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Use of microgrid fiber as a new reinforcement additive to improve compressive strength and ductility properties of cement stabilized sands

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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. Uniaxial compressive strength (UCS), modulus of elasticity, ductility and energy absorption capacities of cement stabilized sand (CSS) mixes reinforced with different polypropylene type geofiber additives were investigated carrying out a series of uniaxial deformability tests. According to the results, MGF type fibers increased the strength and modulus of elasticity values at higher rates in comparison with the conventional PPF product. For a same fiber content, MGF type new additive supplied up to 31% higher UCS values and 26% higher modulus elasticity values than those of the specimens with the conventional PPF additive. In addition, it was determined that MGF type new fiber additives can supply better increases in ductility and energy absorption capacity properties of the CSS compared to the conventional PPF product. Rather than the conventional fiber, the novel MGF additives were assessed to be more effective for having proper adherence and soil reinforcement performances.

Keywords: Geofibers, MGF, Polypropylene fiber, Microgrid fiber, soil reinforcement

1. Introduction

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. To supply a good adherence property, the size and geometry properties of fiber products are decisive (Patel and Singh, 2020; Tiwari et al., 2020; Divya et al., 2020). Also, fiber material effect is a significant one on the strength values of reinforced soils (Zafar et al., 2023; Malicki et al., 2021; Khajeh et al., 2020). Due to their chemical durability against ground water contact, plastic geofiber materials can be preferred over steel fibers in geotechnical engineering operations (Singh and Sharan, 2015; Safdar et al., 2022; Zhao et al., 2020; Cao et al., 2019). Within various engineering plastics, polypropylene is one of the most popular and widely used geofiber materials. Typical polypropylene geofiber strand lengths vary from 1 cm to 5 cm, and 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 (Gul and Mir, 2022; Komurlu, 2023; Langroudi et al., 2021).

Polypropylene is a thermoplastic type synthetic material. In addition to the polypropylene, there are several widely known type of geofiber materials like polyamides, polyethelenes and etc. Although various researches have also been carried out on the use of natural fiber materials in the soil reinforcement works, natural fibers containing organic materials are generally insufficient to provide long-term chemical resistance to environmental conditions. Synthetic polymer fiber products are advantageous to provide proper long-term service lifetimes and chemical resistances. In this experimental study, use of a new polypropylene fiber type called microgrid fiber (MGF) has been investigated to assess its effect on both compressive strength, elastic modulus values and ductility properties of different cement stabilized sand specimens. MGF is the combination of thin plastic fibers in groups of two or more different directions which form mini grids (Figure 1). Microgrids were formerly tested to be an alternative of the classical geogrids (Vieira and Pereira, 2022; Mittal and Shukla, 2020; Mittal and Shukla, 2019).

The “microgrid” term is used for grid sizes below 2.5 mm according to the Leshchinsky et al. (2016).

MGF lengths can vary in the same length interval of conventional geofiber products. As combined fibers can react together, a good adherence property was predicted to obtain from the use of MGF additives. Additionally, the MGF was estimated to supply an improved adherence in soil mixes because of its structural properties. Furthermore, grids were thought to provide an additional friction coefficient for the soil contacts and an interlocking mechanism with the grains (Gu et al., 2017; Hajitaheriha, 2021; Komurlu et al., 2024). Good adherence performances of the geofibers are aimed to supply improvements in crack propagation resistivity, load bearing and energy absorption capacity values (Gui et al., 2022; Zhang et al., 2022; Kou et al., 2021). It is a well-known fact that fiber additives can supply bridging effect across the cracks and improve the crack propagation resistivity. An improvement in the crack propagation resistivity improves the ductility property and the energy absorption capacity values. In the circumstances, adherence properties of fiber additives should be paid attention in terms of the crack propagation resistivity. Because, a good adherence performance is needed to supply a proper bridging effect (Meddah et al., 2023; Kafodya and Okonta, 2021; Kannan and Sujatha, 2023).

Different fiber additives were used in cement stabilized soil (CSS) mixes in this study. Because the cement content is relatively low, the particle surfaces of CSS materials are partially bonded. Nevertheless, the cement binder content can notably increase the strength values of sands. The Portland cement is a traditional binding material that is popular for strengthening sand-type soils. Similar to the soils without a binder content, fiber additives can be also used to improve strength and ductility properties of soil mixes with the cement binder (Wang et al., 2019; Komurlu, 2023; Fatahi et al., 2013). Effect of a conventional polypropylene fiber (PPF) additive and the new microgrid fiber (MGF) on the uniaxial compressive strength and deformability properties of different CSS mixes was investigated with a series of experiments in this study. It should be noted herein that the MGF and conventional PPF additives are made of the same polypropylene type engineering plastic material. For a proper comparison, all the fiber additives used in this study have same strand diameter and fiber length values.

