Research Article

The effect of water content on shear and compressive behavior of polymeric fiber-reinforced clay

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Abstract
Soil reinforcement is a reliable and effective technique for enhancing soil resistance. The present study aims to investigate the impact of water content on the mechanical behavior of a fiber-reinforced clay. To this end, clay specimens were prepared with three water contents (15%, 17.5%, and 20% by clay weight) and three contents of fiber (0.1%, 0.2%, and 0.3% referred to clay weight). Next direct shear and unconfined compressive strength tests were performed to study the effect of water content on the modulus of elasticity, compressive strength, strain energy, shear strength, shear strength ratio, stress–strain behavior, internal friction angle and cohesion coefficient of the prepared clay. The results indicate when the water content is lower than the optimum moisture content (OMC), fiber decreases modulus of elasticity and increases ductile behavior, compressive and shear strength, strain energy, shear strength ratio and cohesion coefficient but when the water content is more than the OMC, fiber increases brittle behavior, compressive and shear strength, strain energy, shear strength ratio and friction angle.

Keywords Reinforced clay · Polymeric fibers · Water content · Compressive strength · Shear strength

1 Introduction

Soil reinforcement has been long recognized and used as a suitable method for enhancing its stability and resistance [1]. Nowadays, soil reinforcement methods are considered among a specialized branch of geotechnical studies. This science deals with materials suitable to reinforce soil with scientific principles, the use of new technologies, and improving the engineering specifications and mechanical properties such as strength, brittleness, elasticity, deformation, and bearing capacity [2]. Reinforced soil is a combination of two different types of materials, including soil grains (to withstand compressive stresses) and reinforcing materials (to withstand tensile stresses). Materials commonly used in soil reinforcement are made of metals, polymeric materials, and even plants' fibers. The mechanism of action and behavior of reinforced soil is based on the interactions between soil and reinforcing element. In this regard, the friction phenomenon between soil and reinforcement element plays an essential role [1]. One of the soil reinforcement methods is to mix fibers with soil. The mixing of soil with fibers creates a composite environment in which the involvement of soil grains with elements of reinforcement improves ductility and strength in different ways. Although various types of fibers distribution can take place inside the soil, a random distribution of fibers inside the soil strengthens the soil in every way and removes the weak surface [3]. In the last few decades, especially since half a century ago, extensive research on the understanding and assessment of the mechanical behavior of fiber-reinforced soil has been launched. Lee et al. [4] investigated the use of fibers in soil reinforcement and reported the increased shear strength of sand mixed with plant fibers in a three-axial load test. Gray and

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Ohashi [5] provided a model for soil and fiber behavior in the shear region by performing direct shear tests. The positive effect of fibers on the behavior of clayey sand was reported by Freitag [6]. Arenzic and Chowdhury [7] carried out a set of laboratory studies using a direct shear test and built a physical model of reinforced soil retaining wall, with its backside built using reinforced beach sand with aluminium flakes. According to these researchers, using these elements enhances the shear strength of the sand depending on the amount and specifications of the reinforcing elements. Benson and Khire [8] investigated the effects of utilizing polyethylene tapes on variations of brittleness and shear strength of sand. They showed that the subgrade reaction modulus of sand and its California bearing ratio (CBR) increase by the installation of polyethylene splinters in the soil. Renjan et al. [9] illustrated the positive impact of fiber reinforcement on the shear strength of sand specimens during the triaxial tests. Tingle et al. [10] carried out direct shear and tests on a mixture of sand and fiber. They showed an increase in the shear strength of fiber-sand mixture by the addition of more fibers. Also, they reported that adding an efficient amount of fibers to the soil significantly increases its strength parameters. Yetimoglo and Salbas [11] studied the shear strength of fiber-reinforced sand with random diffusion with the aid of a direct shear test. They concluded that reinforced samples were more ductile compared to non-reinforced samples and an increase in the fiber in the soil led to increasing the shear strength. In a study conducted by Zornberg [12], it was observed that friction angle between a smooth geomembrane and the clay barrier increased by the addition of fiber to the soil. Viswanadham et al. [13] indicated that swell potential and soil swelling pressure can be efficiently declined by the addition of fiber. Conducting some pullout tests, Tang et al. [14] reported that the interfacial shear resistance of the soil reinforced with fiber is a function of the soil particles' rearrangement, fiber surface roughness, effective interface contact area, and soil compositions.

The main function of the fibers against shear deformations is to mobilize tensile strength against applied tensile stress. This function occurs in the forms of stretch (elongation), slippage, or tearing of fibers. Statistical theoretical methods about the presence of fibers in the site of the shear failure sheet are examined by a few researchers. The empirical hypotheses for the random distribution of the fibers are [1]:

1. Fibers are independent of each other in soil masses.
2. The likelihood of the presence of the fibers in each section of the mixed mass is the same.
3. The likelihood of creating any possible angle in any desired axis by the fibers in the same.

The clays have seldom a uniform water content in the construction projects. Water content variations highly affect the resistance of clays reinforced with fiber. Hence, evaluating the effect of water content variations on the fiber-reinforced efficiency of these clays is of great necessity. In this regard, the previous works [15–17] have focused majorly on the fibers' effect on clayey soils, with few of them conducted on the impact of water content, especially optimum moisture content, on clays reinforced with fiber. Therefore, in this research, the effect of different water content on compressive strength, stress–strain behavior, shear strength, modulus of elasticity, shear strength ratio, strain energy, cohesion coefficient, and internal friction angle of the clay reinforced with a kind of waste polymeric fibers (carpet waste) was studied. For those aims, unconfined compressive strength (UCS) test and direct shear test were performed on the fiber-reinforced clay samples prepared with three fiber contents (0.1%, 0.2%, and 0.3%) and three water contents (15%, 17.5%, and 20%).

2 Laboratory studies

2.1 Soil characteristics

The particle size distribution of the clay used in this study is shown in Fig. 1. The clay studied in this study was collected from Rasht in northern Iran, which is located at the southern side of the Caspian Sea. According to previous studies [18], the properties of clay of Rasht are shown in Table 1.

The critical state parameters for the Rasht Clay are similar to the parameters of the behaviour model proposed for the Weald Clay in the southwest of England. Physical properties of the studied clay are shown in Table 2.

