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Research Article

An Experimental Study on the Effect of Different Geofiber types on the Liquefaction Resistance of a Silty Sand Soil

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Abstract: In this study, use of a new polypropylene geofiber type called microgrid fiber (MGF) was investigated in comparison with a conventional polypropylene fiber (PPF) product. Liquefaction resistances of saturated silty sand type soil mixes reinforced with different polypropylene type geofiber additives were investigated carrying out different laboratory scale cyclic load tests. Depending on the fiber content, liquefaction resistances of soil mixes were significantly improved using the geofiber additives. According to the results obtained from this study, the MGF type fiber increased the liquefaction resistances at higher rates in comparison with the conventional PPF product. It was assessed that MGF type novel additives can be used to supply a better adherence in soil mixes and higher reinforcement performances against the liquefaction, rather than conventional PPF products.

Keywords: Geofiber, Geosynthetics; Liquefaction; Micro grid fiber; Polypropylene fiber

I. INTRODUCTION

The soil liquefaction is a well-known phenomenon which can cause notable damages of the structures. As a liquefied soil behaves like a liquid instead of a solid, it loses its bearing capacity property for a period of time. The liquefaction occurs when an applied load, such as those resulting from an earthquake or some other rapid loading mechanisms, makes the pore water pressure to highly increase and causes remarkable reduces in the effective stress value. With an increase in the pore water pressure, effective stress values decrease. The effective stress can become negative when the pore water pressure is greater than the vertical stress. The negative or quite small effective stress values mean the loss of the internal cohesion, strength and stiffness properties of a soil [1-3].

Liquefaction problems are most likely to occur in watery regions especially including sandy soils [4-6]. If an earthquake load is applied to a sandy soil, its pore pressure increase much easier than a silty or clayey type cohesive soil under a same loading condition. A strong loading and a high water content are generally needed for the liquefaction problem occurrence. Soils in coastal regions or regions with shallow underground water table depths have high liquefaction vulnerability in response to the earthquakes [7-9].

The looseness of soils is another factor which increases the liquefaction possibility. If the pore pressure of the water between soil grains is great enough, it will have the effect of holding the particles apart. The dense soils with relatively low void ratio values are advantageous against the liquefaction problem. Because well graded soil particles make decreases in the void ratio, the particle size distribution of soils is also an effective factor which determines the liquefaction resistance [10-12]. The saturation degree, load magnitudes, number and frequency of the repeated loads are some other important parameters for the liquefaction occurrence and liquefaction deformations [13-16]. Historical data of the region for liquefaction is another effective factor that the liquefied soils generally become more resistive against a new liquefaction problem [17-19].

A liquefaction under buildings can cause remarkable damages and instabilities during earthquakes, since a liquefied soil is unable to bear the loads applied from the foundations. Therefore, engineers consider the earthquake loading and the factors determining the resistance against the liquefaction together in the design of new buildings and infrastructures for prevention of damages and collapses after earthquakes. Even if there is no surcharge on the liquefied soil, significant surface deformations can be observed depending on the cyclic loads, soil water content and soil liquefaction resistance factors. Liquefied soils tend to flow depending on topographic and stratigraphic features [20-22]. As a result of the flow, horizontal displacements are observed in the liquefied soil.

A similar mechanism in small scales exists in the Casagrande test method, which is a quite popular one among the liquid limit experiments. In the Casagrande test, the soil and water mixes are placed in the standard test cup. A groove is formed in the soil along the midsection of the cup, using a standard grooving tool. By this way, soil specimens are cut into two parts with the standard groove. The cup of the Casagrande test equipment is dropped repeatedly until the groove is closed due to the flow of the soil specimen. According to the famous Casagrande test, the liquid limit is determined as the water content for closing the groove under the impact of 25 blows. In case of having a minimum contact length of 13 mm in the cup, the test is stopped and the groove was considered to be closed. Then, samples are taken from the closed portion of the groove for the water content determination. The liquid limit was firstly defined by Swedish scientist Albert Atterberg in 1911 [23]. The liquid limit is a water content to change a soil from plastic to liquid state. In other words, soil materials become a liquid in case of having a higher water content than the liquid limit. As a result of liquefaction, soil materials have highly diminished yield strength values and can no longer maintain a molded shape [24-26].