2. Materials and Methodology

The particle size distribution of soil specimen was determined carrying out the sieve analysis as given in Table 1. According to the unified soil classification system (USCS), the soil sample was classified as a well-graded sand (SW). MGF and PPF type fibers were used in different proportions in the CSS mixes. Content ratios by masses in the mixes are given in Table 2. Strand diameter of MGF and PPF additives is 0.2 mm. As another size parameter, length of both MGF and PPF type fibers is 14 mm. To investigate the fiber geometry effect, two different MGF additives with different width to length ratio (B/L) values of 0.5 and 1.0 were used in the mixes. The MGF type fiber additives used in this study have the grid size of 1.2 mm. Both MGF and PPF products were purchased from the same supplier and made of the same polypropylene type fiber material with tensile strength, modulus of elasticity and density values of 350 MPa, 4.5 GPa, 0.92 g/cm^3, respectively. Soil, cement, water and fiber were added into a lab mixer, respectively. After all contents were added into the mixer, specimens were mixed and homogenized in the mixer for eight minutes according to the ASTM D1632-17e1 coded standard (ASTM, 2020). 3 specimens were moulded for the each specimen type. Specimens were filled into the moulds in three layers and compacted with 20 mallet strokes after each layers. The up-side surfaces were flattened by mallet drops when the specimens are in the plastic moulds. Additionally, roughness of the surfaces of the specimens was gently removed by using a snap blade knife to make a smooth contact with the loading platen. In total, 30 specimens were prepared for 10 different specimen groups (Figure 2). The inner diameter of the cylindrical specimen moulds was 50 mm and the ratio of length to diameter of the specimens was 2 in this study. According to the ASTM D 2166 coded standard for the unconfined compressive strength (UCS) tests of soil specimens, length to diameter ratio can vary from 2 to 2.5. According to the relevant standard, the biggest soil particle size must be smaller than one sixth of the specimen diameter (ASTM International, 2013). The statement of the relevant standard was met since all particles of the soil used in this study passed under the sieve opening of 8 mm.

CSS specimens were remoulded after a day of curing time. Before the UCS test, CSS specimens were cured for a total of 14 days. In the UCS test, the loading rate was chosen to be 0.5 mm/min according to the ASTM D 2166 coded standard which states to use a strain rate from 0.5% to 2%/min (ASTM International, 2013).

Before the UCS test, the specimens were weighed using a precision electronic scale, their lengths were measured precisely, and density values were calculated as given in Table 3. During the UCS test, deformation values were sensitively measured by a LVDT (Linear Variable Differential Transformer) device in the test setup (Figure 3). Stress and strain data was automatically recorded and graphed. Within the tests, modulus of elasticity values, deformability characteristics and ductility properties of the specimens were comparatively examined in addition to the UCS values. As given in Figure 4, the secant elastic modulus values can be calculated using the slope of the line connecting the origin and a specified point on stress-strain graphs. Secant elastic modulus values for 25%, 50% and 75% of the UCS level were calculated to investigate deformability properties under various stress levels. Investigations were also conducted into the strain behaviors of the specimens that fractured after they reached the UCS level. Loading was stopped automatically as the maximum load level decreased by 40%. To investigate the ductility properties of the specimens, plastic strain values after the maximum stress level were taken into account. As another important issue, the area under load (kN) displacement (mm) graphs gives the energy absorption capacity (EAC) values in the unit of Joule (N·m). The load displacement data was used to calculate the EAC values of the specimens. It should be reminded herein that both MGF and PPF additives are made of the same polypropylene material and have the same strand diameter.

To summarize the test program carried out within this research, the experimental study steps can be listed as follows: Taking soil specimen from the field, specimen classification by sieving and the Atterberg limits (liquid and plastic limits) tests, specimen preparation (specimen mixing, specimen molding, demolding and curing), density measurements, uniaxial compressive strength and deformability tests to compare stress and strain behaviors of the specimens.

3. Results and Discussions

The UCS values obtained from the experimental study are given in Figure 5. Changes in the secant elastic modulus values for 25%, 50% and 75% of the UCS level are given in Figure 6. According to the results obtained from this study, MGF additives were found to supply better strength and modulus of elasticity values in comparison with the conventional PPF additive. UCS values were found to increase with an increase in the fiber content to a threshold value which is 1% for this study results. The highest UCS and modulus of elasticity values were obtained in the case of using 1% MGF additive with width to length ratio of 0.5 (B/L: 0.5). To compare the ductility properties of cracked specimens loaded until a 40% decrease from the peak stress level, the stress-strain behaviors of the specimens were investigated. The plastic strain values of specimens after the maximum stress level are given in Table 4. Because an increase in the plastic deformation limit of the cracked samples indicates that the ductility property also increases, MGF additives were found to better increase the ductility property in comparison with the conventional PPF additive. Within different MGF additive types, the best ductility was supplied by the MGF additive with the width to length ratio (B/L) of 0.5. The EAC values calculated from the load-deformation data of both elastic and plastic intervals covering the loading process are seen in Table 5. Considering the EAC values, the most advantageous fiber type was also determined to be the MGF additive with the width to length ratio of 0.5. The other MGF additive with the width to length ratio of 1 also supplied better UCS, modulus of elasticity, ductility and EAC results than the conventional PPF additive. Graphs showing the effect of different fiber additives on the stress-strain behaviours of the CSS mixes are given in Figure 7.

