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Investigation of Strength Parameters of PVA Fiber-Reinforced Fly Ash-Soil Mixtures in Large-Scale Direct Shear Apparatus

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Abstract

Soil reinforcement is an old and still efficient technique in improving soil strength and stiffness properties. Current paper aims at quantifying the effects of different inclusions on mechanical behavior of fiber-reinforced cemented soil. An experimental program was conducted to study simultaneous effects of randomly oriented fiber inclusions and cement stabilization on the geotechnical characteristics of fly ash-soil mixtures. Chamkhaleh sand, polyvinyl alcohol (PVA) fiber, cement and fly ash with some water were mixed and compacted into large scale direct shear apparatus with three equal layers. PVA fibers were randomly distributed in three compacted layers at predetermined weight contents. Direct shear tests were carried out on fly ash-soil specimens prepared with different cement, fly ash and polyvinyl alcohol contents, and 7 different curing periods. Results show that cement increases the strength of the raw fly ash-soil specimens. The fiber inclusion further increases the strength of the cemented and uncemented soil specimens and transforms their brittle behavior to ductile behavior. The fiber reinforcement and distribution throughout the entire specimen results in a significant increase in the strength of fly ash -soil- cement mixtures.

Keywords: Chamkhaleh Sand; Polyvinyl Alcohol (PVA) Fiber; Cement; Fly Ash; Large Scale Direct Shear Apparatus.

1. Introduction

Construction of buildings and other civil engineering structures on weak or soft soils can be highly risky because such types of soils are susceptible to differential settlements due to their poor shear strength and high compressibility. Improvement of certain desired properties like bearing capacity, shear strength and permeability characteristics of soils can be undertaken by a variety of ground improvement techniques such as densification, reinforcement and stabilization.

Recently, engineers are showing more interest in using various types of materials in civil engineering applications to achieve better performance, diminish project costs, facilitate and expedite the program and more than these, to have more environmentally-friendly and strengthened construction scheme. Soils can be reinforced either by inclusion of bars, sheets and strips within a soil mass known as systematically reinforced soils or randomly addition of discrete fibers into a soil fill. Use of natural fibers can be attributed to ancient times. However, nowadays, use of randomly distributed fiber reinforcement techniques has been particularly paid attention to.

Randomly distributed fiber reinforced soils have shown to be superior to those systematically reinforced ones. Apart from being economic and causing significant growth in bearing capacity, soil mechanical properties, tensile and shear

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strength, they provide strength isotropy and confine potential planes of weakness that can be developed parallel to oriented reinforcement [1].

Given that soil cementation results in reducing settlement and enhancing bearing capacity, which are the two most important geotechnical design parameters, artificially soil cementation has been used in many construction sites so far. For instance, cemented fly ash was employed for constructing a man-made island by Horiuchi et al. [2] and Kawasaki et al. [3]. Plus, it is used for back-filling waterfront structures by Kitazume [4]. Also, cemented in situ soil has been employed for retaining wall by Ismail [5]. Although cementation considerably improves elastic modulus and peak strength, at higher cement contents and lower initial mean effective stresses, they show more brittle stress-strain behavior [6]. In certain cases, it can contribute to a sudden failure and can be destructive, particularly in shallower depths because of lower confining stresses, therefore, use of natural or synthetic fibers in cemented soils were proposed [7, 8, 9, 10]. Fibers can induce bonding and friction in the mixture and as fiber-reinforced mixtures can bear loads even after failure, they are very influential in enhancing the soil brittle behavior.

A literature review reveals that various laboratory investigations have been conducted independently either on fly ash / lime stabilization of soils or fiber-reinforced soils by many investigators like Mitchell and Katti [11], Ingles and Metcalf [11], Brown [12] , Gray and Al-Refeai [13], Gray and Maher [14] , Al-Refeai [15], Michalowski and Zhao [16] , Michalowski and Cermak [17], Ranjan et al. [18], Consoli et al. [19]. Kumar and Tabor [20] studied the strength behavior of silty clay with nylon fiber for varying degree of compaction. The study on soil fly ash mixture reinforced with polyester fibers was conducted in India by Kaniraj and Havanagi [9].

Addition of fibers in cemented soils most probably improves the mechanical properties of the mixture [10, 21]. As an illustration, addition of glass fibers in cemented soil enhances compressive and tensile strength by 30 and 38%, respectively [22] . Furthermore, addition of fibrillated-polypropylene fibers (PFs) to the cemented soils increases the indirect tensile strain, the indirect tensile strength (ITS) and the toughness index (TI). Increase of curing time also increases the resilient modulus, but addition of fiber does not enhance the unconfined compressive strength (UCS) [23]. Moreover, Khattak and Arashidi [23] came to the conclusion that the performance of processed cellulose fiber (PCF) modified soil–cement mixture is by far better at an optimum fiber dosage. Maher and Ho [10] declared that fiber inclusion to the cemented samples increases the peak compressive strength, tensile strength and energy absorption capacity. Jamshidi Chenari et al. [24] also examined the effects of adding EPS beads to the cemented fly ash-soil mixture. They reported augmented ductility and reduced strength due to the EPS beads inclusion.