The laboratory scale tests like the Casagrande test are not applied to determine actual liquid limit values in the field because of using sieved soil specimens with relatively fine particle sizes. The Casagrande test method is mostly applied for the purpose of the classification of soils containing fine particles. As in the Casagrande test, investigations based on liquefaction displacements of specimens were carried out in this study. On the other hand, bigger size samples and loading mechanisms than those of the Casagrande test were used within this study. Different polypropylene type geofiber products were used to test their influences on the liquefaction resistance properties of soils. In two different test methods with the details as explained in the methodology section, it was aimed to comparatively evaluate the liquefaction resistances of silty sand type soil specimens with and without geofiber product additives under repeated loads.

The use of geofiber type geosynthetics is a method to reinforce soils. Geofiber additives which provide high adherence to the soil particles are preferred to properly improve strength values of the reinforced soil mixes. For the supply of a good adherence property, the size and geometries of fibers are determinative [27-29]. Also, fiber material has a significant effect on the strength values of reinforced soils [30-32]. Within various engineering plastics, polypropylene is one of the most popular and widely used geofiber materials. Typical polypropylene geofiber strand lengths vary from 1 to 5 cm. Strand diameters of different products generally vary within a range from 30 to 200 micrometers. Ideal length and diameter properties of the geofiber strands can change depending on the soil type [33-35].

In this experimental study, use of a new polypropylene fiber type called microgrid fiber (MGF) has been investigated to assess its effect on liquefaction properties of sand specimens. The new MGF is the combination of thin plastic fibers in groups of different directions which form mini grids (**Fig. 1**). MGF type new geosynthetics include different small mesh openings with sizes like several tens or hundreds of micrometers. Microgrid usage was previously investigated for soil improvement works as an alternative for the classical geogrids [36-38]. The "microgrid" term is suggested to use for grid sizes below 2.5 mm according to the study authored by Leshchinsky et al [39]. As a novelty of this study, microgrids were cut into pieces and used as a new fiber type for soil mixes.

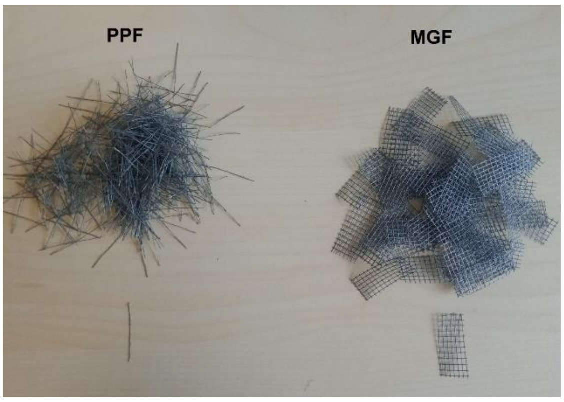

Figure 1. *PPF and MGF additives*

Various structural properties like strand dimensions, planar angles, strand junction characteristics, grid size and grid geometry influence the MGF additive performances. Lengths of MGF type and classical geofibers can vary in a same range. As a motivation of this study, a bettered adherence performance in soil mixes was estimated from MGF additives because combined strands can work together in their use. In addition, grid type physical property was thought to make an additional friction coefficient for the soil particle contacts by attaching particle edges to the grids. Grid type reinforcement inclusions can provide an interlocking mechanism with soil particles, which is an advantage for having a proper adherence [40-42]. Good adherence property of the fiber reinforcement provides improvements in the liquefaction resistance of soils. It is a well-known fact that fiber additives can supply the bridge effect between soil particles. A good adherence performance is needed to supply a proper bridging effect in soil mixes [43-45]. The bridge effect improves the crack propagation resistivity, increases the resistance against the particle separation and moving away from eachother. Hence, fiber additives are usable to improve soil mixes against the liquefaction problem [46-48].