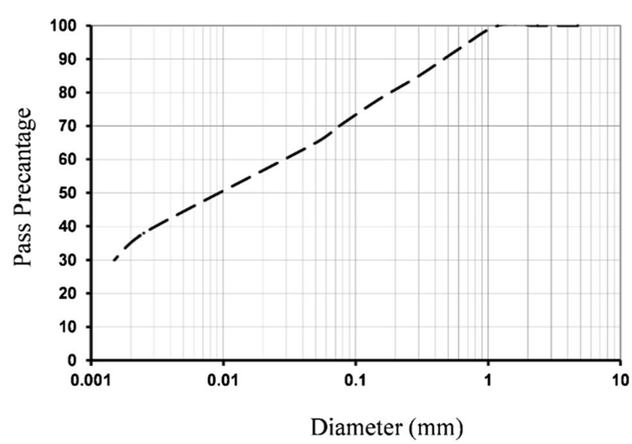


Fig. 1 Particle size distribution

Table 1 Properties of the clay of northern Iran, Rasht

Soil	Drained shear strength (kN/m2)	N_{SPT}	Over-consolidation ratio (OCR)	Critical state parameters			
				M	λ	κ	Γ
Clay	21–155	4–37	1.1–5	1	0.082	0.015	0.998

Table 2 Physical properties of the studied clay

Characteristics	Quantity measured
Mineral composition in decreasing amount	Illite and kaolinite
Liquid limit (%)	37
Plasticity index (%)	18
Plastic limit (%)	19
Soil classification	CL
C_c	0.18
C_s	0.029

2.2 Waste Polymers properties

Acrylic fibers are synthetic fibers made from a polymer (polyacrylonitrile) that have an average molecular weight of 100,000 and consist of about 1900 monomer units. An acrylic polymer contains at least 85% acrylonitrile monomer. The fiber is warm, wool-like, lightweight, and soft and has an average diameter of 25 µm.

Table 3 presents the specifications and the empirical formula of the waste fibers provided by the manufacturer. These fibers were prepared by cutting their lengths to 8 mm (0.315″).

The Acrylic fibers used in this study are shown in Fig. 2.

2.3 Experimental tests

In this study unconfined compressive strength, direct shear tests were performed on reinforced and non-reinforced clay.

2.3.1 Unconfined compressive strength test

The compressive strength of the fiber-reinforced clay was performed according to ASTM, D2166-91 [19]. A clay specimen with a diameter and height of 49 mm and 98 mm, respectively, was loaded at an axial strain rate of 1 mm/min. The load at which specimen failed was recorded and then the UCS was calculated using Eq. (1):

$$UCS = \frac{P}{A} \quad (1)$$

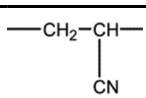
where P is the maximum load to failure (kN) and A is the cross-sectional area of the specimen (m^2).

2.3.2 Direct shear test

To perform a direct shear test, clay samples with dimensions of 50 mm × 50 mm × 20 mm were prepared. Next, the test was conducted according to ASTM D3080-90 [19] at the horizontal displacement rate of 1 mm/min. Figure 3 shows the unconfined compressive test and direct shear test machines used in the present study.

Fig. 2 Acrylic fibers

Table 3 Physical and mechanical properties of the acrylic fiber

Fiber	Empirical formula	Water absorption (%)	Tensile strength (MPa)	Flexural strength (MPa)	Shear strength (MPa)	Compressive modulus (MPa)
Acrylic		0.3–2	71	110	61	2700

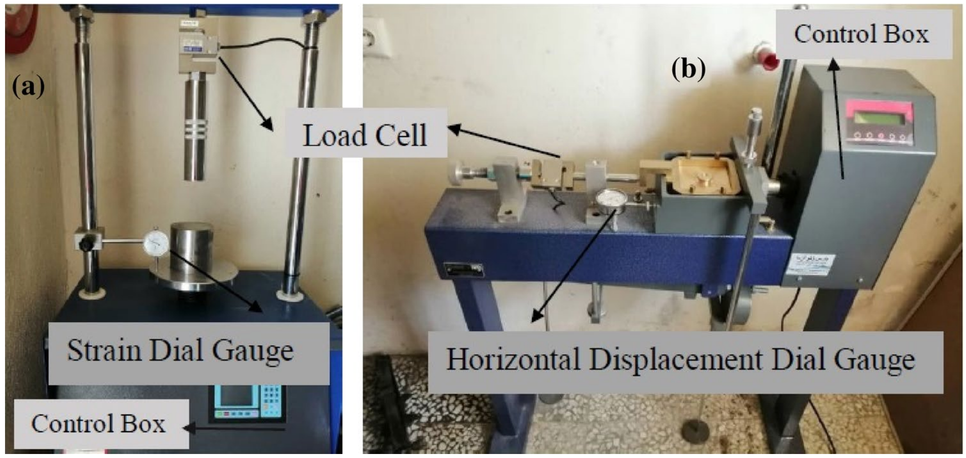


Fig. 3 **a** Unconfined compressive test machine, **b** direct shear test machine

2.4 Sample preparation

Test samples were prepared using water contents of 15%, 17.5%, and 20% and the addition of fiber polymer (Acrylic). The optimum moisture content (ω_{opt}) of the clay was determined to be 17.5%. Fiber length was 8 mm and was added to soil at contents of 0%, 0.1%, 0.2%, and 0.3% (referred to the dry weight of clay). Clay was dried in the oven and passed through a #200 sieve The fiber content for each mixture was estimated using the dry clay mass. After determining the needed amounts of water, fiber, and clay, the clay samples were batched into three equal parts. Each part of the fiber was mixed with water in individual beakers. Next, it was mixed with clay in a mixing. Finally, the mixture was placed in another beaker. This procedure was repeated for the other two parts, as well. To make mixtures homogeneous, they were quickly placed in another beaker and mixed again by hand. Water was added gradually and the clay soil was mixed layer-by-layer. The reason for this is that when fibers are added to clay in the absence of water, they stick together and thus do not adhere to the clay.[20]. As a result, the resulting mixture would be non-uniform. Each mix was tested in triplicate to check the repeatability of the results. Nevertheless, regarding the careful preparation and testing of the specimens, the difference between the results was negligible for the tests.

3 Experimental results and discussions

3.1 Unconfined compressive strength (UCS)

3.1.1 The effect of water content on axial stress–strain behaviour of fiber-reinforced clay

The deformation behavior of fiber-reinforced clays has been studied from the axial failure strains obtained from the stress–strain plots under different testing series. The stress–strain behavior of the specimens is presented in Fig. 4. In this study, the strain is calculated to be up to 20% strain. Referring to Fig. 4a, it can be seen that in specimens made with 15% water content, the fibers lead to ductile behavior of clay, and clay exhibits more ductile behavior at higher fibers content, but in specimens with 17.5% and 20% water content (Fig. 4b, c), fibers have the opposite effect on clay behavior, so that fibers increase brittle behavior of clay and this behavior increases with increasing fibers content.

3.1.2 *The effect of water content on the peak UCS (q_u)*

The peak of UCS, q_u, of fiber-reinforced and non-reinforced clay and the percentage of improvement in q_u is shown in Fig. 5. Figure 5a shows that q_u decreases with an increase in water content. Mirzababaei et al. [16] reported a similar behavior of water content, whereas Patel and Singh [15] and Nataraj and McManis [17] showed that with an increase in water content, the q_u value increases initially and declines, thereafter. According to their results, the highest q_u value occurs at the OMC. The single tiny fiber in the clay is wrapped by the clay particles, the fiber and clay particles contact with each other and produce the interfacial force and friction resistance [21]. Generally, the friction resistance and interfacial force decline with an increase in the water content. This decrease may be due to the reduction in soil suction, which occurs concurrently with the increase in the water contents and the possible development of excess pore water pressure [22].