In case of using fiber additives, it is a well-estimated fact to measure lower density values compared to those of fiberless soils. Because, the density value of the polypropylene fiber additive is lower than the soil grains. In addition, an excessive amount of fiber use makes notable increases in the void ratio (Lawer et al., 2021). Specimen density values were found to decrease with increasing in the fiber content. Since density values of specimens including MGF additive with the B/L ratio of 1 are lower than those of the specimens reinforced with MGF additive with the B/L ratio of 0.5, it can be inferred that the B/L ratio of 1 causes relatively higher void ratios. This situation can be considered as an important reason for obtaining better strength values from the use of MGF additive with B/L: 0.5 case, rather than the case of B/L: 1. MGF widths higher than a threshold value can be assessed as disadvantageous to cause increasing in the void ratio. In future studies, different B/L ratios can be tested to obtain more detailed information for the aim of determination of the most suitable MGF geometry. It can be taken into account that the appropriate B/L ratio should be related to the grid size and the strand diameter parameters. In addition, the type of fiber material can also be examined as another parameter to assess whether it has an effect on the appropriate B/L ratio of the MGF additive geometry.

As confirmed by this study, fiber geometry is an important parameter for the soil reinforcement effect (Jaramillo et al., 2022; Jin et al., 2022; Syed and Guharay, 2020). Because the grid size differs the interlocking performance depending on the soil particle size distribution, it should be also examined as an important parameter for different soil types. Within the tested B/L ratios, the best geometrical choice for the MGF use was determined to have the width to length ratio of 0.5 for the 1.2 mm grid size case. Depending on the grid size and soil particle size distribution, effectiveness supplied by various MGF geometries can be investigated within further researches to assess whether the same geometry is the best choice for different soils, or not.

The correct amount of fiber additive must be used in the soil mixes. Strength values are negatively influenced when the amount of fiber additive is increased above a certain threshold. Using too much fiber additive causes a negative impact on strength values (Singh and Jamatia, 2020; Firoozi et al., 2017; Ayeldeen et al., 2022). As parallel to this information, it was observed that the strength values decreased as the fiber content increased above the threshold value of 1%. In the case of quiet high fiber usage, the fiber surfaces cannot be completely surrounded by soil or binder and free surfaces begin to form. In this case, the fiber adhesion worsens. Hence, there is a decrease in CSS material strength when using higher fiber amounts over the threshold level. Not only in terms of strength, but also in terms of modulus of elasticity values and ductility properties, the test results are negatively affected in case of excessive fiber use. All positive mechanical property contributions provided by the fiber additive occur as a result of having a proper adherence. Factors that negatively affect the adherence reduce fiber usage efficiency. For this purpose, fiber additives must be used in the correct proportion in the mixes. Otherwise, fiber additive can not be able to provide economical solutions.

Different topics like strand diameter, grid geometry, fiber length and geometry, fiber material can be investigated for using MGF additive in different soil mixes (Shafei et al., 2021; Zheng et al., 2019; Ghanbari and Bayat, 2022). The polypropylene type fiber material was used in this study. In terms of choosing another appropriate fiber material, plastic materials with hydrophilic surfaces should be preferred to provide a good adhesion to cementitious mixes, instead of the hydrophobic materials (Komurlu, 2023; Komurlu et al., 2017). MGF additives are new geofiber types and open for investigations on different topics as a new research area of the geosynthetics branch of the geotechnical engineering discipline. In the geotechnical engineering, new materials have supplied new solutions. The geosynthetics field is a good example for the positive influences on the innovative solutions and developments in the geotechnical engineering. Geofibers are an important product type in the field of geosynthetics. It is important for geotechnical engineers to follow the developments in new geofiber products. Material and geometry issues are considerable for significant developments in the field of geofibers and effectiveness of their use. This study was carried out on the change in fiber geometry. It has been evaluated that fiber geometry containing the microgrids provides significant advantages in terms of the soil reinforcement performance.

Geofiber additives are used not only to increase the strength values of the soil mixes, but also to improve the crack propagation resistivity, ductility and energy absorption capacity (EAC) values (Divya et al., 2020; Kafodya and Okonta, 2021; Motamedi et al., 2021; Kumar et al., 2023). The geofiber additives are used to prevent or minimize damages of the ground fills. Some popular examples in the regard of applications using geofibers are road embankments and soil fills behind the retaining walls. Due to the increase in the crack propagation resistivity, ductility and EAC properties of CSS mixes are also improved. The high crack propagation resistivity and EAC properties supply a significant advantage for the soil mixes by increasing the service lifetimes and bettering the durability against the external forces and factors. Increases in the crack propagation resistivity result from a bettered adherence of fiber additive in soil mixes (Isik et al., 2021; Chebi et al., 2020; Gui et al., 2022). Ductility and EAC values of MGF-added soils were higher than those of the PPF added specimens. For this reason, it is possible to prefer MGF type fiber additives in future applications instead of the conventional fiber products to provide better reinforcement performances.