The influences of different types of geofiber products on the soil liquefaction resistance property were comparatively investigated within this study. Examination of the effect of the MGF type new geofiber additive on the soil liquefaction resistance can be noted as the most important issue regarding the novelty of this study. Novel MGF type and conventionel type geofiber products were tested for the use of various fiber amounts in soil mixes. It should be noted herein that both fiber products are made of the same polypropylene type engineering plastic. The aim of this study is to test the effect of the new fiber additive type of MGF on the liquefaction resistance and compare it with the conventional fiber additives. Within this purpose, various laboratory scale liquefaction tests were carried out to determine the ideal fiber type to better improve the liquefaction resistance of a sandy soil. Material and methodology details about the experimental study are given in the next section.

II. MATERIALS AND METHODS

Soil specimens of this study were taken from Giresun city of the Black Sea Region of Turkiye. To use in the experimental study, soil specimens were firstly sieved before tests to prepare all the particles for passing the 8 mm sieve. To classify the soil specimens with particles under 8 mm, size distribution analyses were carried out using 4.00 mm, 2.00 mm, 1.00 mm, 0.50 mm, 0.25 mm, 0.125 mm and 0.074 mm sieves (**Fig. 2**). The particle size distribution of soil specimens is given in **Table 1**. The soil specimen was evaluated to respectively have the coefficient of uniformity (Cu) and the coefficient of curvature (Cc) values of 8.8 and 0.4. As the soil has not a Cc value between 1 and 3, it was assessed to be poorly-graded (ASTM D2487-17).

To classify the soil with 7% content of particles passing the No. 200 sieve (0.074 mm), liquid and plastic limits (Atterberg limits) were determined. The famous Casagrande test was carried out for determination of the liquid limit value (**Fig. 3**). The methodology stated in the ASTM D4318-10 coded standard was fully followed in the Casagrande test [49]. The liquid limit was determined as the water content of soil specimens for closing the groove due to the impact of 25 blows of the Casagrande cup. The soil specimen passing under the No. 40 (0.425 mm) sieve was used in the Casagrande test. The water content was calculated as the ratio of mass of water to mass of dry soil. To make dry soil, specimens were heated in the 105 °C stove for a day. The plastic limit test is performed by rolling soil rods on the standard glass plate. As stated in the ASTM D4318-10 coded test standard, the plastic limit was determined as the water content of soil rods which just crumbles when it is carefully and gently rolled to a diameter of 3 mm. Liquid and plastic limits of the soil were determined as 39% and 27%, respectively. According to the unified soil classification system (USCS), the soil sample can be classified as SP-SM (Poorly-graded sand with silt).

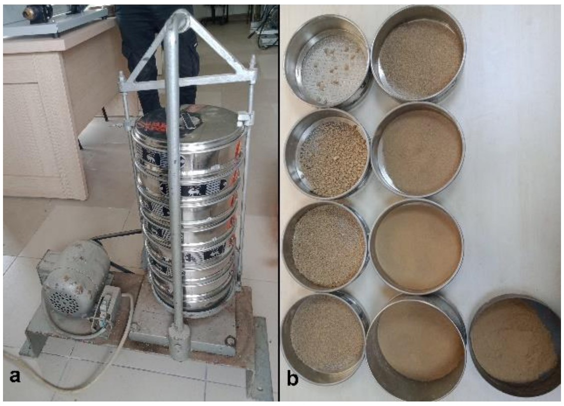

Figure 2. *Photos from the sieve analyses (a and b)*

Table 1. *Particle size distribution of the soil*

Sieve aperture (mm)	***Passing percentage (%)***
8	100
4	92
2	78
1	66
0.5	56
0.25	42
0.125	25
0.075	7