From Fig. 5b it can be found that adding fibers increase q_u, but the percentage of increase of q_u depends on the water content. In the samples made with different percentages of water content, the lowest and highest q_u are observed for the samples made with 0.1% and 0.3% fibers, respectively. When specimens are made

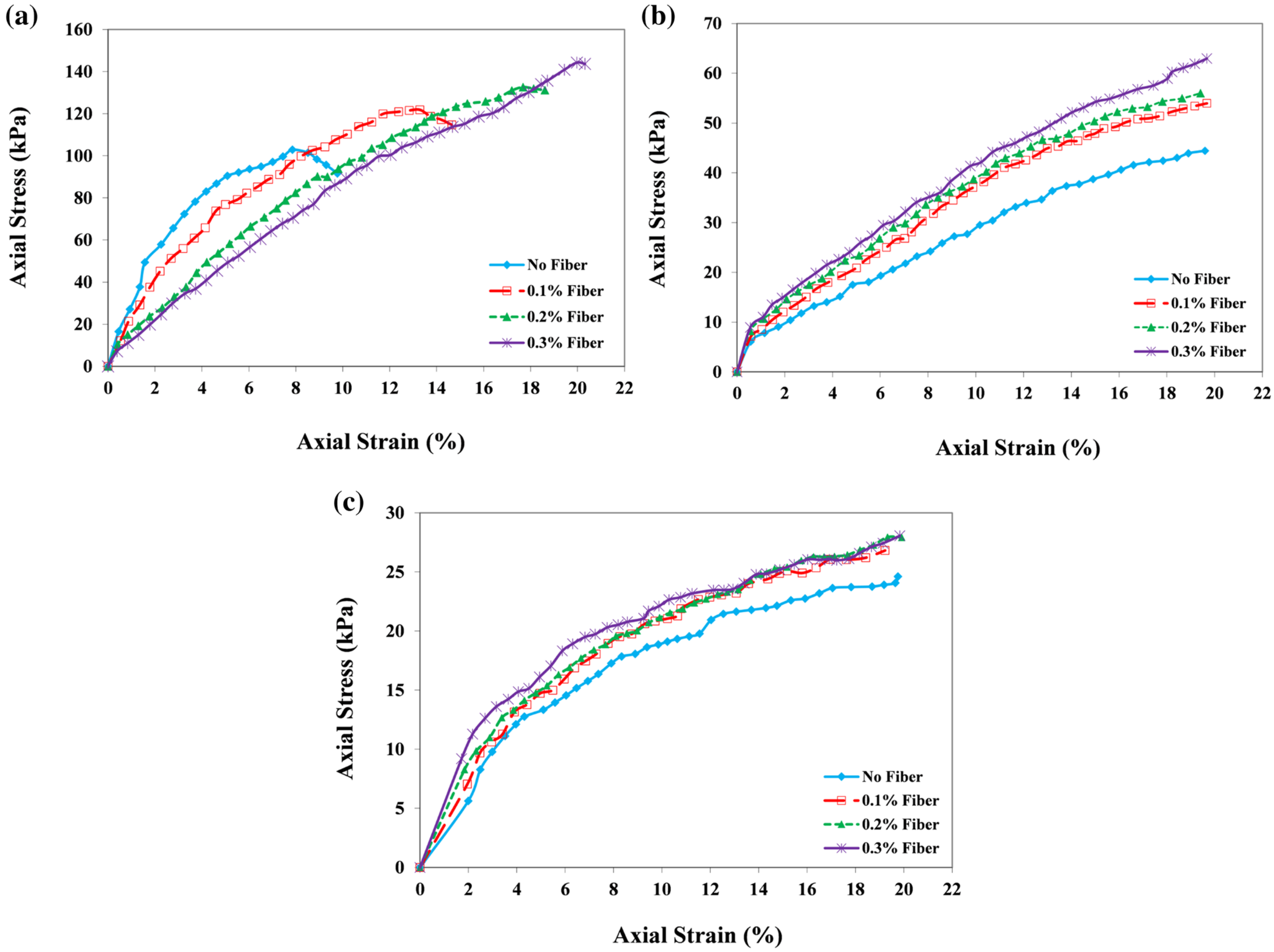


Fig. 4 The stress–strain behavior of the specimen made various fibers content and **a** 15%, **b** 17.5%, **c** 20% water content

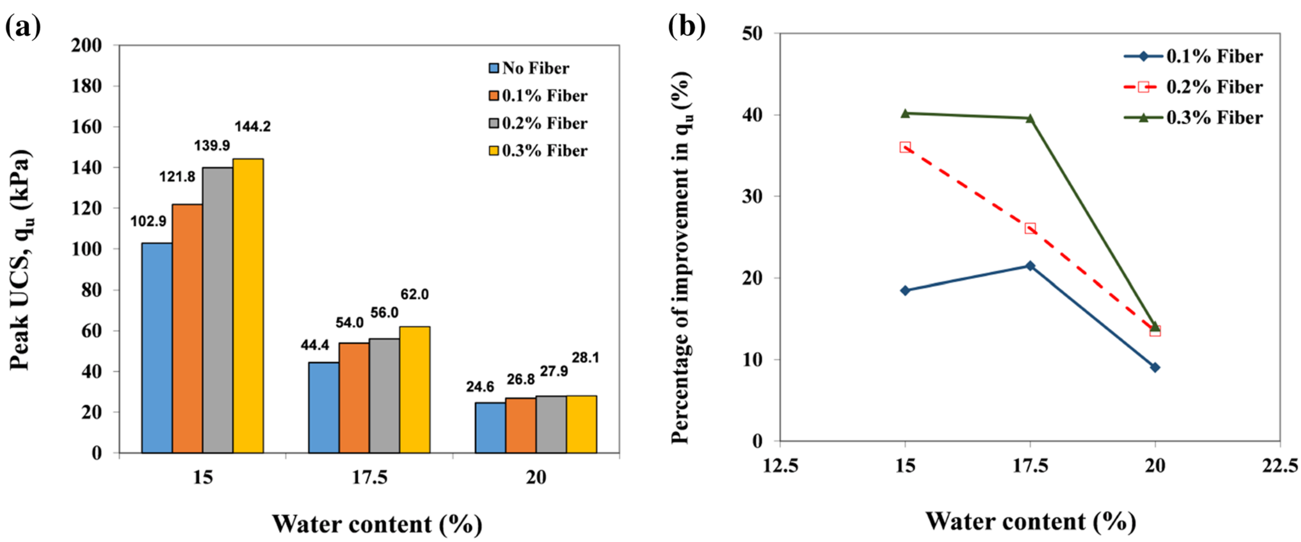


Fig. 5 Variation of **a** q_u and **b** the percentage of improvement in q_u, versus water content for different fiber content

with 0.1% and 0.2% fibers with 15% water content each, strength increases about 18.4% and 36.1%, respectively. Also, no significant increase in strength is observed with increasing fiber from 0.2% to 0.3% (about 4 percentage). For samples containing 17.5% water content and reinforced with 0.1% and 0.2% fibers, the strength increases 21.4% and 26.1%, respectively, and when increase fibers to 0.3%, the strength increases up to 40%. Adding 0.1%, 0.2%, and 0.3% fibers to the samples containing 20% water content increase the strength by 9.1%, 13.5, and 14.1%, respectively. Therefore, it can be concluded that the least effect of adding fibers (up to 0.3%) is on samples made with 20% water content.

