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USING CEMENT AND FIBERS AS ADDITIVES FOR LIQUEFACTION MITIGATION OF SANDY SOILS

Ahmed Elzamel[1], Ayman Altahrany[2] and Mahmoud Elmeligy[3]

[1,2,3] Structural engineering department, Faculty of Engineering, Mansoura University, Egypt

*Corresponding Author, Received: 24 March 2022, Revised: 28 May 2022, Accepted: 12 June 2022

ABSTRACT: Liquefaction is one of the most significant earthquake-related phenomena that reduce the resistance of saturated loose sandy soils. To minimize the potential for liquefaction, polypropylene fibers, geofibers, and polypropylene fibers with cement were used as stabilization materials. A series of laboratory stress-controlled undrained cyclic triaxial tests has been conducted as per ASTM D3999 and ASTM D5311. Dry sand–cement mixes were prepared using an electric mixer with randomly distributed polypropylene fiber at different percentages of fiber contents. Polypropylene fibers have lengths of 10 mm and 20 mm. Cemented specimens with cement content varying from 0 % to 2 % by weight of dry sand were prepared and cured for 3 days. Geofiber specimens were prepared by placing 6.5 cm diameter geofibers inclusions in various horizontal arrangements in the sample. It was found that the liquefaction improvement factor (LIF) increased when fiber content and fiber length increased. LIF of the addition of 1% polypropylene fibers (PF) of 20 mm was equal to 215.38% at cyclic stress ratio (CSR) = 0.20. The addition of geofibers increased the liquefaction resistance as the number of layers increased. The addition of geofibers increased the liquefaction resistance as the number of layers increased. The addition of 2% cement (C) +1% P.F. provided the best liquefaction resistance in this study compared with other additives. LIF of samples reinforced with 2% C+1% PF equals 893.33% at CSR= 0.30. This study proposes cement and fiber as good soil improvement techniques that can improve liquefaction resistance.

Keywords: Liquefaction, Shear modulus, Cyclic stress, Geofibers

1. INTRODUCTION

One of the most important earthquake-related processes is liquefaction, which diminishes the resistance of saturated loose sandy soils. To meet the demands of geotechnical engineering, stabilization techniques have been widely used to increase the strength characteristics of sand. The principal processes of liquefaction in a loose sand deposit during earthquakes are the creation of increased pore water pressure and a drop in mean effective stress [1]. In soil reinforcement laboratory testing, geotextiles, geofibers, fibers, rubber, and cement were most commonly used [2-3].

The additives for reinforcement have been widely used in material sciences [4-8]. The cyclic resistance of strengthened samples towards liquefaction capability improved because the number of geotextile layers increased. Liquefaction resistance was improved when the geotextile layer was placed close to the specimen's top (load application part) [9]. The addition of fibers enhanced the sand's shear modulus and reduced the liquefaction phenomenon. When discrete fibers are mixed with the soil, shear strength is improved and post-peak strength loss is minimized [10]. Under cyclic triaxial conditions, drained triaxial tests were performed on cemented sand specimens strengthened with randomly polypropylene fibers and cement contents ranging from 0% to 10% by weight of dry sand. Cement increases sand stiffness, peak strength, and brittleness. Cement and fiber insertions have a significant effect on the stress–dilatancy behavior of the sand [11]. Shear modulus increased as fiber content increased (f.c = 0, 0.5, and 1 %). The ideal fiber content is demonstrated to be variable and is influenced by the deviator stress ratio [12]. Using cyclic triaxial testing, results of fiber content, relative density, and confining pressure were studied on loose and medium dense sand strengthened with polypropylene fibers. The number of loading cycles leading to liquefaction increased as the fiber content and fiber length increased. At a relative density (D_r) of 40 %, fiber length of 18 mm, and CSR=0.25, the improvement in liquefaction resistance was 220 % [13]. The effect of fiber reinforcement and dispersion on the strength of fiber-reinforced cemented sand was investigated using a series of unconfined compression experiments. Fiber-reinforced specimen outperformed a non-fiber-reinforced specimen by a factor of two. The specimen with five fiber inclusion layers was 1.5 times stronger than the specimen with one fiber inclusion layer in the center when the same number of fibers were used to strengthen both specimens [14].