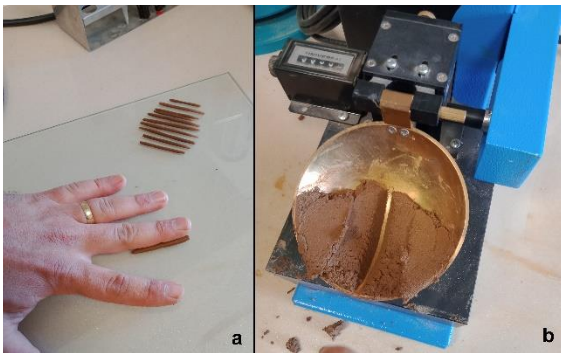

Figure 3. *The plastic (a) and liquid limit (b) tests*

Strand diameter of MGF and PPF additives is 0.2 mm. Length of both MGF and PPF type fibers is 20 mm. MGF additives with the width to length ratio (B/L) value of 0.5 were used in the mixes. As another parameter, the grid size of the MGF type fiber additives used in this study is 1.2 mm. Contents of the mixes were sensitively weighed using an electronic scale. Soil and fiber additives were mixed in a plastic basin and homogenized by hand for 7 minutes before the molding processes. Different fiber contents of 0%, 0.5%, 1.0%, 1.5% and 2.0% were tested in this study. It should be noted that the fiber contents are given herein as the ratio of fiber to soil by mass.

Two different liquefaction experiments were designed and carried out using both fiber reinforced and unreinforced specimens. In the first of these experiments, a horizontal shaking (HS) mechanism was used to repeatedly load specimens with a diameter of 10 cm and a height of 15 cm. Before the HS test, specimens were soaked in water for a day to make them saturated before the cyclic load procedure supplied by the horizontal shaking mechanism. The cylindrical molds used in this test have two layers (Fig. 4). Soil specimens were filled into the cylindrical inner-side molds in three layers and 25 standard Proctor hammer drops were applied to make compaction after each filling step of the layers. It should be noted herein that molding and remolding processes were totally same for all the specimens. When the filled soil specimen level exceeded the height of the inner-side mold, the slit plastic collar which is the outside part of the double layer mold was removed. Then, the soil remaining above the inner-side mold with the height of 15 cm was slowly and gently removed using a spatula to prepare the upside of the specimens flattened. Specimens in the cylindrical inner mold were soaked in water for a day. Just before the horizontal shaking (HS), the inner side plastic molds were removed by opening the slit. Both outer-side and inner-side molds have slit to make the specimen remolding process practical. The height of the outer-side mold was higher than the inner-side mold height (**Fig. 4**)

The HS test specimens were exposed to horizontal cyclic loads in a circular shape plexiglass chamber with an inner diameter of 20 cm (Fig. 5). The shaking plate unit moves horizontally by the electrical motor of the setup and repeats loading cycles twice per second. Depending on the shaking duration, the number of load repetitions increases proportionally. The horizontal displacement interval was 4 cm in the horizontal shaking test. The load cycle numbers were recorded and considered in order to comparatively examine the resistances of the specimens against the liquefaction. The horizontal shaking tests were finalized when specimens fully spread having a horizontal surface in the plexiglass chamber.

Figure 4. *Specimen molding for the HS test: a) soil layer compaction, b) double molds with slits, c) soil specimen level exceeded the height of the inner-side mold, d) opening the outer side mold's slit, e) removing the soil above the inner-side mold by using spatula*

Figure 5. *HS (Horizontal shaking) test mechanism and a specimen before the load cycles (a), liquefaction after the load cycles (b)*

Fig. 5 shows the liquefaction displacement in the test. A laboratory sieve shaker machice was used to apply the HS test. The plexiglass was placed on the framed table of the sieve shaker machine for the 20 cm diameter standard sieves. The plexiglass were specifically purchased to have the convenient diameter for fitting well on the table of the sieving machine. Additionally, the plexiglass were fixated and gripped using the screwed tightening devices of the test setup.

In the second and other liquafection test, bigger size specimens were used in comparison with the cylindrical specimens of the HS test. A rectangular chamber with 0.4 m x 0.3 m x 0.3 m sizes were used in the second liquafection test which is a slope liquefaction model (SLM) test. Same silty sand soil was used in both tests. To supply a proper homogenization of specimens, each of specimens were mixed in a basin for 7 minutes before molding. Specimens were filled into the test chamber in four layers and compacted with 100 standard Proctor hammer strokes after each layers (**Fig. 6**). The standard Proctor hammer has the mass of 2.5 kg and the drop height of 31 cm for the compaction. Hammer strokes were applied on all of the surface area of the layers. The height of the compacted specimens were 10 cm in the SLM test chamber. To make the saturation, specimens were filled with water to 15 cm height which is 5 cm above from the compacted soil level. Before carrying out the SLM test, water filled specimens were waited for a day for making them saturated. The specimen filled chamber is placed on the vibration table at 20° from the horizontal. Soil specimen surfaces had 20° angle at the start of the test and became horizontal at the end of the test. The same vibration with the frequency of 50 Hz was applied on all type of specimens in the SLM test. As shown in the **Fig. 7**, the chamber was gripped strongly by the fixation mechanism of the vibration table. The vibration was continued until the specimen surfaces become full horizontal as a result of vibrations. The horizontalization could be noticed because the water level and soil level were seen together during the experiment. Additionally, the horizontalization was checked by measuring the difference between the soil and water levels at different points along specimens (**Fig. 8**). In the SLM test, the liquefaction resistances of saturated soils were examined by considering vibration durations.