Jadhav and Nagarnaik [25] carried out an experimental study to evaluate the performance of silty soil- fly ash –fiber mixture. The used fibers were randomly oriented polypropylene fibers. The performance was assessed by using 50%-50% soil- fly ash proportion. Kumar and Singh [26] studied the effects of polypropylene fiber reinforcements on conventional parameters of fly ash such as unconfined compressive strength, modulus of elasticity, shear strength and C.B.R. The effect of reinforcements and confinements on permanent strength, resilient strain and resilient modulus of fly ash were also studied. Tests were carried out to study the effect of reinforcement on rut depth formation on a laboratory model simulating field condition. Based on the results, it was concluded that fly ash is a suitable alternative for sub-base construction, if it is reinforced with polypropylene fibers. Chauhan et al. [27] reported performance evaluation of silty-sand subgrade reinforced with fly ash and fiber reinforcement (coir fibers and synthetic fibers). Extensive laboratory investigation indicated that both the permanent and resilient strains in all materials decrease with confining pressure but increase with number of load cycles and deviator stress in reinforced and un-reinforced conditions. Coir fiber shows better resilient response against the synthetic fibers by higher coefficient of friction. Sadek et al. [28] carried out the experimental study for evaluating the shear strength of fiber reinforced sand. Mishra et al. [29] concluded that the reinforcement of soil mixed with fly ash further increases the strength of soil used for construction activity. Fiber reinforced soil can be considered to be good ground improvement technique specially in engineering projects on weak soils where it can act as a substitute to deep/raft foundations, reducing the cost as well as energy. Both the length and content of coir have important role in developing the strength properties of stabilized soil. But the strength properties are mostly affected by coir content than by size of coir fiber. Swati Sucharita Rout [30] concluded that optimum moisture content (OMC) increases with fly ash content and percentage of coir fiber. Maximum dry density (MDD) increases with fly ash content but decreases with the percentage of fiber. The inclusion of fly ash is improving Unconfined Compressive Strength (UCS) and CBR value of all the mixed proportion, but there is an abrupt rise in CBR at 10% fly ash content. Addition of coir fiber increases the CBR value and UCS value in soil+10% fly ash. Deshpande and Puranik [31] concluded that the black cotton soil mixed with fly ash and polypropylene fibers can be considered a good ground improvement technique especially in engineering projects on expansive soils where it can act as a substitute to deep/raft foundations, reducing the cost. The UCS value of soil increases with the polypropylene percentage. The optimum percentages of fly ash and polypropylene are 15 % and 1.5 % from the UCS point of view, respectively. Hence, it is concluded that this project is to meet the challenges of society to reduce the quantities of wastes, producing useful materials from non-useful waste materials that lead to the foundation of sustainable society.

Also, remarkable improvements and modifications in the engineering characteristics of soils can be achieved using fiber inclusions. Various types of tests have been performed by researchers on fiber reinforced soils such as triaxial tests, unconfined compression tests, CBR tests, direct shear tests, and tensile and flexural strength tests [32-34].

The current study aims at investigating geotechnical characteristics of fly ash-soil specimens, cement-soil specimens, and cement-fly ash-soil specimens mixed with different proportions of randomly oriented polyvinyl alcohol (PVA) fibers. Cement and fly ash were added to the sand at 4%, 6% and 8% by dry weight. Specimens were cured for 7 days after which they were prepared for direct shear. Samples were tested with 0%, 0.2% and 0.6% PVA fibers. Results of the experimental study and their corresponding conclusions have been presented.

2. Experimental Investigation

The experimental program includes assessing properties of the investigated materials, preparing samples, and performing large-scale direct shear tests.

2.1. Materials

Chamkhaleh sand, supplied from Caspian Sea beach, is used in this study. It is classified as poorly graded sand and its grain size distribution curve along with its properties are shown in Figure 1 and Table1, respectively. From the particle size distribution curve (as shown in Figure 1), the uniformity coefficient, C_u and the coefficient of curvature, C_c values have been determined.

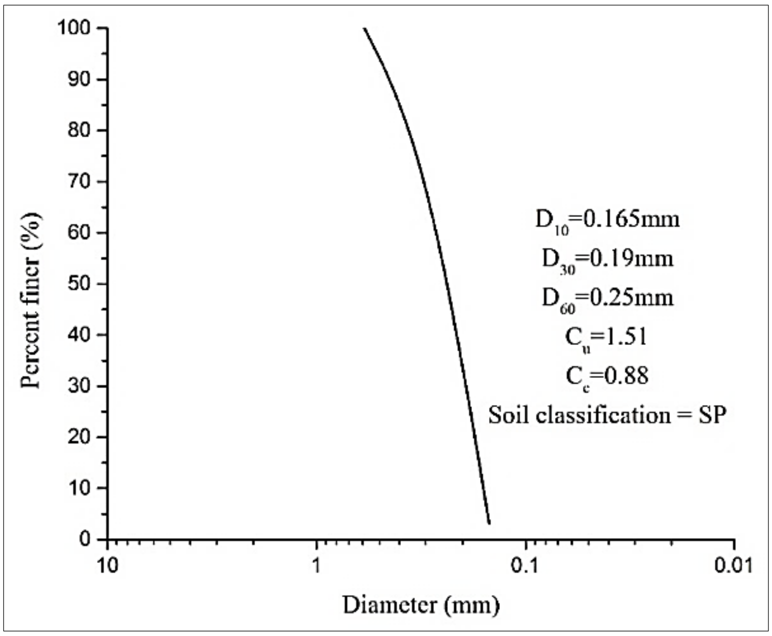

Figure 1. Grain size distribution of used sand in current study

Table 1. Physical properties of used sand

Description	Sand bed
G_s	2.63
Coefficient of uniformity, C_u	1.51
Coefficient of curvature, C_c	0.88
D_{10} (mm)	0.165
D_{30} (mm)	0.19
D_{50} (mm)	0.24
D_{60} (mm)	0.25
e_{max}	0.85
e_{min}	0.63

