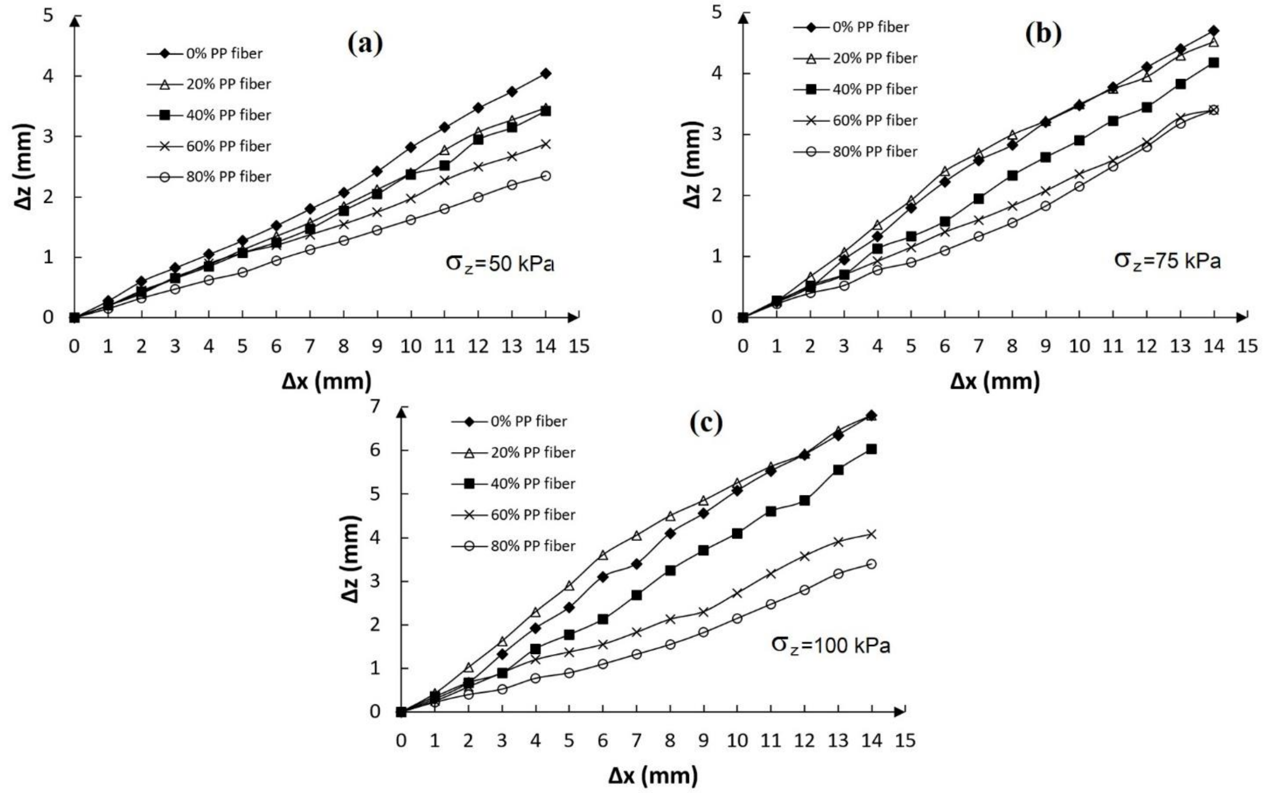

Fig. 6 Effect of the fiber content on the volumetric behavior of the EPS geofoam at: (a) σ_z=50 kPa, (b) σ_z=75 kPa and (c) σ_z=100 kPa