The liquefaction resistance, undrained shear strength, and stiffness all improved when polymer fibers and cement were added to silty and clean Toyoura sand. The inclusion of 0 – 2 % fibers improves the situation only slightly. In proportion to the percentage added, cement increases the stiffness and liquefaction resistance of the soil [15]. The strength of the recycled tiles improved significantly, but only for samples with low cement content. The strength of both samples treated with OPC alone and those treated with Ordinary Portland Cement (OPC) plus 20 % recycled tiles was found to be a maximum of 6% OPC [16]. On both untreated and treated marine clay, a series of laboratory stress-controlled cyclic triaxial experiments were performed. The untreated marine clay showed a higher permanent axial strain rate under cyclic loading than the treated clay due to the presence of extra cementing components following treatment with recycled tiles and a minor amount (2%) of cement [17]. In monotonic triaxial drained compression tests, samples of Toyoura sand-cement-fiber mixtures with varying percentages of fiber and cement (for example, 0 – 3 %) additives were tested. Small-strain stiffness is observed to be marginally reduced when fibers are included. Adding cement to pure Toyoura sand samples, on the other hand, improves their small-strain stiffness properties [18].This research uses cyclic triaxial testing to characterize the liquefaction resistance of sand–cement-fiber mixture. The majority of past research has been focused on the strength and deformation characteristics of fiber-reinforced soil under static loads. However, as far as the authors are aware, little research has been conducted to assess the liquefaction resistance of sand–cement-fiber mixture.

2. RESEARCH SIGNIFICANCE

Soil liquefaction is a critical scientific and engineering challenge that can cause substantial damage to numerous engineering structures and infrastructure around the world due to an increase in pore water pressure and a drop in mean effective stress. The main goal of this research is to use cyclic stress-controlled triaxial testing to assess the liquefaction resistance of different additives such as geofibers, polypropylene fibers, cement, and cemented fine sand specimens reinforced with randomly polypropylene fibers. Finally, a comparison between different types of additives is conducted.

3. MATERIALS AND METHODS

3.1 Test Materials

The basic properties of the sand used in this study are presented in Table 1. The sand is collected from a site in New Damietta in the north of Egypt. This sand is classified as poorly graded sand (S.P.) according to the Unified Soil Classification System. The maximum and minimum void ratios are 0.977 and 0.728, respectively. Fig. 1 presents the grain size distribution for the sand used in this study.

Table 1 The properties of the sand used in this study

Property	Value
The specific gravity of the solids	2.69
D_{10} (mm)	0.15
Uniformity coefficient (Cu)	1.75
Curvature coefficient (Cc)	0.87
Unified Soil Classification System	SP
e_{max}	0.977
e_{min}	0.728

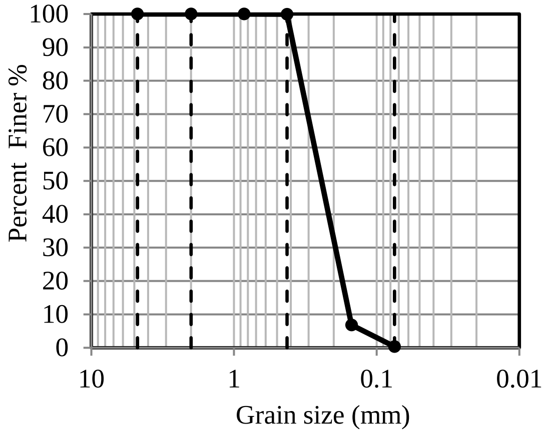

Fig. 1 Grain size distribution for sand used in the study

Polypropylene fibers were utilized in this study as soil reinforcement as shown in Fig.2. Polypropylene fibers are 0.018mm in diameter and have lengths of 10 and 20 mm, and have a specific gravity of 0.91. Fiber contents in reinforced samples were 0.0, 0.5, and 1 % by weight of dry soil. For geofibers specimens, as each sand layer is created, the 6.5 cm diameter geofibers inclusions are put horizontally in the sample. The density of geofibers is 520 gm/m^2, with a thickness of 2.10 mm and a tensile strength of 13.20 KN/m'. Fig. 3 depicts the geofibers used in this work [19].