The fly ash used in the current research was collected from a single electrostatic precipitator of thermal power station. Table 2 shows the chemical composition and physical properties of the fly ash. The fly ash is classified as Class F fly ash as per ASTM C 618 [35]. Plus, ordinary Portland cement and polyvinyl alcohol (PVA) fibers are used in this study. PVA fiber is a synthetic fiber that has recently been used in fiber-reinforced concrete, since its weather resistance, chemical resistance, and tensile strength are superior to that of polypropylene fiber. PVA fiber has a significantly lower heat shrinkage than nylon or polyester. It has a specific gravity of 1.3, a good adhesive property to cement, and high anti-alkali characteristics. For this reason, it is suitable for mixing with cement and is widely used in concrete and cement reinforcement. Characteristics of the PVA fiber, as shown in Figure 2 and used as reinforcement elements, are given in Table 3. Distilled water was used in all specimen preparations.

Table 2. Chemical Composition and Physical Properties of Used Fly Ash

Composition or Property	Value
Chemical Composition (%)	
SiO_2	59.3
Al_2O_3	23.4
Fe_2O_3	4.8
CaO	8.6
MgO	0.6
K_2O	-
Na_2O	3.2
SO_3	0.1
Physical Property	
Specific gravity	2.1
Loss on ignition (%)	1.5
Specific surface area (cm^2/g)	4000

Figure 2. PVA fiber used in this study

Table 3. Properties of PVA fiber

Specific Gravity	Cut length (mm)	Diameter (mm)	Tensile strength (MPa)	Young's modulus (GPa)
1.3	1.5	0.2	1080	20

2.2. Large Direct Shear Test Apparatus

The direct shear test results can be influenced by the size of the shearing box. Generally, the boundary effect and device friction have more significant impacts than the smaller shear box. For instance, Ingold [36] reported that the friction angle obtained from 60 × 60 mm shear area was 2°–3° higher than the friction angle obtained from a 300 × 300 mm shear area. A large automated direct shear system is an electro-mechanical direct shear testing device for large samples, up to 380 mm square which has been employed for this study and demonstrated in Figure 3. The system consists of a computer-controlled unit that utilizes micro-stepper motors for applying vertical and horizontal loads to the soil specimen. In addition, the system is capable of applying a constant strain rate from 0.1 to 60 mm/min. It should be mentioned that direct shear test setup consists of upper and lower boxes. During the test, the upper box is fixed, and lower box can sustain horizontal loading up to 100 kN. Data collection system consists of two linear variable displacement transformers (LVDT) and a load cell. Components of a large direct shear test setup is shown in Figure 4 schematically.

Figure 3. Large direct shear test apparatus used in this study [37]

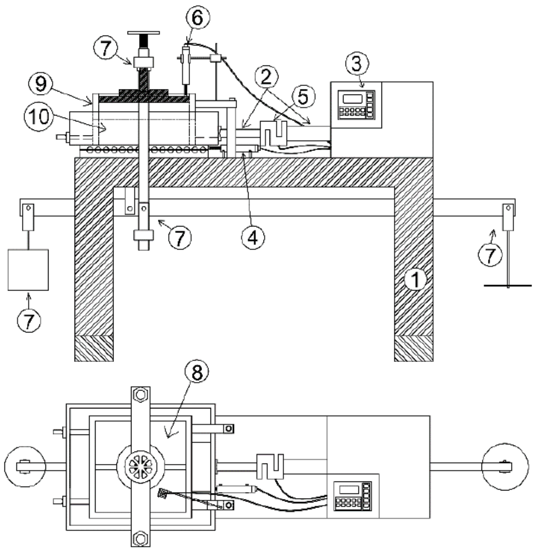

Figure 4. Details of the cyclic large direct shear test apparatus [37]

2.3. Fiber Mixing and Sample Preparation

The weight fraction for cement, fly ash and PVA fiber is based on dry sand. The procedure for the preparation of the specimen is also referred to as Park [31]. The cement ratio, ρ_c fly ash ratio, ρ_{FA} and the fiber ratio, ρ_F are defined as follows:

$$\rho_C = \frac{W_C}{W_S} \times 100 \tag{1}$$

$$\rho_{FA} = \frac{W_{FA}}{W_S} \times 100 \tag{2}$$

$$\rho_F = \frac{W_F}{W_S} \times 100 \tag{3}$$

Where W_c, W_{FA}, W_F and W_s are the weight of cement, fly ash, PVA fiber and dry sand, respectively.

All specimens in this study were prepared at a target dry density of 1502 kg/m^3 with a water content of 4% by weight of the mix, utilizing the dry tamping compaction technique. A total of 27 different mix designs were investigated in which the amount of cement varied from 2% to 8% and the amount of fly ash varied from 0% to 4% of the dry weight of the sand. The fiber-reinforced specimens contained an additional 0%, 0.2% and 0.6% by weight of dry sand.