Figure 6. *A photo from the soil layer compaction work for the SLM test specimen preparation*

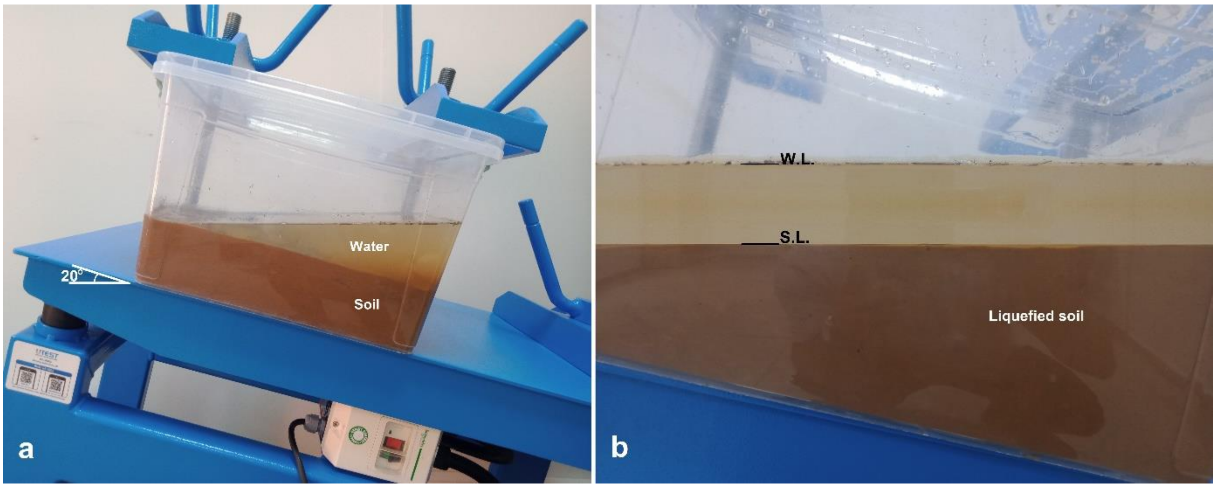

Figure 7. *A SLM test specimen before (a) and after (b) vibrations (W.L.: Water level, S.L.: Soil level)*

Figure 8. *A photo of controlling the horizontalization of the liquefied SLM test specimens*

III. RESULTS

The results obtained from the horizontal shaking (HS) test and SLM test are respectively given in **Table 2** and **3**. Additionally, results of this study are graphically shown in **Fig. 9** and **10**. As seen from the results, geofiber additives were found to be effective for increasing the liquefaction resistance. As another remarkable finding, it has been determined that fiber additive ratio is an important parameter for the liquefaction resistance properties of soil mixes. Among the used fiber content ratios, the most ideal ratio for all fiber types was found to be 1% according to the HS test results. For an initiation of decreases in the liquefaction resistance with increasing fiber content, 1% was found to be the threshold fiber content for the HS test mechanism. As an advantage seen in the HS test, the decrease after exceeding the 1% fiber content was found to be more limited in the case of using MGF additive.