(1) (2)

(1) Polypropylene fiber (10 mm)
(2) Polypropylene fiber (20 mm)

Fig. 2 Photograph of the polypropylene fibers used in this work

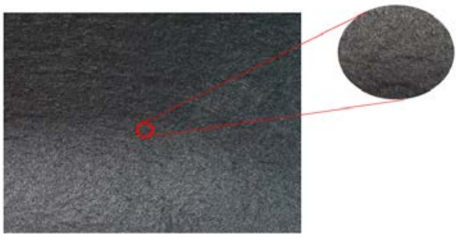

Fig. 3 Photograph of the geofibers used in this work

3.2 Test Equipment

All of the stress-controlled cyclic triaxial tests in this study were carried out using a tri-axial device that can perform static and dynamic tensile and compressive load tests in the threshold and alternating load range. Cylindrical specimens having a diameter of 70 mm and a height of 140 mm were tested in this device. Fig. 4 depicts an overview of the device. The following things make up the primary system components: load frame and actuator, triaxial cell, air/water bladder, and pressure controlling APC to convert a regulated pressure in a practical pressure range up to 9 bar from a pneumatic pressure supply of up to 10 bar.

A sinusoidal loading frequency up to 5 Hz is provided by the cyclic triaxial equipment. A displacement transducer with a travel distance of 50 mm was used to measure axial displacement. A load cell with a capacity of 10 kN was used to detect axial load. The electronic volume measuring device works on the differential pressure concept and is designed for monitoring minor changes in liquid volume at a high base pressure of up to 10 bar. During testing, an air/water bladder was employed to maintain cell pressure.

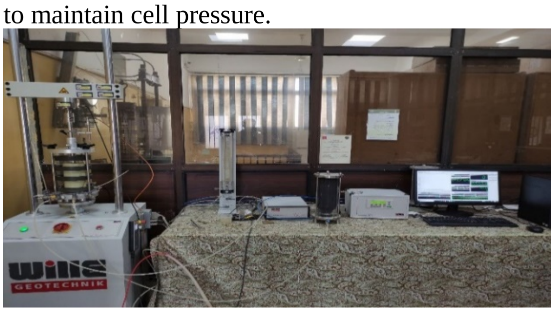

Fig. 4 The cyclic triaxial apparatus used in the study

3.3 Sample Preparation

A moist tamping specimen preparation process was used in this study. This method has the advantage of allowing any specimen with a wide range of void ratios to be prepared [1]. The under-compaction technique is used to obtain homogeneous specimens [20]. In the preparation phase, the two operations are mixing and fabrication. For the mixing procedure, the necessary amount of oven-dried sand was combined with cement and then with water. To allow the sand to mix with the fibers and keep them from floating, water is required. The water content used is about 10%. In an electric mixer, the fibers are combined with sand and cement. For sample fabrication, the mixture was divided into five equal portions, each of which was placed in a split mold measuring 70 mm in diameter by 140 mm in height and compacted with a metal rod until the desired height was obtained. To facilitate appropriate bonding, the top of each layer was scraped slightly before laying the following layer. To achieve the desired relative densities of 30%, samples were produced in five layers. For the geofibers addition, as each sand layer is created, the 6.5 cm diameter geogrid inclusions are put horizontally in the sample. Fig. 5 shows the different arrangements of geofibers used in this study.

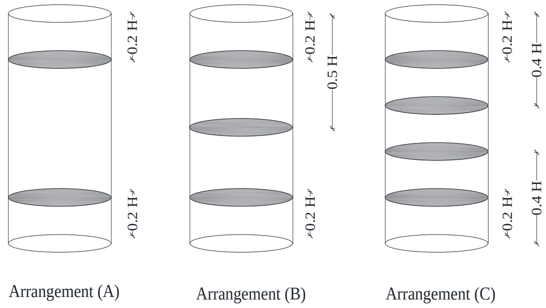

Fig. 5 Different geofibers arrangements in specimens used in this study

3.4 Test Procedure

In this study, series of cyclic stress-controlled tests were conducted using ASTM D5311/D5311M-13 and ASTM D3999/D3999M−11 [21-22].

Table 2 summarizes the important characteristics of the series of tests conducted throughout this study. The series contains conducting tests on sand, polypropylene fiber, cement, polypropylene fiber with cement, and different arrangements of geofibers. The sample was prepared, then a vacuum of 5 kPa was given to the specimen to achieve the required stability, and the mold was dismantled for the non-cement samples. After the triaxial cell was built and filled with water, the cell pressure was adjusted to 50 kPa, and then distilled de-aired water was passed through the sample at a pressure of 20 kPa to remove air bubbles in the sample pores. Backpressure was used to achieve full saturation. The samples containing cement do not require a vacuum of 5KPa to achieve the required stability. At a confining pressure (C.P.) of 100 kPa, the specimens were isotopically consolidated. After the consolidation phase was finished, stress-controlled testing was performed under undrained conditions.

Axial loads, vertical displacements, and pore water pressures were measured at intervals of 0.005 seconds for the applied sinusoidal waveform with a frequency of 1.0 Hz.