3.1.3 *The effect of water contents on the modulus of elasticity (E_{50}) of fiber-reinforced clay*

The secant modulus at 50% of the qu (i.e., E_{50}) is applied to estimate the stuffiness of materials in the elastic domain [23, 24]. Figure 6 presents the calculated values of E_{50} for the tested samples.

This figure shows that the effect of fibers on the modulus of elasticity of clay depends on the amount of water; so that increasing the fiber content in the samples with water content less and more than OMC causes a decrease and increase in modulus of elasticity, respectively. Figure 6a shows that in specimens made with 15% water content, fibers increase q_u but reduce E_{50} and as a result, fibers increase more soil ductility properties. Also, soil ductility increases further with increasing fiber content. But, in specimens contain with 17.5% and 20% water content, fibers lead to increase both q_u and E50 and more increasing soil stiffness and soil stiffness increases further with increasing fiber content (Fig. 6b, c).

3.1.4 *The effect of water contents on strain energy at peak (E_u) of fiber-reinforced clay*

The area under the curve (UCS) of stress–strain up to the failure/ peak point (E_u) is defined as strain energy at peak. This parameter, also known as energy adsorption capacity, is applied to measure the material's toughness [25]. Figure 7 presents the variations of E_u and the corresponding q_u values for the specimens prepared with various water contents.

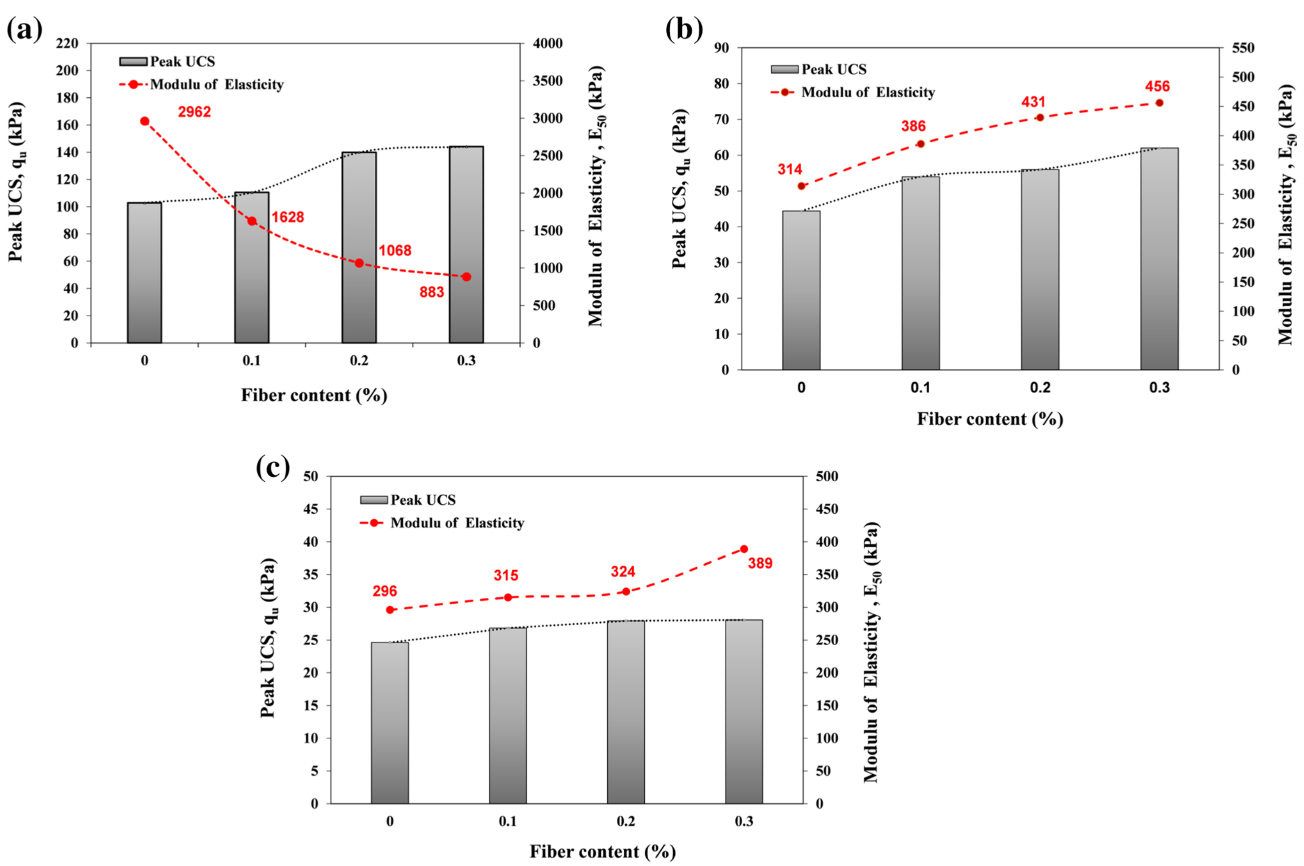


Fig. 6 Variations of the modulus of elasticity, E50, along with with the corresponding peak UCS values q_u, against fibers content for specimens with **a** 15%, **b** 17.5%, **c** 20% water content