In the SLM test, the highest liquefaction resistance was also observed at 1% content for the specimens with the PPF type fiber additive. However, the situation was different in samples with the MGF type geofiber. In addition to the fiber contents used in the HS test (0%, 0.5%, 1%, 1.5%), 2.0% fiber content was also investigated in the SLM test to see whether it is an enough high MGF type fiber content to cause the liquefaction resistance decreases. As seen in the SLM test results, even 2.0% fiber content did not cause a decrease in the liquefaction resistances of MGF added specimens. However, the rate of increase in the liquefaction duration with increasing fiber content was determined to notably decrease in the case of using 2.0% MGF additive in the soil mix.

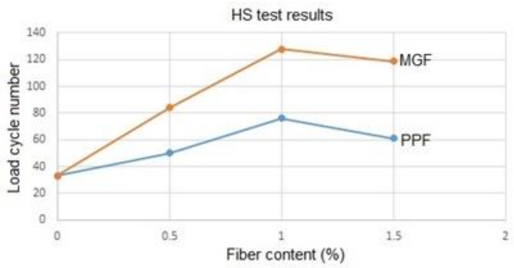

Figure 9. *HS test results*

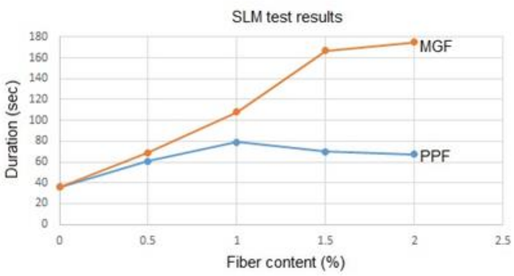

Figure 10. *SLM test results*

Table 2. *HS test results*

Specimen type	***Load cycle number***
NF	33
PPF (0.5%)	50
PPF (1.0%)	76
PPF (1.5%)	61
MGF (0.5%)	84
MGF (1.0%)	128
MGF (1.5%)	119

Table 3. *SLM test results*

Specimen type	***Duration (sec)***
NF	36
PPF (0.5%)	61
PPF (1.0%)	79
PPF (1.5%)	70
PPF (2.0%)	68
MGF (0.5%)	69
MGF (1.0%)	108
MGF (1.5%)	167
MGF (2.0%)	175

It has been observed that new MGF type geofiber additives are more advantageous in terms of increasing in the liquefaction resistance, in comparison with the conventional PPF type additive. For all fiber content ratios, the MGF additive supplied better liquefaction resistances than those of the soil specimens with the conventional PPF additive. According to the findings, the MGF type new geofiber is preferable rather than the conventional PPF additive.

IV. Discussions and conclusion

As confirmed by this study, geofiber additives can be used to increase the liquefaction resistance of soils [50-52]. It is known that geofibers increase liquefaction resistance because of providing adherence to the soil particles and preventing or limitating grains to move away from each other [53, 54]. Results of this study confirms that the physical structure of MGF additive is advantageous in terms of providing a better reinforcement in comparison with the conventional fiber products. The content ratio of fiber additives in soil mixes is an issue that varies the liquefaction resistance. It was also confirmed by this study that excessive use of fiber additives is not economical and negatively affects the soil liquefaction resistance [55-57]. MGF was found to supply higher liquefaction resistances than conventional PPF additives for all the tested fiber contents. The differences between results obtained from MGF and PPF added specimens were found to increase with an increase in the fiber content. Therefore, it can be noted that the MGF is more advantageous in case of using high fiber contents.

To deal about the costs in the year of 2024, it can be noted that the price of conventional PPF and MGF products used in this study are 5.2 and 5.5 USD per a kilogram, respectively. Although unit cost of the MGF additive is slightly high because of its manufacturing details, it can be assessed to be more economical than the conventional PPF additive as a result of its significantly better soil reinforcement performances. According to the results, it is possible to use less MGF compared to PPF contents for a proper reinforcement performance.

Findings from previous studies confirm that MGF is more advantageous because it provides higher adherence in comparison with those supplied by the conventional polypropylene fiber (PPF) additives. In a previous study conducted by Komurlu, MGF-type fiber additives were utilized in cement-stabilized aggregate mixes [58]. Similar to the findings of this study, it was observed that polypropylene MGF-type fibers provided better increases in strength values than conventional PPF products. Komurlu concluded that MGF-type novel additives supply improved adherence and reinforcement performances under both compression and indirect tension (splitting) conditions compared to conventional PPF additives. Within another study carried out by Komurlu et al., MGF was tested as a new polypropylene fiber additive in resin added sand type soil mixes to compare it with the conventional PPF additive. According to the findings obtained from the uniaxial compressive strength (unconfined compressive strength) tests, it was determined that the new MGF type fiber increased the strength values at higher rates in comparison with the conventional PPF [59].