Table 2 Summary of the main series characteristics of tests conducted during the current study (CP =100 kPa and D_r = 30 %)

	Type	Fiber Content (%)	Cement Content (%)	Fiber Length (mm)	Curing period
1	sand	-	-	-	-
2	PF	1.0	-	10	-
3	PF	1.0	-	20	-
4	PF	0.5	-	20	-
5	C	-	1.0	-	3days
6	C	-	2.0	-	3days
7	PF+C	1.0	1.0	20	3days
8	PF+C	1.0	2.0	20	3days
9	Geofiber (A)	-	-	-	-
10	Geofiber (B)	-	-	-	-
11	Geofiber (C)	-	-	-	-

3.5 Formulation Used

As shown in Fig. 6, the shear modulus is calculated as the slope of a secant line connecting the extreme points on a hysteresis loop at a given shear strain. The slope of the secant line connecting the extreme points on the hysteresis loop is the young modulus (E) as determined by cyclic triaxial test results [23].

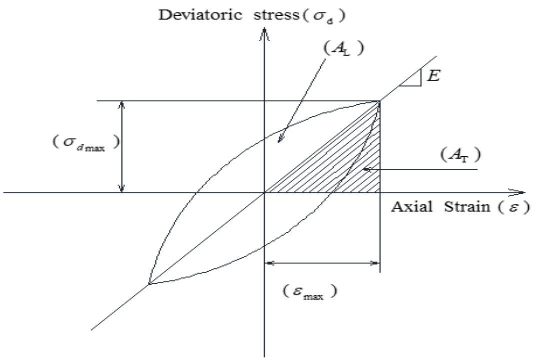

Fig. 6 Hysteretic stress-strain relationship [24]

$$\gamma = (1+\mu)\varepsilon \quad (1)$$

$$E = \frac{\sigma_{d\max}}{\varepsilon_{\max}} \quad (2)$$

$$G = \frac{E}{2(1+\mu)} \quad (3)$$

$$CSR = \frac{\sigma_1' - \sigma_3'}{2 * \sigma_3'} \quad (4)$$

where σ_1' and σ_3' are, respectively, the maximum and the minimum principal effective stresses.
The liquefaction improvement factor (LIF) that aids in the evaluation of reinforcing efficiency is defined as follows:

$$LIF = [\frac{N_r - N_u}{N_u}] * 100 \quad (5)$$

Where N_u and N_r are the numbers of liquefaction cycles for unreinforced and reinforced samples, respectively.

4. TEST RESULTS AND DISCUSSION

Fig. 7(a)~(d) depicts typical outcomes from a cyclic stress triaxial test on a reinforced specimen with a 30% initial relative density, 100 kPa confining pressure, 1% polypropylene fiber, and 2% cement. As seen in the figure, applying cyclic stress causes the pore water pressure to rise, the axial deviator stress to fall and the corresponding strain to increase. The axial stress was also found to be quite low before liquefaction. Similar observations were presented by [25]. When the peak excess pore water pressure matches the starting effective confining pressure, failure is defined as a full or 100 % pore pressure ratio ($r_u = \frac{\Delta u}{\sigma_0'} = 1.0$).

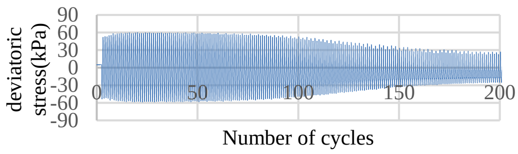

Fig.7 (a) dynamic axial stress with the number of cycles for reinforced sand

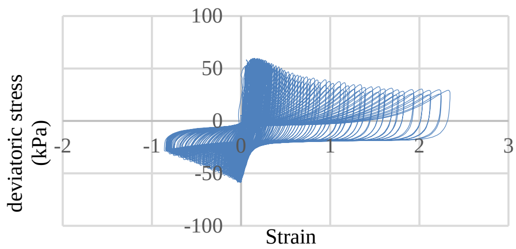

Fig.7 (b) dynamic axial stress with dynamic axial strain for reinforced sand

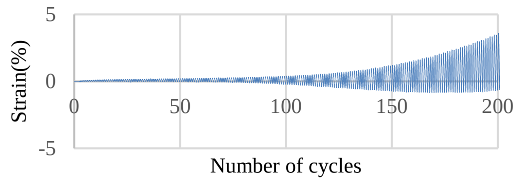

Fig.7 (c) dynamic axial strain with the number of cycles for reinforced sand

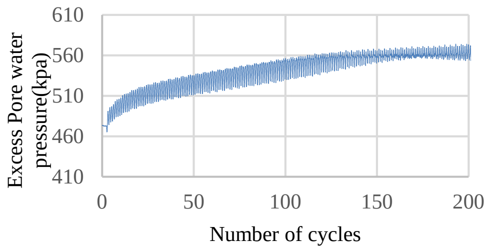

Fig.7(d) dynamic excess pore water pressure with the number of cycles for reinforced sand.