To prepare specimens, first dry fly ash and soil have been weighed and mixed, then the considered amount of water has been added. However, some other specimens include cement as the stabilizer and some others have fibers as the reinforcing agent. In the former case, first cement is mixed to the dry fly ash-soil mixture and then water is added. Whereas, in the latter condition, the dry fly ash-soil mixture is first mixed with water and then fibers are added. From the experimental works, it has been concluded that fibers are mixed more effectively in the moist state.

Moreover, in some samples, both cement and fibers are added as the stabilizer. In such cases, a moist fly ash-soil-cement mixture is prepared first and then fibers are added. It is also important to note that mixes are done manually, and it has been well tried to prepare homogeneous mixtures.

Table 4 provides the details of different fly ash-soil-cement mixtures and notations used for them in this paper. The designations used are: C for the cement, FA for the fly ash, F for the PVA fiber. The sum of the three numbers is the number of total parts in the fly ash-cement-PVA mixture in soil. Thus C3FA1F0.6 represents a 3% cement, 1% fly ash and 0.6% PVA fiber, for example. Also, fly ash-soil-cement mixture with 0.2% PVA fiber is shown in Figure 5.

Table 4. Details of different fly ash-soil-cement mixtures with PVA fiber inclusion

Cement Content (%)	Fly ash Content (%)	Fiber Content (%)	Mixture designation
4	0	0	C4FA0F0
		0.2	C4FA0F0.2
		0.6	C4FA0F0.6
3	1	0	C3FA1F0
		0.2	C3FA1F0.2
		0.6	C3FA1F0.6
2	2	0	C2FA2F0
		0.2	C2FA2F0.2
		0.6	C2FA2F0.6
6	0	0	C6FA0F0
		0.2	C6FA0F0.2
		0.6	C6FA0F0.6
4.5	1.5	0	C4.5FA1.5F0
		0.2	C4.5FA1.5F0.2
		0.6	C4.5FA1.5F0.6
3	3	0	C3FA3F0
		0.2	C3FA3F0.2
		0.6	C3FA3F0.6
8	0	0	C8FA0F0
		0.2	C8FA0F0.2
		0.6	C8FA0F0.6
6	2	0	C6FA2F0
		0.2	C6FA2F0.2
		0.6	C6FA2F0.6
4	4	0	C4FA4F0
		0.2	C4FA4F0.2
		0.6	C4FA4F0.6

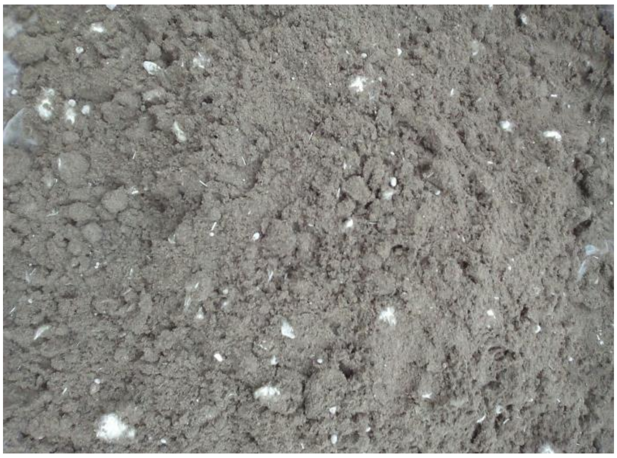

Figure 5. Fly ash-soil-cement mixture with 0.2% PVA fiber

3. Results and Discussion

Representative illustrations of direct shear test results on pure sand and fiber reinforced specimens under normal stresses of 30, 60 and 120 kPa are shown in Figure 6 and 7, respectively. It can be observed that the shear strength remains roughly unchanged after reaching its maximum value in the unreinforced sand while it shows a decreasing trend after reaching the peak in the reinforced sample. Such behavior can be traced to the sand density, which is higher in the reinforced mixture, hence, it shows a dilative behavior. Based on previous research, fiber reinforced specimens have more ductile behavior. As shown in Figure 7, fiber reinforced specimens did not show significant strength loss after failure. Also, the horizontal displacement at the peak shear strength increased from about 20 mm for unreinforced specimens to 25 ~ 30 mm for specimens reinforced with 0.6% fiber content. The result of these tests is in a good agreement with findings of other studies [32, 33].