4. Conclusion

According to the results, it was assessed that the MGF reinforcement is able to better improve the strength values of cement stabilized sand (CSS) mixes compared to the conventional PPF type additive. To give a quantitative data to compare the strength values for a same fiber amount, it can be noted that the UCS values of MGF added CSS mixes were up to 31% higher than those of PPF added specimens. In addition to the UCS values, MGF type novel fiber additives were assessed to supply higher modulus of elasticity values compared to the PPF added specimens. Rather than the conventional PPF product, the MGF additive was also determined to be more advantageous to increase ductility and energy absorption capacity values. For a same fiber amount, the EAC values of the MGF added specimens were more than 76% higher than those of the PPF added ones. The geometry and size properties of MGF additives are important in terms of their reinforcement effectiveness. Within different fiber geometries tested in this study, the most effective reinforcement was supplied by the MGF additive with width to length ratio of 0.5 for the grid size of 1.2 mm. In the near future, a large number of new research topics can be studied regarding novel MGF products with different designs and their application in different soil mixes. Considering the findings from this study, MGF-type new geofibers can be estimated to soon become more popular in geotechnical engineering.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Tables

Table 1. Particle size distribution of the soil specimen

Sieve size	0.075 mm (No. 200)	0.150 mm (No. 100)	0.300 mm (No. 50)	0.850 mm (No. 20)	2.00 mm (No. 10)	4.76 mm (No.4)
% Passing	4.1	9.7	20.2	41.3	67.9	93.4

Table 2. Contents of CSS mixes (NF: No fiber, M_{cement}: Mass of cement, M_{water}: Mass of water, M_{sand}: Mass of sand, M_{CWS}: Sum of cement water and sand masses, M_{fiber}: Mass of fiber, 0.5PPF and 0.5MGF: 0.5% fiber content, 1.0PPF and 1.0MGF: 1.0% fiber content, 1.5PPF and 1.5MGF: 1.5% fiber content, B/L: Ratio of width to length of MGF additives)

Specimen type	M_{cement}/M_{CWS}	M_{water}/M_{CWS}	M_{sand}/M_{CWS}	M_{fiber}/M_{CWS}
NF (0% fiber)	0.12	0.09	0.79	0
0.5% PPF	0.12	0.09	0.79	0.005
1.0% PPF	0.12	0.09	0.79	0.010
1.5% PPF	0.12	0.09	0.79	0.015
B/L: 0.5, 0.5% MGF	0.12	0.09	0.79	0.005
B/L: 0.5, 1.0% MGF	0.12	0.09	0.79	0.010

B/L: 0.5, 1.5% MGF	0.12	0.09	0.79	0.015
B/L: 1.0, 0.5% MGF	0.12	0.09	0.79	0.005
B/L: 1.0, 1.0% MGF	0.12	0.09	0.79	0.010
B/L: 1.0, 1.5% MGF	0.12	0.09	0.79	0.015

Table 3. Mean density (ρ) values of specimens

Specimen type	ρ (g/cm^3)
NF (0% fiber)	2.06
0.5% PPF	1.84
1.0% PPF	1.77
1.5% PPF	1.65
B/L: 0.5, 0.5% MGF	1.90
B/L: 0.5, 1.0% MGF	1.82
B/L: 0.5, 1.5% MGF	1.69
B/L: 1.0, 0.5% MGF	1.81
B/L: 1.0, 1.0% MGF	1.72
B/L: 1.0, 1.5% MGF	1.58

Table 4. Strain values of specimens during 40% stress decrease from the peak stress level ($\Delta\varepsilon_p$) (SN: Specimen number, SD: Standard deviation)

Specimen type	SN	$\Delta\varepsilon_p$	SD for $\Delta\varepsilon_p$
NF (0% fiber)	3	0.004	0.0005
0.5% PPF	3	0.012	0.0011
1.0% PPF	3	0.015	0.0013
1.5% PPF	3	0.009	0.0007
B/L: 0.5, 0.5% MGF	3	0.023	0.0018
B/L: 0.5, 1.0% MGF	3	0.026	0.0018
B/L: 0.5, 1.5% MGF	3	0.024	0.0020
B/L: 1.0, 0.5% MGF	3	0.025	0.0017
B/L: 1.0, 1.0% MGF	3	0.028	0.0016
B/L: 1.0, 1.5% MGF	3	0.026	0.0021

Table 5. Energy absorption capacity (EAC) values of specimens

Specimen type	SN	EAC (J)	SD for EAC (J)
NF (0% fiber)	3	2.2	0.2
0.5% PPF	3	6.9	0.4