The influence of test parameters (such as fiber content and fiber length) is shown and discussed in this section. This includes cement content and geofibers layers on liquefaction resistance and shear modulus of unreinforced and reinforced specimens.

5. LIQUEFACTION RESISTANCE

5.1 Shear Modulus

This section computes and explains the shear modulus of unreinforced and reinforced sands. Fig. 8 depicts the variation in maximum shear modulus (G_{max}) as a function of fiber content percentage. The values of (G_{max}) in Fig. 8 for plain sand and sand with polypropylene fibers are close to those reported by [13].

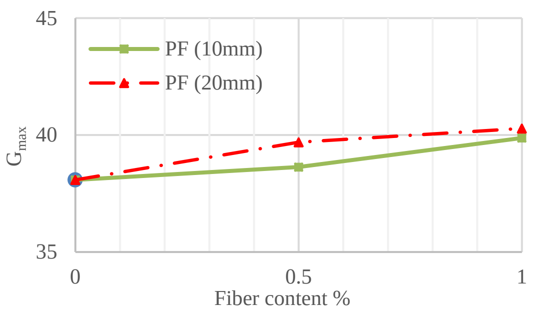

Fig. 8 G_{max} vs. polypropylene fiber content (D_r=30%, CP=100 kPa)

5.2 Effect of the Fiber Length

Fig. 9 illustrates the effect of the length of polypropylene fibers with different cyclic stress ratios. The figure indicates that at the same fiber content, polypropylene fiber with a length of 20mm outperforms polypropylene fiber with a length of 10mm, indicating that fiber length is crucial in liquefaction resistance. The number of liquefaction cycles that the specimen with a length of 20mm can sustain is approximately twice that of the fibers with a length of 10 mm at CSR=0.20. The liquefaction improvement factor (LIF) of the addition of 1%PF of 20mm is equal to 215.38% at CSR =0.20 , D_r=30% and CP =100 kPa. The results are comparable with the results presented by [13].

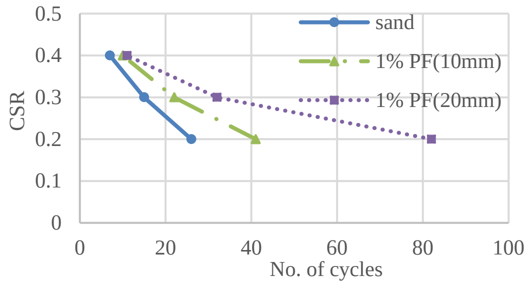

Fig. 9 CSR vs. number of cycles for different polypropylene fiber lengths (D_r=30%, CP =100kPa)

5.3 Effect of Fiber Content

Fig.10 illustrates the influence of fiber content on liquefaction resistance. The addition of 1.0 % of polypropylene fibers showed greater liquefaction resistance than 0.50 % of polypropylene fibers. The insertion of fibers improves soil grain interlocking and allows for uniform pore water pressure distribution within the specimen. The liquefaction improvement factor (LIF) of the addition of 1.0 % of polypropylene fibers is equal to 1.22 the addition of 0.50 % of polypropylene fibers at CSR = 0.20, D_r=30%, and CP=100 kPa, so the fiber content has a great effect on the liquefaction resistance.

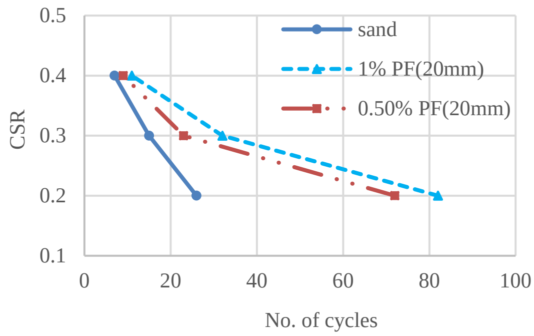

Fig.10 CSR vs. number of cycles for different polypropylene fiber contents (D_r=30%, CP=100kPa)

5.4 The Effect of Adding Geofibers

Fig.11 compares the results of the addition of geofibers with a different arrangement, as shown in Fig. 6. The arrangement (C) of geofibers gave more liquefaction resistance than other arrangements. The liquefaction improvement factor (LIF) of the addition of geofibers (arrangement C) is equal to 165 % at CSR = 0.20, D_r =30% and CP=100 kPa. Fig.12 shows the degree of enhancement of adding geofibers to sand specimens. The increase in the arrangement of geofiber layers gave a better enhancement to the liquefaction resistance. Similar findings were presented by [9].