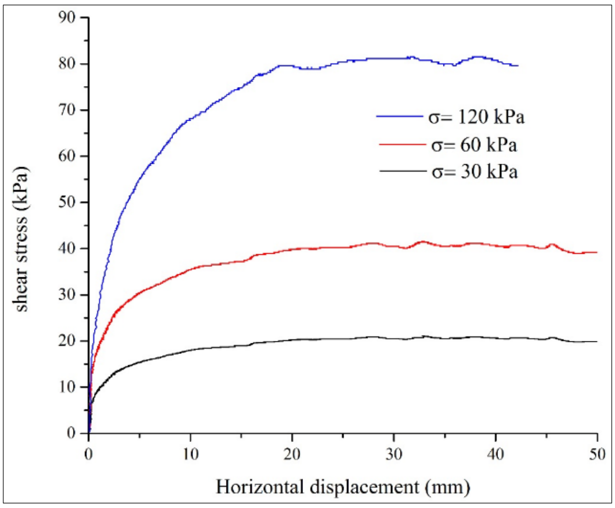

Figure 6. Shear stress- horizontal displacement response of pure sand

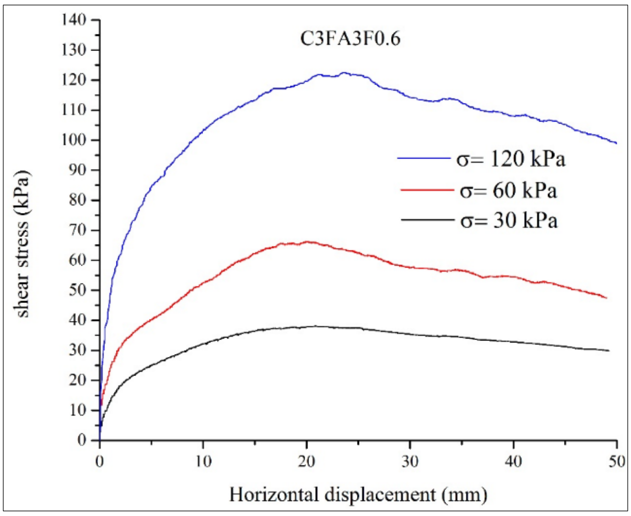

Figure 7. Shear stress- horizontal displacement response of fly ash-sand-cement mixtures with 0.6 % PVA fiber

Friction angle and apparent cohesion of fiber reinforced specimens calculated from direct shear tests results are illustrated in Figure 8 and 9, respectively. It can be concluded that increase in the fly ash and cement contents has significant effects on the internal friction angle value and apparent cohesion. The results of these tests show that fiber reinforcement has increased both the friction angle and the cohesion of the soil. Friction angle of unreinforced soil was 33.8°. The maximum friction angle of fiber reinforced soil reached to 50 degrees with 8% cement content and 0.6% of PVA fiber content fiber. Comparing its value with the friction angle of unreinforced soil shows 48% improvement. Cohesion of unreinforced soil was zero. Its value increased for fiber reinforced soil in its maximum state to 15.5 kPa. The maximum increment of the cohesion of fiber reinforced soil was also achieved with 8% cement content and 0.6% of PVA fiber content.

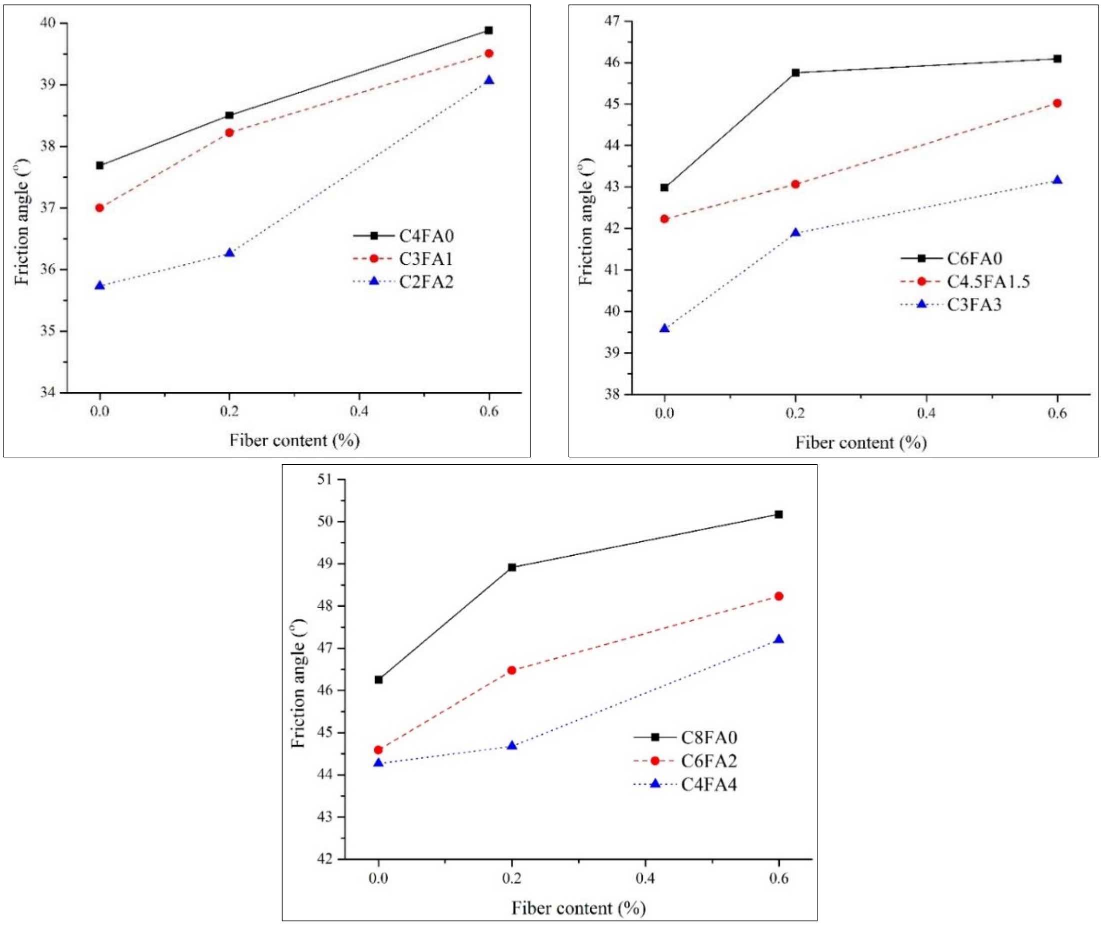

Figure 8. Effect of the PVA fiber reinforcement on the friction angle of the soil