1.0% PPF	3	9.3	0.6
1.5% PPF	3	5.6	0.5
B/L: 0.5, 0.5% MGF	3	12.9	0.8
B/L: 0.5, 1.0% MGF	3	18.8	1.1
B/L: 0.5, 1.5% MGF	3	16.5	0.9
B/L: 1.0, 0.5% MGF	3	10.4	0.7
B/L: 1.0, 1.0% MGF	3	17.0	1.0
B/L: 1.0, 1.5% MGF	3	13.8	1.1

List of Figures

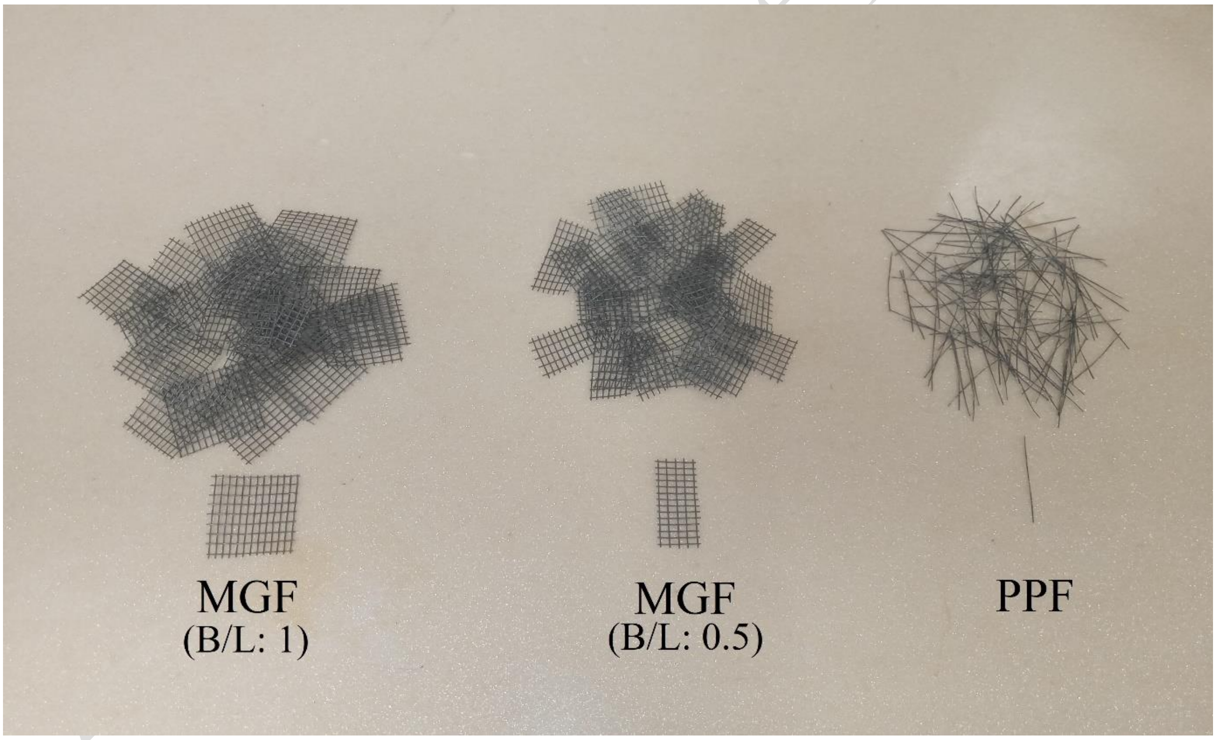


Figure 1

Figure 2

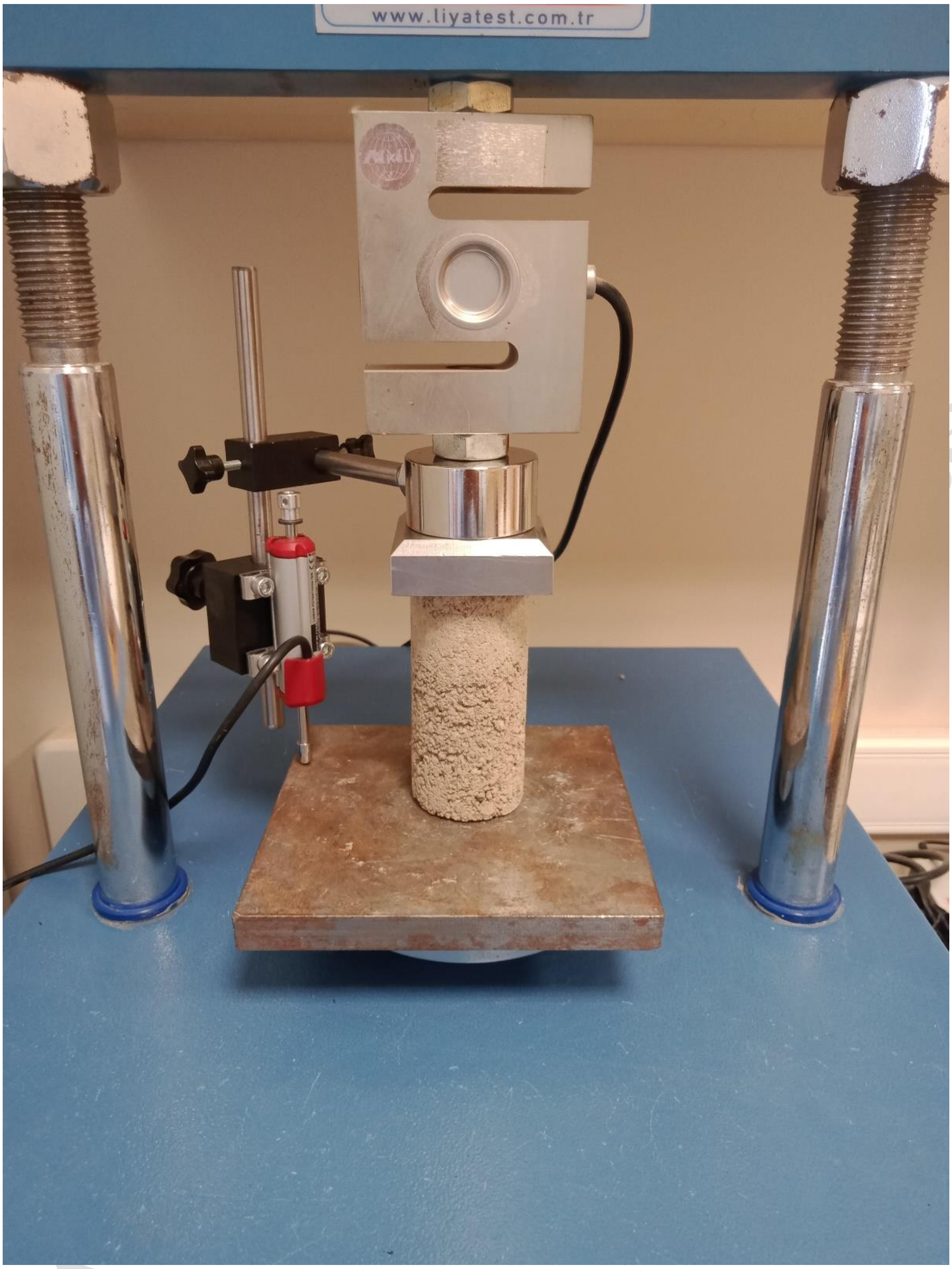
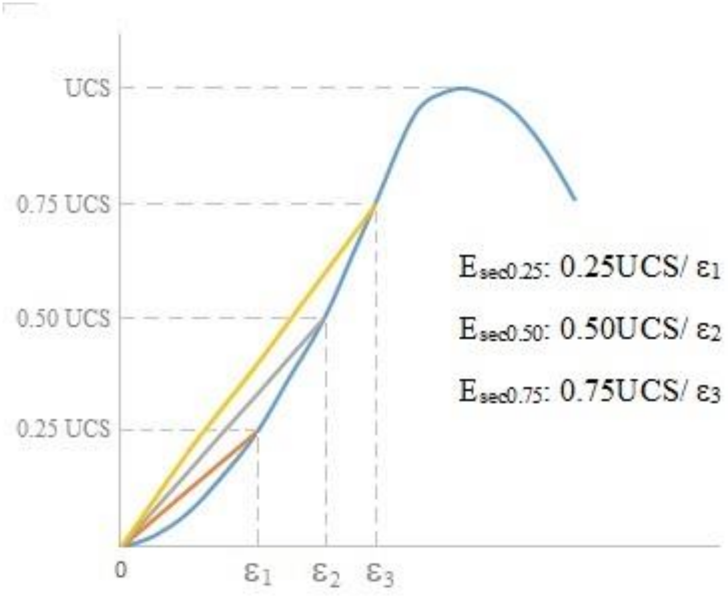


Figure 3



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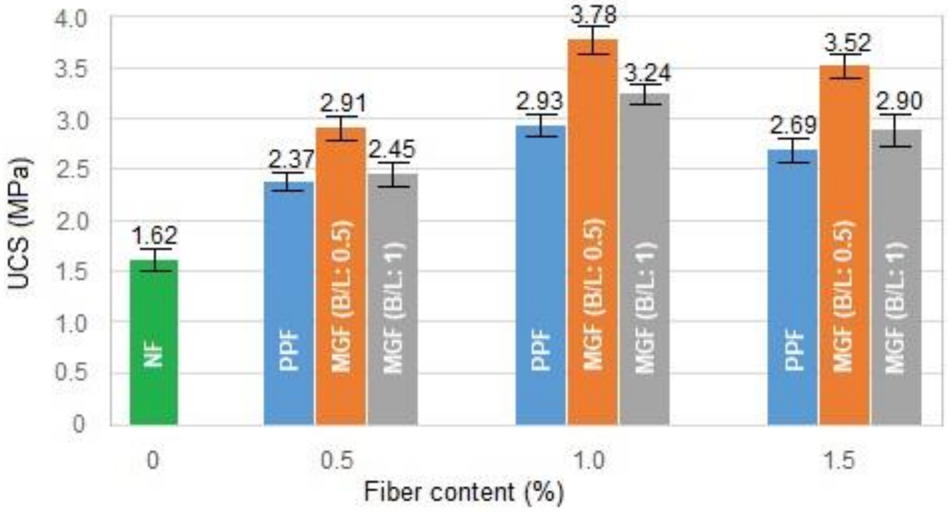