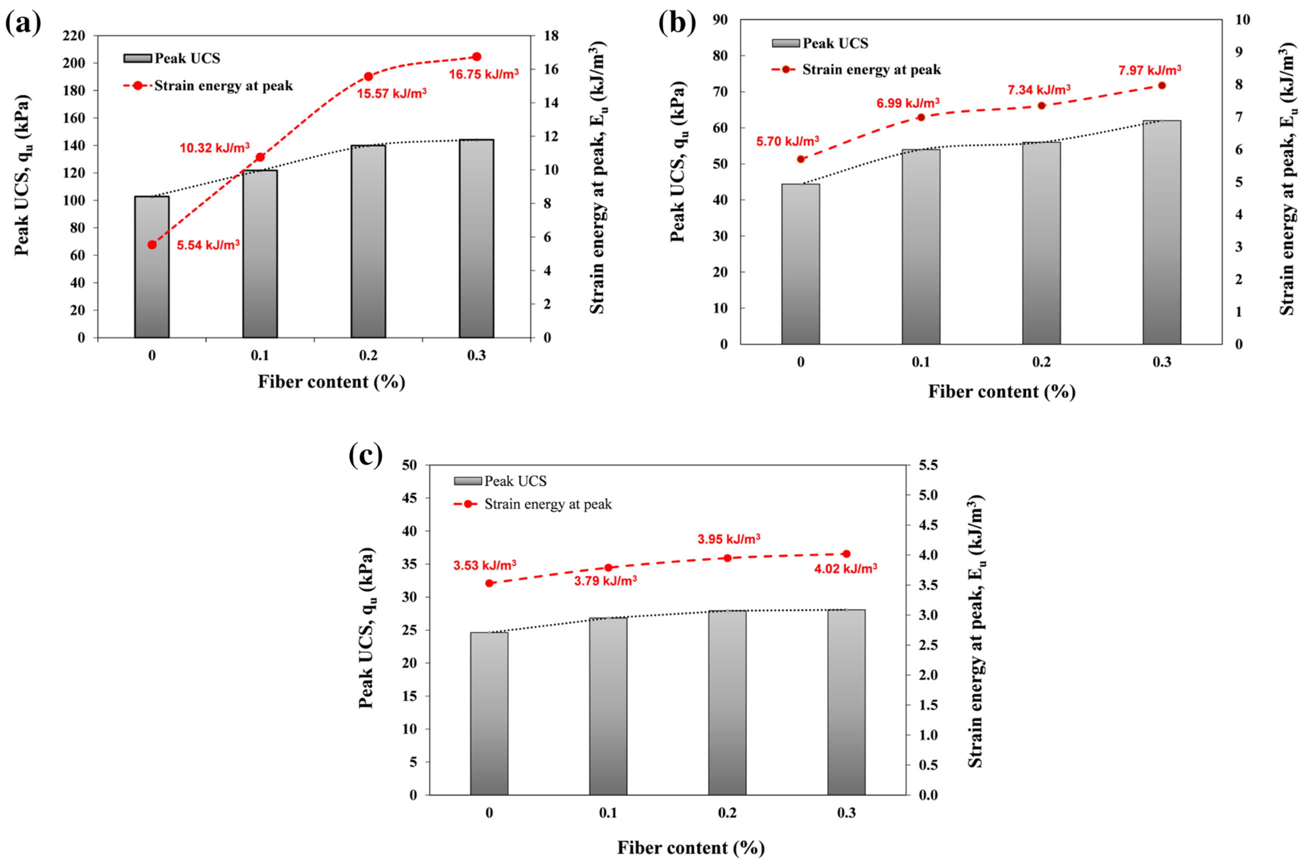


Fig. 7 Variations of the strain energy at peak E_u along with the corresponding peak UCS values q_u, against fibers content for the made samples with **a** 15%, **b** 17.5% and **c** 20% water content

As can be seen, the variation of strain energy at the peak is similar to the variation of peak USC. Thus, it is suggested that for greater fibers content, the corresponding E_u will be larger. This is consistent with the results published by Maher and Ho [26] and Mirzababaei et al. [16]. Higher strain energy at peak values indicates an increase in the peak UCS or axial strain at the failure point. According to Fig. 4, both axial strain at UCS peak (ε_u) and q_u increase with increasing the fiber content. This result suggests that uniformity of fibers randomly distributed within the clay specimen leads to continuous energy absorption before the sample's failure [15]. In all tested fiber-reinforced clay specimens, E_u decreased with an increase in water content. Mirzababaei et al. [16] reported a similar effect of water content on E_u. Also, the results show that the increase in E_u with increasing fibers content in the samples made with 15% and 17.5% water content is more significant than the samples made with 20% water content. In general, the effect of fibers on the increase of the E_u is noticeable with decreasing water content.

3.2 Direct shear test

3.2.1 The effect of water content on shear stress displacement of fiber-reinforced clay

In the direct shear test, the deformation behavior of fiber-reinforced clays has been studied from the shear displacement obtained from the shear stress–displacement plots. Shear stress displacement behavior of fiber-reinforced samples of various moistures tested at vertical stresses corresponding to 100 kPa is presented in Fig. 8. These figures clearly show the effect of water content on the ductile or brittle behavior of fiber-reinforced specimens. Moreover, for most of the fiber-reinforced samples, the peak strength occurred at larger horizontal displacement in comparison to the unreinforced soil. Also for specimens made with the same water content, increased fibers content lead to increase both of the residual and peak shear strength.