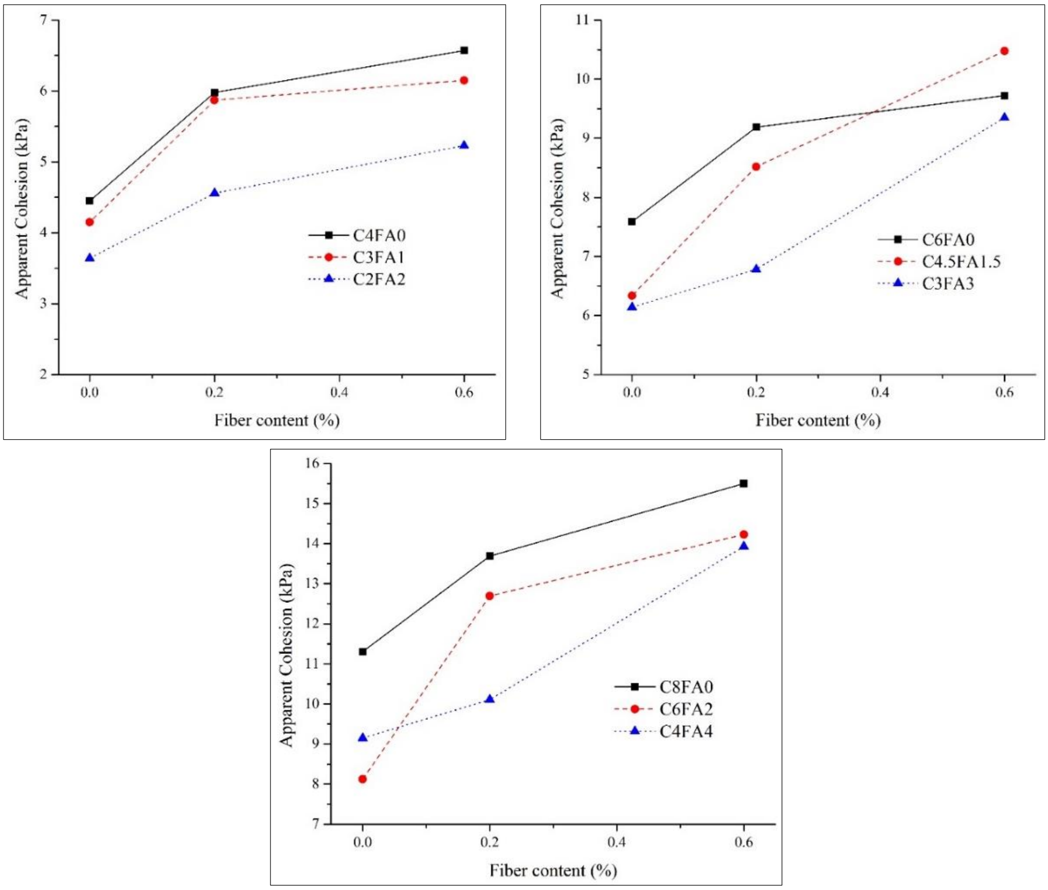

Figure 9. Effect of the PVA fiber reinforcement on the cohesion of the soil

4. Conclusion

Direct shear test is admittedly one of the most common laboratory tests conducted to evaluate shear properties of the soils. In the present study, an experimental program was undertaken on fly ash-soil-cement specimens of different proportions, to investigate the individual and combined effects of randomly oriented fiber inclusions on the geotechnical characteristics of fly ash-soil-cement-PVA fiber mixtures. Fly ash and cement have long shown improvement in strength and deformation properties of earthen materials. However, although their use as soil improvement additives has been admitted by practitioners of the field, they are sometimes prohibitively expensive, and experts have always sought any sort of environmentally friendly alternatives to partially replace such expensive materials. On the other hand, additives such as cement or fly ash do not enhance all aspect of the material properties and fibrillated inclusions are always welcome to impart additional shear strength to the composite soil materials. PVA fibers were investigated in current research to examine their effect on the mechanical behaviour of fly ash-soil-cement composite. The contribution of different constituents like cement, fly ash, and PVA fibers were discussed in terms of shear strength parameters of cohesion and internal friction angle while are simple, but universally known Mohr-Coulomb shear strength parameters. Furthermore, the slope of shear-stress-shear strain profiles was chosen to represent brittleness and ductility.

Most prominent findings include:

- Direct shear test results indicated that the randomly oriented fiber inclusion increases the shear strength of the fly ash-soil-cement specimens. The trend in the change of friction angle and cohesion due to fiber inclusions was found to be fairly consistent.
- A marked brittle behaviour was observed for specimens stabilized by fly ash and cement rather than un-stabilized specimens. The shear behaviour of un-reinforced samples showed brittle while reinforced ones were more ductile.
- The sand optimum performance is offered when fly ash-soil-cement specimens is used with C8FA0F0.6 designation.
- Increase of fly ash and cement contents showed to have noticeable effects on enhancing cohesion and friction angle values.
- Use of an almost 0.6% of PVA fiber in a fly ash- soil- cement mixture, is strongly recommended for an efficient performance to achieve.