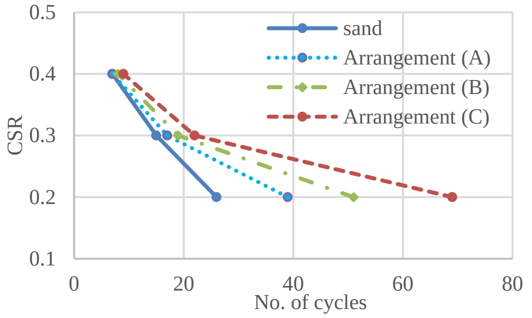

Fig. 11 CSR vs. the number of cycles for different arrangements of geofibers (D_r=30%, CP =100 kPa)

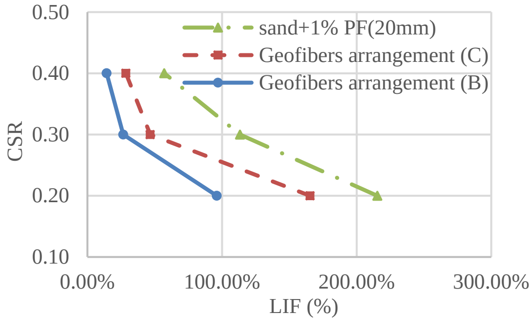

Fig. 12 CSR vs. LIF for different arrangements of geofibers (D_r=30%, CP=100kPa)

5.5 The Effect of Adding Cement and Cement with Polypropylene Fibers

The effect of adding cement to sand specimens and the effect of adding polypropylene fibers to cement are shown in Fig.13.The inclusion of cement increases the strength and resistance to liquefaction phenomena, and the addition of fibers to cement increases the strength and resistance to liquefaction phenomena even more because the cement coats the fibers and bonds them to the sand. The liquefaction improvement factor (LIF) of the addition of 2.0 % C + 1% PF is equal to 1.70 times the addition of 2.0 % C at CSR= 0.30, D_r=30%, and CP=100 kPa so the addition of fibers to cement enhances the liquefaction resistance to a large extent.

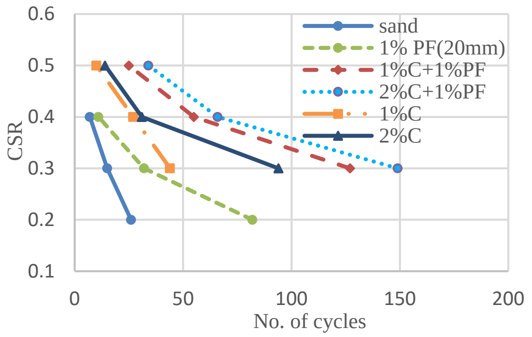

Fig.13 CSR vs. number of cycles for specimens reinforced with cement and polypropylene fibers (D_r=30%, CP =100 kPa)

5.6 Comparison between Different Types of Additives

Fig.14 illustrates the degree of improvement in the strength and liquefaction resistance of the additives used in the present study. The addition of 2%C+1%PF gave the best liquefaction resistance compared to other additives. LIF of samples reinforced with 2%C+1%PF equals 893.33% at CSR=0.30, D_r=30%, and CP =100 kPa, so the reinforcement with cement and fibers plays an important role in liquefaction resistance.

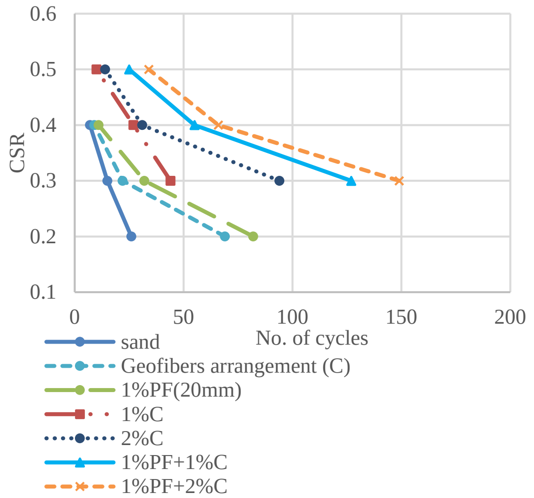

Fig.14 CSR vs. number of cycles for specimens reinforced with different additives (D_r=30%, CP=100kPa)

6. CONCLUSIONS

An experimental program was conducted to evaluate the effects of several types of additives on the liquefaction behavior of sandy soil. A series of cyclic stress triaxial tests was performed on both unreinforced and reinforced sand.