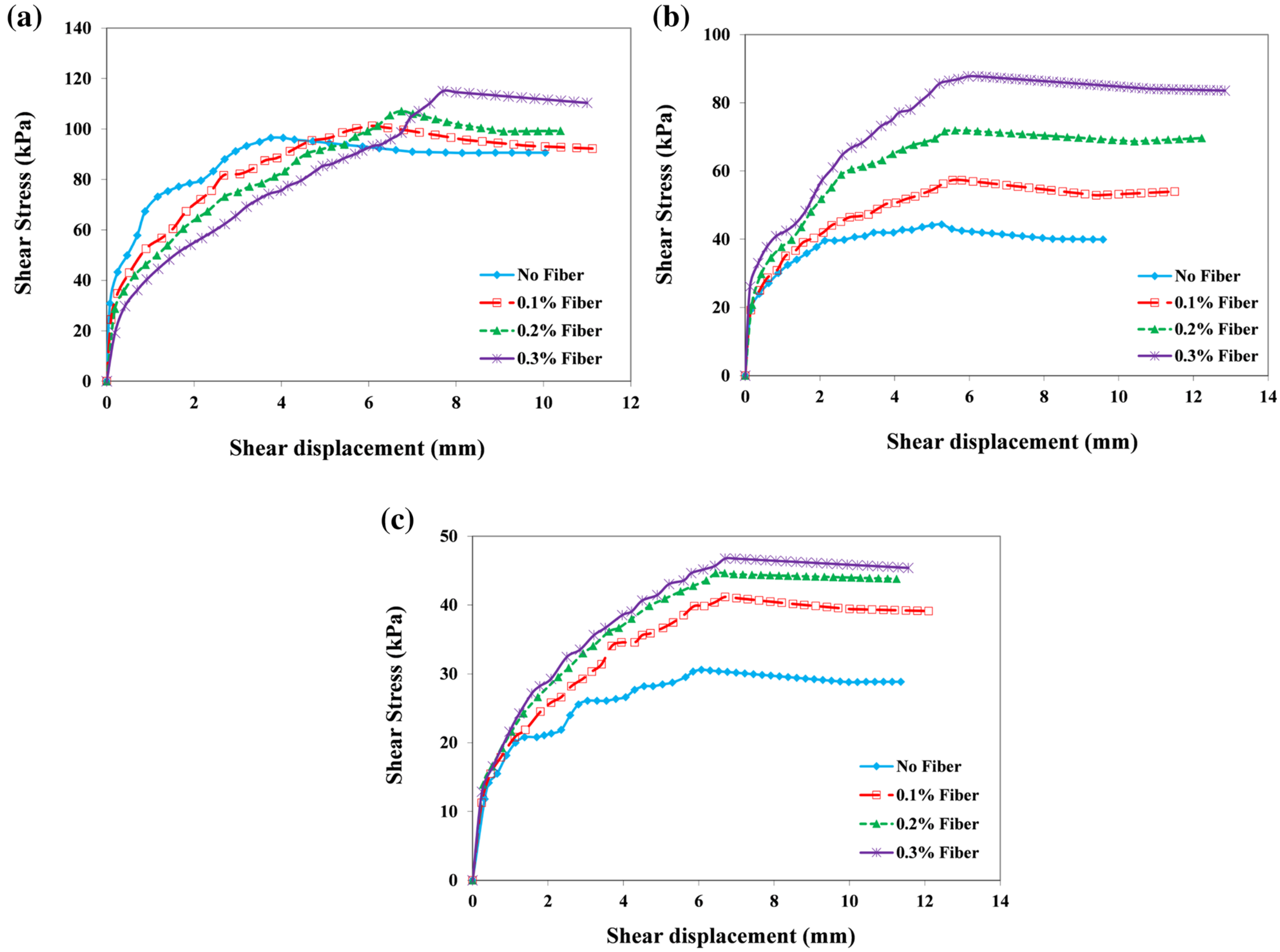


Fig. 8 Stress-shear displacement behavior of the made specimen with various fiber content and **a** 15%, **b** 17.5%, **c** 20% water content for the vertical stress of 100 kPa

3.2.2 The effect of water content on shear stress of fiber-reinforced clay

Variations of the shear strength, at varying normal stresses, against fibers content for the specimens made with different water content are provided in Fig. 9. This figure shows that, as expected, with increasing water content, the shear strength decreases. Stress is transferred from the clay to fibers, which possesses high tensile strength. A stronger adhesion between the clay and fibers is accompanied by a higher reinforcing effect. Higher water content in the clay reinforced with fiber results in a decrease in the adhesion between the clay and fibers. This can explain the shear strength reduction with the increase in water content. Also, results show that for a constant water content, shear stress increases with increasing fibers content but this increase in lower normal stresses aren't noticeable and by increasing the normal stresses, the effect of the fibers becomes more evident. It has been reported by many researchers [5, 11, 27] that the strength of non-reinforced and reinforced soil specimens improved with increase in normal stresses in direct shear tests.

3.2.3 The effect of water content on shear strength ratio of fiber-reinforced clay

The shear strength ratio is defined to studying the effect of fibers on the shear strength of the clay [28]. This ratio is expressed as:

$$R_{SP} = \frac{\tau_P^R}{\tau_P} \tag{2}$$

where τ_P and τ_P^R are respectively stresses of non-reinforced and fiber-reinforced clay samples at the peak point. The variation of shear strength ratio with normal stress can be defined under different experimental normal stresses using the mentioned method. Figure 10 illustrates an

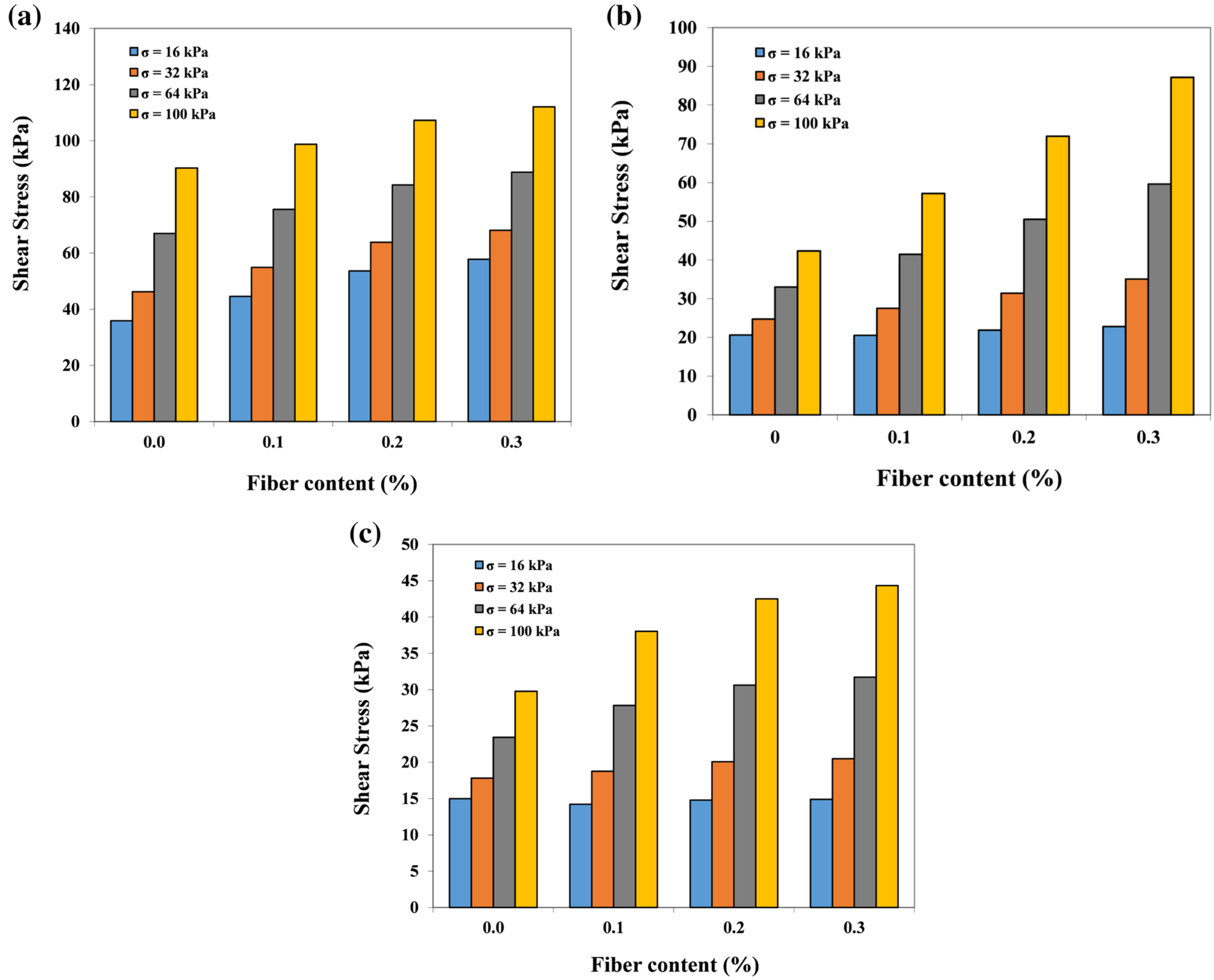


Fig. 9 The variations of the shear strength, at varying normal stresses, against fibers content for the prepared samples with **a** 15%, **b** 17.5%, **c** 20% water content

increase in the shear strength rate of fiber-reinforced samples under higher normal stress with an increase in their fiber content. Also, it is seen that increasing the fiber content result in an increase in the shear strength ratio at the same normal stress.