5. Conflicts of Interest

The authors declare no conflict of interest.

6. References

[1] Asghari E, Toll DG, Haeri SM. Triaxial Behaviour of a Cemented Gravely Sand, Tehran Alluvium. Geotech. Geol. Eng. 2003; 21(1): 1–28, doi: 10.1023/A:1022934624666.

[2] Horiuchi S, Taketsuka M, Odawara T, Kawasaki H. Fly-Ash Slurry Island: I. Theoretical and Experimental Investigations. J. Mater. Civ. Eng. 1992; 4(2): 117–133, doi: 10.1061/(ASCE) 0899-1561(1992)4:2(117).

[3] Kawasaki H, Horiuchi S, Akatsuka M, Sano S. Fly-Ash Slurry Island: II. Construction in Hakucho Ohashi Project. J. Mater. Civ. Eng. 1992; 4(2): 134–152, doi: 10.1061/ (ASCE) 0899-1561(1992)4:2(134).

[4] Kitazume, Masaki. “Centrifuge Mode Tests on Failure of Cement Stabilized Fly Ash Ground.” Soils and Foundations 38, no. 3 (1998): 143–152. doi:10.3208/sandf.38.3_143.

[5] Ismail, M A. “Performance of Cement-Stabilized Retaining Walls.” Canadian Geotechnical Journal 42, no. 3 (June 2005): 876–891. doi:10.1139/t05-021.

[6] Schnaid, Fernando, Pedro D. M. Prietto, and Nilo C. Consoli. “Characterization of Cemented Sand in Triaxial Compression.” Journal of Geotechnical and Geoenvironmental Engineering 127, no. 10 (October 2001): 857–868. doi:10.1061/(asce)1090-0241(2001)127:10(857).

[7] Consoli, Nilo C., Pedro D. M. Prietto, and Luciane A. Ulbrich. “Influence of Fiber and Cement Addition on Behavior of Sandy Soil.” Journal of Geotechnical and Geoenvironmental Engineering 124, no. 12 (December 1998): 1211–1214. doi:10.1061/(asce)1090-0241(1998)124:12(1211).

[8] Consoli, Nilo Cesar, Márcio Antonio Vendruscolo, and Pedro Domingos Marques Prietto. “Behavior of Plate Load Tests on Soil Layers Improved with Cement and Fiber.” Journal of Geotechnical and Geoenvironmental Engineering 129, no. 1 (January 2003): 96–101. doi:10.1061/(asce)1090-0241(2003)129:1(96).

[9] Kaniraj, Shenbaga R., and Vasant G. Havanagi. “Behavior of Cement-Stabilized Fiber-Reinforced Fly Ash-Soil Mixtures.” Journal of Geotechnical and Geoenvironmental Engineering 127, no. 7 (July 2001): 574–584. doi:10.1061/(asce)1090-0241(2001)127:7(574).

[10] Pincus, HJ, MH Maher, and YC Ho. “Behavior of Fiber-Reinforced Cemented Sand under Static and Cyclic Loads.” Geotechnical Testing Journal 16, no. 3 (1993): 330. doi:10.1520/gtj10054j.

[11] Mitchell, James Kenneth. "Soil improvement-state of the art report." In Proc., 11th Int. Conf. on SMFE, vol. 4, pp. 509-565. 1981.

[12] Brown RW. Practical Foundation Engineering Handbook McGraw-Hill New York. USA Google Sch. 1996.

[13] Gray, Donald H., and Talal Al‐Refeai. "Behavior of Fabric‐Versus Fiber‐Reinforced Sand." Journal of Geotechnical Engineering 112, no. 8 (August 1986): 804‐820. doi:10.1061/(asce)0733-9410(1986)112:8(804).

[14] Gray, D. H., and M. H. Maher. "Admixture Stabilization of Sand with Discrete Randomly Distributed Fibers." In Proceedings of XII International Conference on Soil Mechanics and Foundation Engineering, Rio de Janeiro, Brazil, vol. 2, pp. 1363-1366. 1989.

[15] Al-Refeai, Talal O. "Behavior of Granular Soils Reinforced with Discrete Randomly Oriented Inclusions." Geotextiles and Geomembranes 10, no. 4 (January 1991): 319–333. doi:10.1016/0266-1144(91)90009-l.

[16] Michalowski, Radoslaw L., and Aigen Zhao. "Failure of Fiber-Reinforced Granular Soils." Journal of Geotechnical Engineering 122, no. 3 (March 1996): 226–234. doi:10.1061/(asce)0733-9410(1996)122:3(226).

[17] Michalowski, Radoslaw L., and Jan Čermák. "Triaxial Compression of Sand Reinforced with Fibers." Journal of Geotechnical and Geoenvironmental Engineering 129, no. 2 (February 2003): 125–136. doi:10.1061/(asce)1090-0241(2003)129:2(125).

[18] Ranjan, Gopal, R. M. Vasan, and H. D. Charan. "Probabilistic Analysis of Randomly Distributed Fiber-Reinforced Soil." Journal of Geotechnical Engineering 122, no. 6 (June 1996): 419–426. doi:10.1061/(asce)0733-9410(1996)122:6(419).