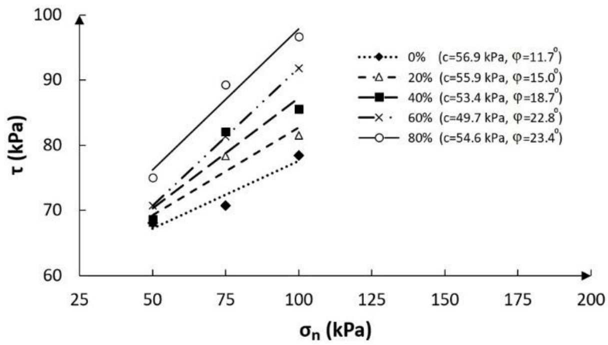

Fig. 7 Effect of the fiber content on the failure envelope of the EPS geofoam

experiences a drastic decline at σ_z=100 kPa compared to the other two imposed normal stresses as Fig.6 shows. For example, at Δx=10 mm and χ_F=60%, the percentage decline in the compressibility is 30.1% and 32.4% for σ_z=50 and 75 kPa respectively and jumps to 46.3 for σ_z=100 kPa. It can be reasoned that at higher fiber content, single threads of the fiber may partially disconnect the interlocking bonds among the geofoam beads, allowing them to slide and roll

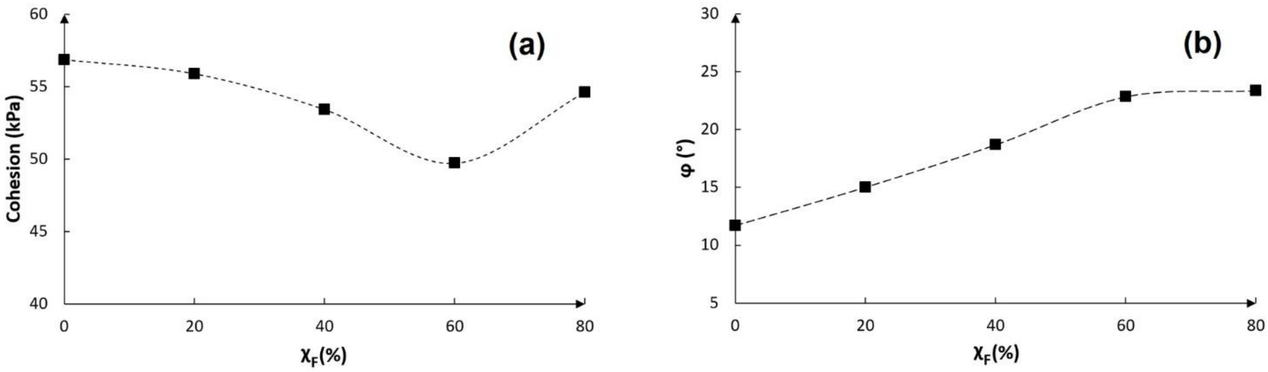

Fig. 8 Effect of the fiber content on the: (a) cohesion and (b) internal friction angle of the FGC

against each other more freely. The progressing tendency to dilation ensuing from the freedom to rolling as explained, may justify the resulting decrease in the compressibility as the χ_F goes up.

4.2 Shear strength parameters

The Mohr-Coulomb shear failure envelopes associated with EPS geofoam mixed with different fiber contents are illustrated in Fig.7. Since, no peak in the shear stress was observed in any of the tested samples, shear strength corresponding to Δx=10 mm was taken to determine the shear strength parameters (cohesion and internal friction angle).