New materials and additives can provide new solutions in geotechnical engineering. Therefore, it is important for geotechnical engineers to follow progressions in geosynthetics. MGF additives are new geofiber types and open for new investigations on different topics. It should be reminded herein that polypropylene type fibers were tested in this study. Some other engineering polymers can be investigated as new MGF materials in further investigations. Fiber material, size and geometrical properties are some deterministic parameters for the fiber adherence and reinforcement performances [60-63]. Different MGF size and geometry properties effect on reinforcement performances in various types of soils should be investigated to better analyze the MGF usage within upcoming researches.

In this study, MGF additive with the width to length ratio (B/L) value of 0.5 was used. Within a study carried out by Komurlu, the effect of different fiber geometries on soil strength values were examined, and the most ideal B/L ratio of MGF fiber additive was found to be 0.5 [64]. It should be noted herein that MGF additives with same grid size as that in this study were used in the aforementioned study by Komurlu. Different geometries effect on liquefaction resistances of soil mixes can be tested in future studies. New analyzes will be very beneficial to make the right decision about more ideal fiber and grid sizing.

There is no difference in the application procedures of MGF and conventional fiber additives in engineering studies. Like other geofiber products, the MGF reinforced soil is prepared by mixing the fiber additive in the soil to be filled. Geofiber products are usable for the purpose of strengthening soil fill mixes. The new MGF type geofiber products and conventional fibers can be used in the same application areas with the same procedure. For instance, MGF type new fiber additives can be seen in various geotechnical engineering works like embankments, road constructions, soil fillings within various landscaping purposes, sub-foundation fills, foundation pit filling applications, benching fill operations, backfilling behind retaining walls and etc.

This is one of preliminary studies to investigate the MGF additive as a new fiber type to use in soil mixes. In another study examining MGF as a new fiber additive, CBR test results of a sand type soil were examined by Komurlu. MGF type fiber was found to increase the CBR values at higher rates in comparison with the conventional PPF product [65]. It was assessed that MGF type novel geofiber additives can be used to make higher adherence and soil reinforcement performances rather than the conventional PPF products. The good adherence property also supplies high crack propagation resistivity and energy absorption capacity (EAC) properties for the reinforced soil mixes [66-70]. The high crack propagation resistivity and EAC properties are advantageous because of bettering the durability against the external forces and factors [71-76].

The following sentences can be noted to conclude this study: According to the results, the liquefaction resistances of the silty sand type soil specimens were assessed to notably increase as a result of the use of geofiber additives. Within this experimental study, different fiber types were comparatively tested and the microgrid fiber (MGF) was investigated as a new geofiber type. Considering the outcomes of this study, the new MGF reinforcement was assessed to be able to supply a better liquefaction resistance improvement of silty sands in comparison with the conventional PPF product. Depending on the fiber content, MGF additive was assessed to supply more than 100% higher liquefaction resistances considering the cyclic load time durations applied on the mixes. The new MGF additive was determined much more effective than the conventional fiber, especially for 1% and more fiber contents up to %2. The use of conventional PPF amounts above 1% did not increase the liquefaction resistance, whereas the increases continued in the samples with new MGF additive. Findings of this study confirmed that the MGF type fiber is advantageous and can be effectively used in soil reinforcement works. It is suggested to use the MGF in mixes to obtain bettered reinforcement performances while reducing the costs of the geofiber added soil mixes. There are numerous new research topics on MGF products with different designs and their use in different soil mixes. It is believed that MGF type new geofiber additives have a significant potential to become more popular in the near future of geotechnical engineering.

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AUTHOR CONTRIBUTIONS

E. Komurlu: Conceptualization and design, experimental study, data collection and analyses, writing

A.G. Celik: Writing, review and editing.

H.B. Dogan: Experimental study

Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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