But the important point is that the most shear strength ratio is related to the sample with 17.5% water content that is the OMC of the clay, Therefore, in order for fibers to have the most influence on shear strength ratio of the clay, it is best to make samples with water content near OMC.

3.2.4 The effect of water contents on cohesion coefficient and friction angle of fiber-reinforced clay

The variations of cohesion coefficient (C) and friction angle (ϕ) of non-reinforced and fiber-reinforced clay and the effect of fibers and water content on these two parameters is presented in Fig. 11. In samples made with 15% water content, fibers increase the cohesion coefficient but haven't any significant effect on friction angle. Therefore, it can be concluded that an increase in the shear strength at this water content by an increase in fibers content is due to the increase in cohesion coefficient; thus, cohesion is the determining factor in the samples containing 15% water content. By increasing the water content to 17.5% or 20%, it can be seen that cohesion coefficient decreases with the increase in fiber content, but the friction angle increases. Therefore, it can be concluded that the effect of increasing friction angle in an increasing shear strength outweighs the effect of decreasing cohesion in decreasing the shear strength.

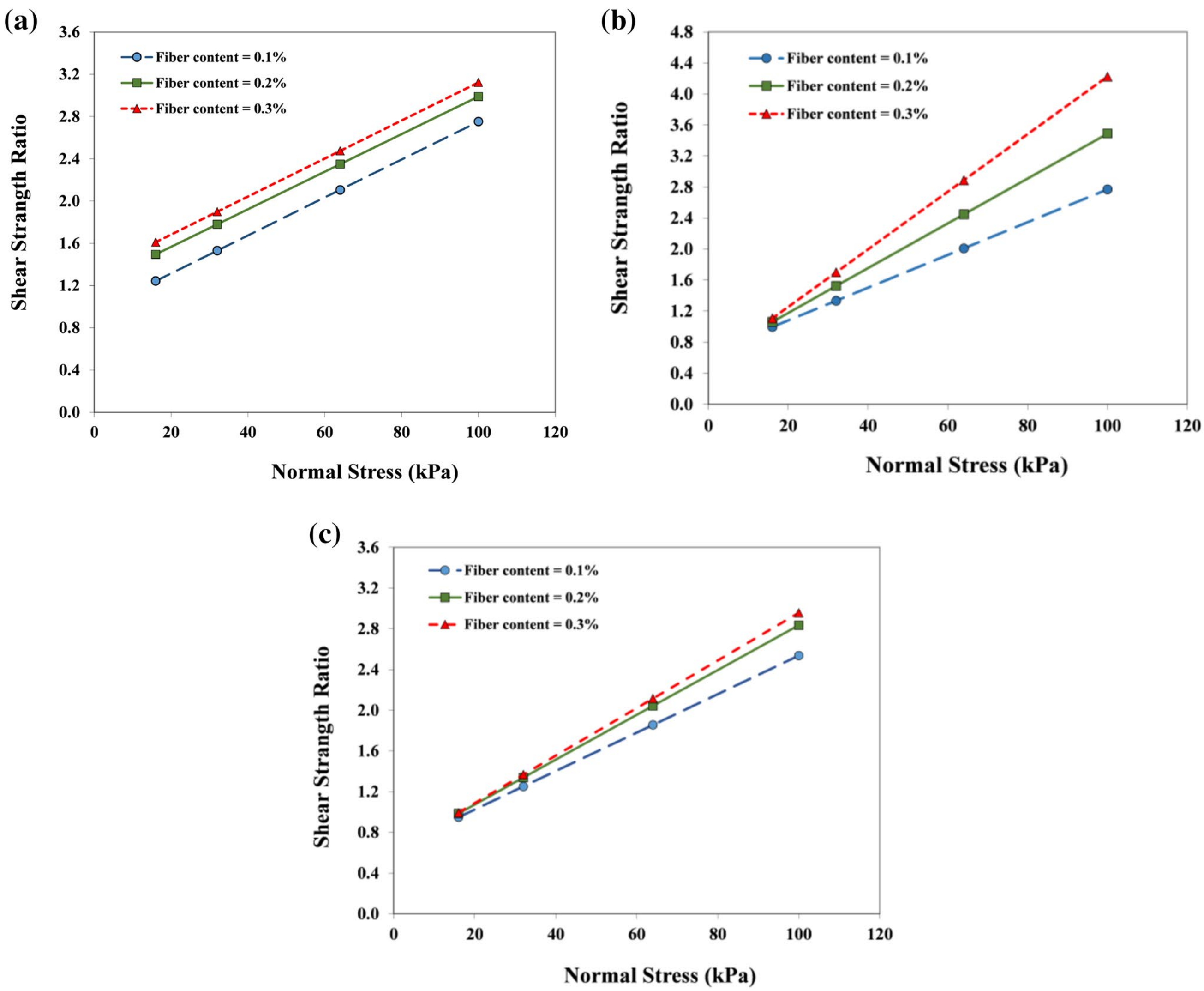


Fig. 10 Peak shear strength ratio versus normal stress of the made specimens with various fibers content and **a** 15%, **b** 17.5%, **c** 20% water content

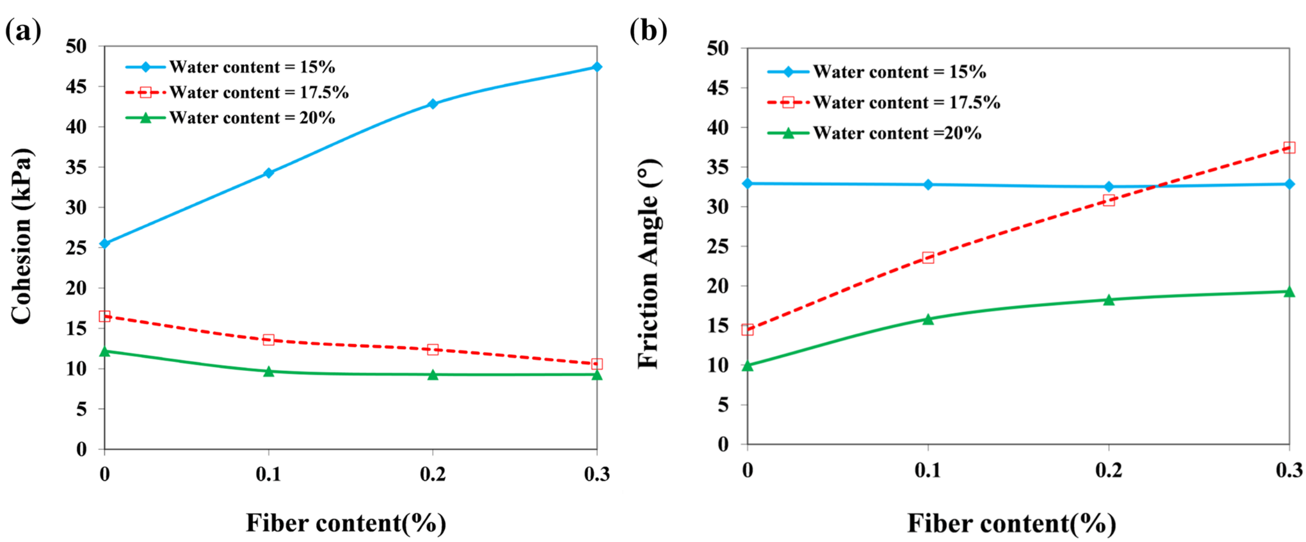


Fig. 11 Variation of **a** cohesion and **b** internal friction angle versus fibers content for various water contents