The liquefaction improvement factor (LIF) increased when fiber length increased. LIF of the addition of 1%PF of 20 mm is equal to 215.38% at CSR = 0.20, D_r=30 % and CP =100 kPa.

With increasing fiber content, the number of liquefaction cycles increased. LIF of the addition of 1.0 % of polypropylene fibers is equal to 1.22 times the addition of 0.50 % of polypropylene fibers at CSR = 0.20, D_r =30 % and CP =100 kPa.

The addition of geofibers increased the liquefaction resistance as the number of layers increased. The arrangement (C) gave better liquefaction resistance than other arrangements. LIF of the addition of geofibers (arrangement C) is equal to 165 % at CSR = 0.20, D_r=30% and CP =100 kPa.

The inclusion of cement increases the strength and resistance to liquefaction phenomena, and the addition of fibers to cement increases the strength and resistance to liquefaction phenomena even more. LIF of the addition of 2.0 % C + 1% PF is equal to 1.70 times the addition of 2.0 % C at CSR= 0.30, D_r=30%, and CP=100 kPa at CSR= 0.30, D_r = 30%, and CP = 100 kPa.

In comparison to unreinforced sands, the addition of 2% C+1% P.F. gave the best liquefaction resistance in this study. LIF of samples reinforced with 2%C+1%PF equals 893.33%, so cement and fiber reinforcement play a significant role in liquefaction resistance.

7. REFERENCES

[1] Ishihara K., Liquefaction and flow failure during earthquakes, Geotechnique, vol. 43, no. 3, 1993, pp. 351–451, DOI: 10.1680/geot.1993.43.3.351.

[2] Naeini S.A., Zakiyeh E., Effect of Geotextile on the Liquefaction Behavior of Sand in Cyclic Triaxial Test, Sci. Coop. Int. Work. Eng. Branches, Koc Univ. ISTANBUL/TURKEY, no. August 2014, 2014, pp. 63–67.

[3] Kumar S., Sahu A.K., Naval S., Study on the swelling behavior of clayey soil blended with geocell and jute fiber, Civ. Eng. J., vol. 7, no. 8, 2021, pp. 1327–1340, DOI: 10.28991/cej-2021-03091728.

[4] Iqhrammullah M., Suyanto H., Rahmi, Pardede M., Karnadi I., Kurniawan K.H.,Chiari W., Abdulmadjid S.N., Cellulose acetate-polyurethane film adsorbent with analyte enrichment for in-situ detection and analysis of aqueous Pb using Laser-Induced Breakdown Spectroscopy (LIBS), Environ. Nanotechnology, Monit. Manag., vol. 16, no. May, 2021, p. 100516, DOI: 10.1016/j.enmm.2021.100516.

[5] Fathana H., Iqhrammullah M., Rahmi R., Adlim M., Lubis S., Tofu wastewater-derived amino acids identification using LC-MS/MS and their uses in the modification of chitosan/TiO2 film composite, Chem. Data Collect., vol. 35, no. March,2021,p.100754,DOI:10.1016/j.cdc.2021.100754.

[6] Safitri E., Humaira H., Murniana M., Nazaruddin N., Iqhrammullah M., Sani N.D.M., Esmaeili C., Susilawati S., Mahathir M., Nazaruddin S.L., Optical pH sensor based on immobilization anthocyanin from dioscorea alata L. Onto polyelectrolyte complex pectin–chitosan membrane for a determination method of salivary pH, Polymers (Basel)., vol. 13, no. 8, 2021, DOI: 10.3390/polym13081276.

[7] Al-Bared M.A.M., Harahap I., Marto A., Abad S., Ahmed M.O., Undrained shear strength and microstructural characterization of treated soft soil with recycled materials, Geomech. Eng., vol. 18, no. 4, 2019, pp.427–437, DOI: 10.12989/gae.2019.18.4.427.