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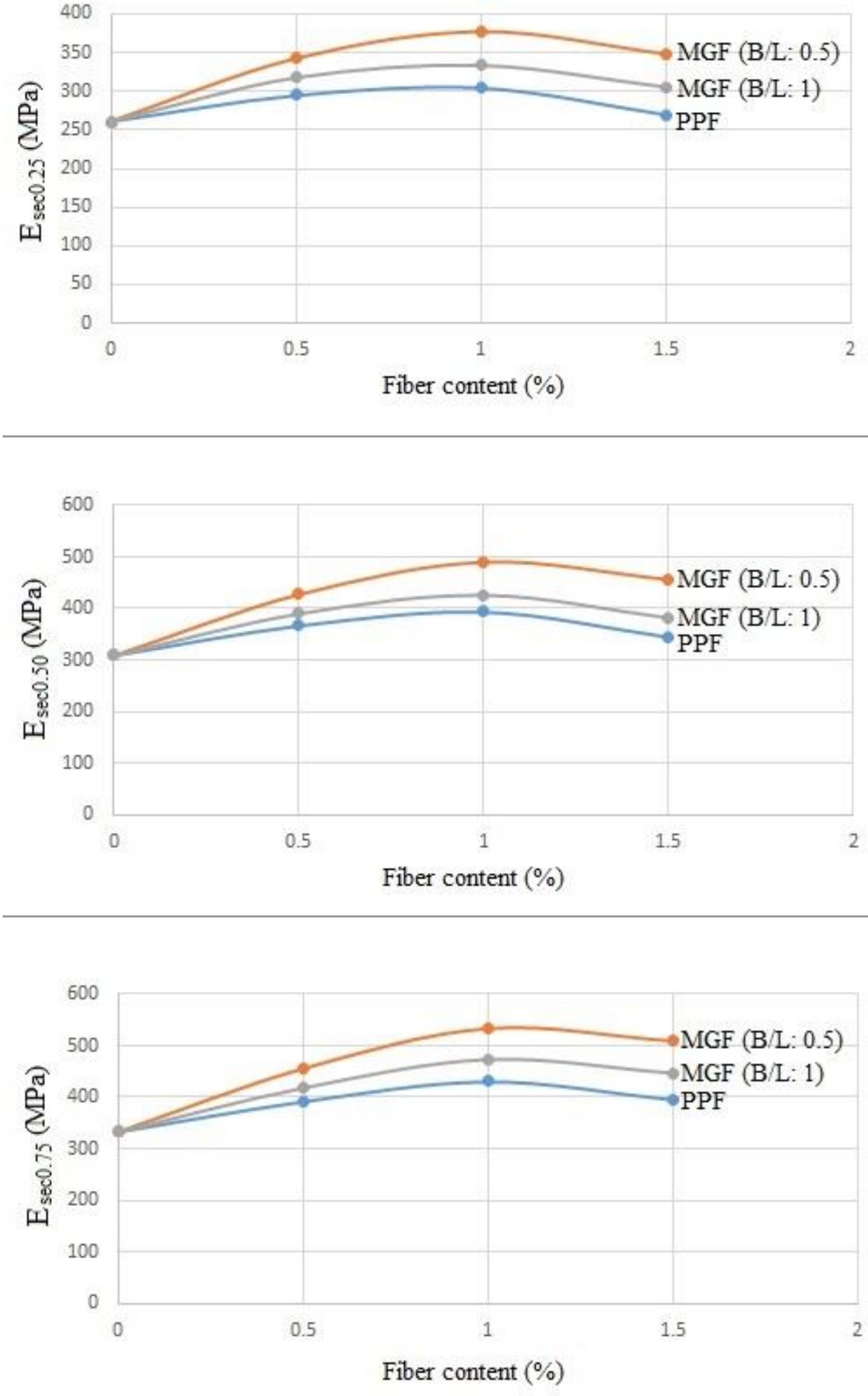