Variations of the cohesion and internal friction angle with respect to χ_F at Δx=10 mm are shown in Fig. 8(a) and Fig. 8(b) respectively. As Fig. 8(a) shows, the cohesion declines slightly with an increase in the χ_F, reaches a minimum at χ_F =60% and grows slightly afterward. Although the maximum value of cohesion (c_{max}) occurred at χ_F=0%, only 12.6% fall in the cohesion with respect to c_{max} occurred at χ_F=60%, where the cohesion fell to a minimum. In addition, the cohesion intercept of the composite for χ_F=80% is only 4% lower than c_{max}. Furthermore, the variation of the internal friction angle with the fiber content is increasing from χ_F=0% to χ_F=60%, and practically levels off beyond χ_F=60%. It appears that in comparison with the cohesion, the friction angle has been highly affected by the inclusion of the PP fiber so that there is almost a two-fold rise in the ϕ at χ_F=60% and 80% in contrast to pure geofoam (Fig. 8(b)). Overall, it can be said that adding the PP fiber to the EPS geofoam, causes the behavior of the EPS geofoam to be slightly less cohesive and highly more frictional. It can be argued that the inclusion of the PP fiber on the one hand reduces the cohesion of the EPS geofoam by interrupting the bonds among the geofoam beads and on the other hand, enhances cohesion owing to its relatively high tensile strength. These two opposing effects may result in a reduction or a rise in the total cohesion of the composite as laboratory results in Fig.7(a) demonstrate. In addition, it can be said that as the fiber content in the composite goes up, the probability of the bonds among the EPS geofoam beads to be interrupted by the threads of the PP fibers grows, allowing the geofoam beads to slide and roll more freely against each other. It follows that as the χ_F increases, more geofoam-geofoam bonds are affected leading to more reduction in the cohesion and more increase in the internal friction angle. The decline in the cohesion and the corresponding rise in the ϕ between χ_F=0% to χ_F=60%, as Fig.8 depicts, may be regarded as proving evidence to this argument. However, with the increase in the fiber content beyond χ_F=60%, the relatively high tensile strength of the fibers helps the development of the cohesion on the one hand and it inhibits further rolling and sliding of the geofoam beads onto each other on the other hand, leading to an increase in the cohesion and bringing the increasing trend in internal friction angle to a halt, as Fig. 8 illustrates. The change in the behavior of the reinforced geofoam blocks from cohesive to cohesive-frictional was also observed in the geofoam mattresses reinforced with geocell, geocell-geofoam composite (Arvin et *al.* 2021).

5. Conclusions

In designing the lightweight fills made of EPS geofoam blocks, internal and external stability must be ensured (Arellano *et al.* 2011). In order to improve the internal stability of the EPS geofoam lightweight fills, the stress level within the EPS blocks must be in the acceptable range. In this study, the EPS geofoam reinforced with the PP fiber has been introduced as an attempt to improve the mechanical properties of the EPS geofoam blocks and hence to increase the internal stability of the EPS geofoam lightweight fills. Samples of the fiber-geofoam composite (FGC) with different fiber contents (χ_F =0%, 20%, 40%, 60% and 80%) were fabricated in the factory by solidifying the mixture of the geofoam beads and short PP fibers under controlled heat and pressure. Then, the shearing behavior of the samples was assessed through a series of direct shear tests using a 10 cm × 10 cm × 5 cm direct shear apparatus. The following are the main findings of the current study:

1- Inclusion of the PPF was found to be effective in the improvement of the shear behavior of the reinforced EPS geofoam. The shear strength of the samples increased and their compressibility declined as the fiber content grew. Up to 23.3% increase in the shear strength and 57.6% reduction in the vertical displacement (Δz) were observed at Δx=10 mm and χ_F =80%.

2- It was observed that the relative reduction in the GGC compressibility was increased with the rise in the vertical stress and fiber content. It can be argued that with the increase in fiber content, bonds between the adjacent geofoam beads are more likely to be partially disconnected by the fiber threads, leading to a more effortless movement of the geofoam beads onto each other and hence a tendency to increase the GGC volume.

3- The Mohr-Coulomb shear failure envelopes of the tested materials suggest that the cohesion of the reinforced geofoam experiences an initial decline and a subsequent growth with the increase in the fiber content. However, the internal friction angle of the reinforced material always followed an increasing trend. The minimum cohesion, associated with χ_F =60%, was only 12.6% less than the c_{max}. The inclusion of the PP fiber was found to have changed the internal friction angle of the EPS geofoam nearly twofold at χ_F =60% and χ_F =80%. Overall, fiber inclusion changes the behavior of the EPS geofoam from predominantly cohesive to cohesive-frictional. The same behavior observed in the geofoam mattresses reinforced with geocell (Arvin *et al.* 2021).

4- The changes in the cohesion with the fiber content were attributed to two opposing effects namely, the reduction in the cohesion due to interruption of the bonds between the geofoam beads and the increase in cohesion due to the tensile strength of the fiber. In addition, the increasing trend in the internal friction angle of the reinforced geofoam was explained to be caused by the ability of the geofoam beads to move more freely, resulting from the interruption of the bonds among the geofoam beads by the PP fiber.

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