[8] Zainuddin N., Yunus N.M., Al-Bared M.A.M., Marto A., Harahap I.S.H., Ahmad S. A., Measuring the engineering properties of marine clay treated with disposed granite waste, Meas. J. Int. Meas. Confed., vol. 131, 2019, pp. 50 – 60, DOI: 10.1016/j.measurement.2018.08.053.

[9] Alibolandi M., Moayed R.Z., Liquefaction potential of reinforced silty sands, Int. J. Civ. Eng., vol. 13, no. 3–4, 2015, pp. 195–202, DOI: 10.22068/IJCE.13.3.195.

[10] Tang C., Shi B., Gao W., Chen F., Cai Y., Strength and mechanical behavior of short polypropylene fiber reinforced and cement stabilized clayey soil, Geotext. Geomembranes, vol. 25, no. 3,2007, pp. 194-202,DOI:10.1016/j.geotexmem.2006.11.002.

[11] Consoli N.C., Vendruscolo M.A., Fonini A., Rosa F.D., Fiber reinforcement effects on sand considering a wide cementation range, Geotext. Geomembranes, vol. 27, no. 3,2009, pp. 196–203,DOI:10.1016/j.geotexmem.2008.11.005.

[12] Sadeghi M.M., Masoud, Beigi F.H., Dynamic behavior of reinforced clayey sand under cyclic loading, Geotext.Geomembranes, vol. 42, no. 5, Oct.2014, pp.564-572, DOI:10.1016/J.GEOTEXMEM.2014.07.005.

[13] Noorzad R., Amini P.F., Liquefaction resistance of Babolsar sand reinforced with randomly distributed fibers under cyclic loading, Soil Dyn. Earthq. Eng., vol. 66,2014, pp. 281–292,DOI:10.1016/j.soildyn.2014.07.011.

[14] Park S.S., Effect of fiber reinforcement and distribution on unconfined compressive strength of fiber-reinforced cemented sand, Geotext. Geomembranes, vol. 27, no. 2, 2009, pp. 162–166, DOI: 10.1016/j.geotexmem.2008.09.001.

[15] Safdar M., Newson T., Schmidt C., Sato K., Fujikawa T., Shah F., Effect of fiber and cement additives on the small-strain stiffness behavior of toyoura sand, Sustain., vol. 12, no. 24, 2020, pp. 1–17, DOI: 10.3390/su122410468.

[16] Al-Bared M.A.M., Harahap I., Marto A., Abad S.V., Mustaffa Z., Ali M., Mechanical behaviour of waste powdered tilesand portland cement treated soft clay, Geomech.

Eng., vol. 19, no. 1, 2019, pp. 37 - 47, DOI: 10.12989/gae.2019.19.1.037.
[17] Al-Bared M.A.M., Harahap I., Marto A., Mohamad H., Abad S.V., Mustaffa Z., Cyclic behavior of RT-cement treated marine clay subjected to low and high loading frequencies, Geomech. Eng., vol. 21, no. 5, 2020, pp. 433 - 445, DOI: 10.12989/GAE.2020.21.5.433.
[18] Safdar M., Newson T., Schmidt C., Sato K., Fujikawa T., Shah F., Shear wave velocity of fiber-reinforced cemented toyoura silty sand, Geomech. Eng., vol. 25, no. 3, 2021, pp. 207–219, DOI: 10.12989/gae.2021.25.3.207.
[19] Enka Solutions. https://enkasolutions.com/
[20] Ladd R. S., Preparing Test Specimens Using Undercompaction, Geotech. Test. J., vol. 1, no. 1, 1978, pp. 16–23.
[21] ASTM D5311/D5311M-13, Standard test method for load controlled cyclic triaxial strength of soil (D5311-92). Annual book of ASTM standards, 2013.
[22] ASTM D3999/D3999M− 11."Standard Test Methods for the Determination of the Modulus and Damping Properties of Soils Using the Cyclic Triaxial Apparatus.", 2013.
[23] Towhata I., Springer Series in Geomechanics and Geoengineering: Geotechnical Earthquake Engineering. 2008.
[24] Kirar B., Maheshwari B. K., and Jakka R. S., Dynamic Properties of Solani Sand Reinforced with Coir Fibers, 15th World Conf. Earthq. Eng. Lisbon Port., 2012.
[25] Rasouli H., Fatahi B., Nimbalkar S., Liquefaction and post-liquefaction assessment of lightly cemented sands, Can. Geotech. J., vol. 57, no. 2, 2020, pp. 173–188, DOI: 10.1139/cgj-2018-0833.