[19] Consoli, Nilo Cesar, Júlio Portella Montardo, Pedro Domingos Marques Prietto, and Giovana Savitri Pasa. "Engineering Behavior of a Sand Reinforced with Plastic Waste." Journal of Geotechnical and Geoenvironmental Engineering 128, no. 6 (June 2002): 462–472. doi:10.1061/(asce)1090-0241(2002)128:6(462).

[20] Kumar, Sanjeev, and Everett Tabor. "Strength characteristics of silty clay reinforced with randomly oriented nylon fibers." Electronic Journal of Geotechnical Engineering 8, no. 2 (2003): 10.

[21] Khattak, Mohammad J., and Mohammad Alrashidi. "Mechanistic Characteristics of Processed Cellulose-Fiber Reinforced Soil-Cement Mixtures." Advances in Pavement Engineering (October 9, 2005). doi:10.1061/40776(155)8.

[22] Mo Y, Hongtao P, Tingwu L, Suping Y, Zhang X. Optimization Design of Parameters for the Reinforcement of Soil–cement Mixtures with Fiberic Glass. In. Proc. 99 Int. Conf. Agric. Eng., Beijing, China. 1999.

[23] Gaspard KJ, Mohammad L, Wu Z. Laboratory Mechanistic Evaluation of Soil Cement Mixtures with Fibrillated-Polypropylene-Fibers. In. 82nd Transp. Res. Board Annu. Meet. January. 2003; 12–16.

[24] Jamshidi Chenari RJ, Fatahi B, Ghorbani A, Nasiri Alamoti M. Evaluation of strength properties of cement stabilized sand mixed with EPS beads and fly ash. Geomechanics and Engineering. 2018 Apr 30;14(6):533-44, doi: 10.12989/gae.2018.14.6.533.

[25] Jadhao, Pradip D., and P. B. Nagarnaik. "Influence of polypropylene fibers on engineering behavior of soil− fly ash mixtures for road construction." Electronic Journal of Geotechnical Engineering 13 (2008): 1-11.

[26] Kumar, Praveen, and Shalendra Pratap Singh. "Fiber-Reinforced Fly Ash Subbases in Rural Roads." Journal of Transportation Engineering 134, no. 4 (April 2008): 171–180. doi:10.1061/(asce)0733-947x(2008)134:4(171).

[27] Chauhan, Mahipal Singh, Satyendra Mittal, and Bijayananda Mohanty. "Performance Evaluation of Silty Sand Subgrade Reinforced with Fly Ash and Fibre." Geotextiles and Geomembranes 26, no. 5 (October 2008): 429–435. doi:10.1016/j.geotexmem.2008.02.001.

[28] Sadek, Salah, Shadi S. Najjar, and Fadi Freiha. "Shear Strength of Fiber-Reinforced Sands." Journal of Geotechnical and Geoenvironmental Engineering 136, no. 3 (March 2010): 490–499. doi:10.1061/(asce)gt.1943-5606.0000235.

[29] Mishra M, Maheshwari UK, Saxena NK. Improving Strength of Soil Using Fiber and Fly Ash-A Review. 2016.

[30] Rout SS, Sahoo MM, Sahoo RR. Influences of Fly Ash and Coir Fiber on Strength Properties of Soft Soil. 2017; 6(10): 1–9.

[31] Deshpande, Saurabh. Sanjay, and M.M Puranik. "Effect of Fly Ash and Polypropylene on the Engineering Properties of Black Cotton Soil." International Journal of Civil Engineering 4, no. 4 (April 25, 2017): 52–55. doi:10.14445/23488352/ijce-v4i4p111.

[32] Park, Sung-Sik. "Effect of Fiber Reinforcement and Distribution on Unconfined Compressive Strength of Fiber-Reinforced Cemented Sand." Geotextiles and Geomembranes 27, no. 2 (April 2009): 162–166. doi:10.1016/j.geotexmem.2008.09.001.

[33] Ghiassian, H., R. Jamshidi, and A. R. Tabarsa. "Dynamic Performance of Toyoura Sand Reinforced with Randomly Distributed Carpet Waste Strips." Geotechnical Earthquake Engineering and Soil Dynamics IV (May 14, 2008). doi:10.1061/40975(318)44.

[34] Jamshidi, R., I. Towhata, H. Ghiassian, and A.R. Tabarsa. "Experimental Evaluation of Dynamic Deformation Characteristics of Sheet Pile Retaining Walls with Fiber Reinforced Backfill." Soil Dynamics and Earthquake Engineering 30, no. 6 (June 2010): 438–446. doi:10.1016/j.soildyn.2009.12.017.

[35] ASTM, C., 618, 1993. Standard speciation for fly ash and raw or calcined natural pozzolan for uses as a mineral admixture in Portland cement concrete. American Society for Testing and Materials, Philadelphia, Pennsylvania, doi: 10.1520/C0618-17A.

[36] Selig, ET, and TS Ingold. "Some Observations on the Laboratory Measurement of Soil-Geotextile Bond." Geotechnical Testing Journal 5, no. 3 (1982): 57. doi:10.1520/gtj10804j.

[37] Karimpour Fard, Mehran, R. Jamshid Chenari, and F. Soheili. "Shear Strength Characteristics of Sand Mixed with EPS Beads Using Large Direct Shear Apparatus." Electronic Journal of Geotechnical Engineering 20, no. 8 (2015): 2205-2220.