400
350
300
250
200
150
100
50
0
$E_{sec0.25}$ (MPa)
0
0.5
1
1.5
2
Fiber content (%)
MGF (B/L: 0.5)
MGF (B/L: 1)
PPF
600
500
400
300
200
100
0
$E_{sec0.50}$ (MPa)
0
0.5
1
1.5
2
Fiber content (%)
MGF (B/L: 0.5)
MGF (B/L: 1)
PPF
600
500
400
300
200
100
0
$E_{sec0.75}$ (MPa)
0
0.5
1
1.5
2
Fiber content (%)
MGF (B/L: 0.5)
MGF (B/L: 1)
PPF

Figure 6

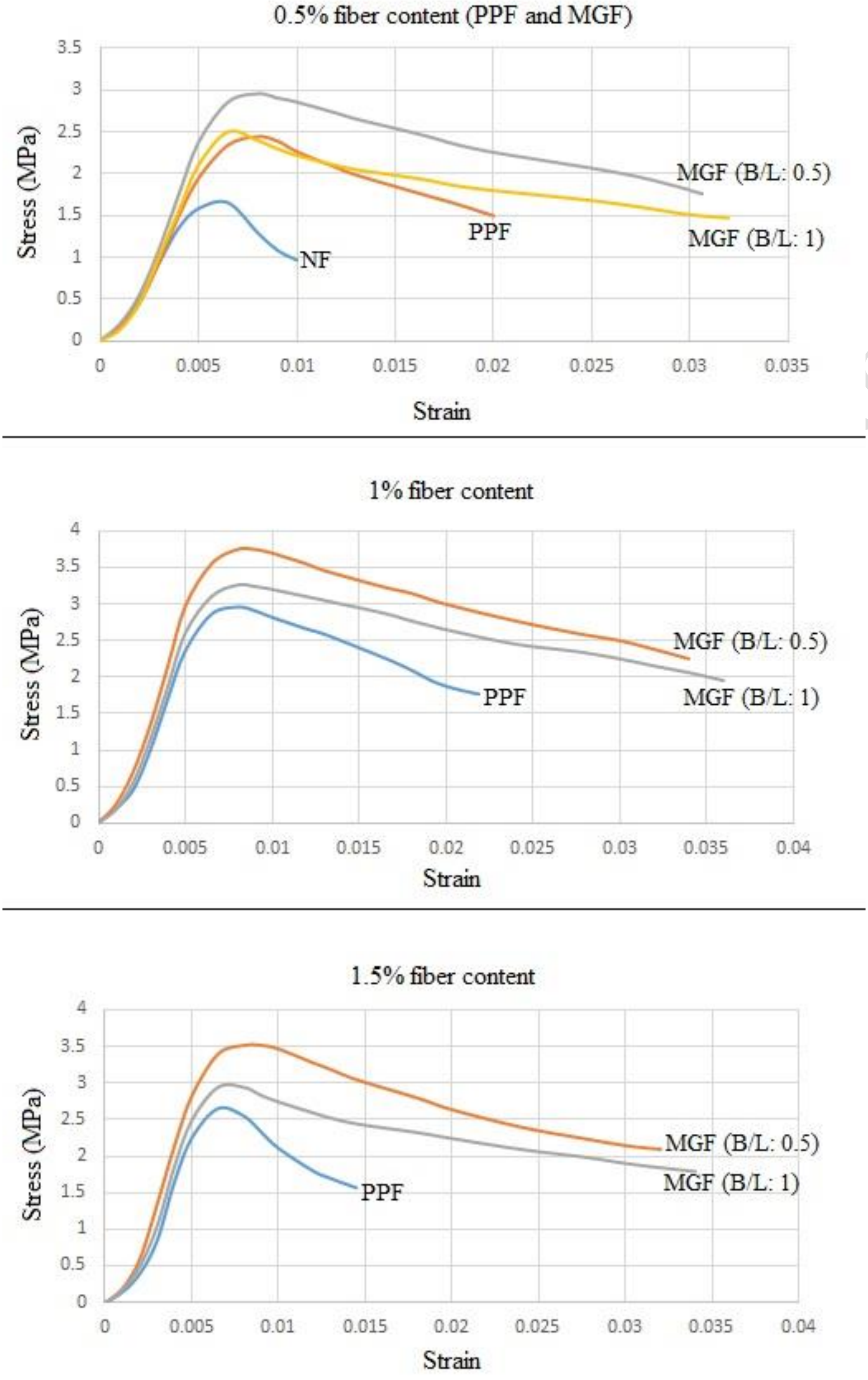
0.5% fiber content (PPF and MGF)
Stress (MPa)
3.5
3
2.5
2
1.5
1
0.5
0
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
Strain
MGF (B/L: 0.5)
PPF
MGF (B/L: 1)
NF
1% fiber content
Stress (MPa)
4
3.5
3
2.5
2
1.5
1
0.5
0
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
Strain
MGF (B/L: 0.5)
PPF
MGF (B/L: 1)
1.5% fiber content
Stress (MPa)
4
3.5
3
2.5
2
1.5
1
0.5
0
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
Strain
MGF (B/L: 0.5)
MGF (B/L: 1)
PPF

Figure 7