There is a direct relationship between the effect of fibers and water content on friction angle and soil brittleness, as well as the cohesion coefficient and ductility of the clay. It was observed that in samples made with 15% water content, fibers increase the ductility and also cohesion coefficient but when samples are made with 17.5% and 20% water content, fibers increase the brittle behavior and also friction angle.

Generally, in executive projects, the amount of water that should be added to the fiber-clay mixture is selected according to the purpose of using the fiber-reinforced clay. For example, if the purpose of reinforcement is to increase the cohesiveness and ductility of the soil, the clay-fiber composites should be mixed with water content less than OMC. If the goal, however, is to increase the modulus of elasticity, friction angle and brittleness behavior, at least the water content equal to OMC is required.

4 Conclusion

The type of behavior expected from the fiber-reinforced clay depends on its water content. The present study was conducted to evaluate the effect of water content on the shear and compressive behavior of the fiber-reinforced clay. The laboratory examination of the prepared specimens demonstrates the water content has a considerable effect on the fiber-reinforced clay. The results of the laboratory tests carried out in this study are as follows:

- In specimens made with water contents lower than the OMC, fibers increase q_u but reduce E_{50} and moreover; fibers can increase soil ductility properties. Also, soil ductility behavior increases further with increasing fibers content. But, specimens made with OMC and water contents higher than the OMC, fibers increase both q_u and E_{50}. Furthermore, fibers cause brittle behavior of the clay and this behavior increases further with increasing fiber content.
- The level of increase in compressive strength depends on the amount of water added to the fiber-reinforced specimens such that in specimens prepared with water content more than OMC, the increase in compressive strength decreases sharply. Generally, when water content is less than OMC, the interfacial force of the soil-fiber matrix is controlled by the adhesion and suction forces. When soil is wetter, the development of pore water pressure results in a decrease in the interfacial force and thus a reduction in strength values.
- The effect of fibers on an increase of the E_u is noticeable with decreasing water content.
- The presence of higher water content in the fiber-reinforced clay leads to decrease the adhesion between the fibers and the clay. It is the reason for the reduction of shear strength with an increase in water content.
- The highest of strength ratio parameter is related to the sample with 17.5% water content that is the OMC of the clay.
- For sample made with water contents lower than the OMC, fibers increase the cohesion coefficient but they have no effect on friction angle. In samples made with OMC and more than OMC, fibers decrease cohesion coefficient and increases the friction angle
- There is a direct relationship between the effect of fibers and water content on friction angle and soil brittleness, as well as the cohesion coefficient and ductility behavior of the clay. For samples made with OMC and more than the OMC, fibers increase the brittleness behavior and also friction angle of clay, but adding fibers to samples made with water contents lower than the OMC resulted in an increase in cohesion and ductility of the clay.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

1. Maher MH, Gray DH (1990) Static response of sands reinforced with randomly distributed fibers. J Geotech Eng 116(11):1661–1677
2. Kumar S, Tabor E (2003) Strength characteristics of silty clay reinforced with randomly oriented nylon fibers. Electron J Geotech Eng 8(2):10
3. Hoare DJ (1982) Synthetic fabrics as soil filter: a review. J Geotech Eng Div 108(10):1230–1245
4. Lee KL, Adams BD, Vagneron J (1973) Reinforced earth retaining walls. J Soil Mech Found Div 99:sm10
5. Gray DH, Ohashi H (1983) Mechanics of fiber reinforcement in sand. J Geotech Eng 109(3):335–353
6. Freitag DR (1986) Soil randomly reinforced with fibers. J Geotech Eng 112(8):823–826
7. Arenicz R, Chowdhury R (1988) Laboratory investigation of earth walls simultaneously reinforced by strips and random reinforcement. Geotech Test J 11(4):241–247
8. Benson CH, Khire MV (1994) Reinforcing sand with strips of reclaimed high-density polyethylene. J Geotech Eng 120(5):838–855
9. Ranjan G, Vasan R, Charan H (1996) Probabilistic analysis of randomly distributed fiber-reinforced soil. J Geotech Eng 122(6):419–426
10. Tingle JS, Santoni RL, Webster SL (2002) Full-scale field tests of discrete fiber-reinforced sand. J Transp Eng 128(1):9–16

11. Yetimoglu T, Salbas O (2003) A study on shear strength of sands reinforced with randomly distributed discrete fibers. Geotext Geomembr 21(2):103–110
12. Zornberg JG (2005) Geosynthetic reinforcement in landfill design: US perspectives. Geotech Spec Publ 130–142:3135–3151
13. Viswanadham B, Phanikumar B, Mukherjee RV (2009) Swelling behaviour of a geofiber-reinforced expansive soil. Geotext Geomembr 27(1):73–76
14. Tang C-S, Shi B, Zhao L-Z (2010) Interfacial shear strength of fiber reinforced soil. Geotext Geomembr 28(1):54–62
15. Patel SK, Singh B (2017) Strength and deformation behavior of fiber-reinforced cohesive soil under varying moisture and compaction states. Geotech Geol Eng 35(4):1767–1781
16. Mirzababaei M, Miraftab M, Mohamed M, McMahon P (2013) Unconfined compression strength of reinforced clays with carpet waste fibers. J Geotech Geoenviron Eng 139(3):483–493
17. Nataraj M, McManis K (1997) Strength and deformation properties of soils reinforced with fibrillated fibers. Geosynth Int 4(1):65–79
18. Akbarzadeh Kasani H, Eslami A (2019) Geotechnical properties of Rasht clay and silt in Northern Iran. Int J Geotech Eng 13(6):566–580
19. ASTM A (2000) Annual book of ASTM Standards. ASTM International, New York
20. Arabani M, Haghsheno H (2020) The effect of polymeric fibers on the mechanical properties of cement-stabilized clay soils in Northern Iran. Int J Geotech Eng 14(5):557–568
21. Tang C, Shi B, Gao W, Chen F, Cai Y (2007) Strength and mechanical behavior of short polypropylene fiber reinforced and cement stabilized clayey soil. Geotext Geomembr 25(3):194–202
22. Abu-Farsakh M, Coronel J, Tao M (2007) Effect of soil moisture content and dry density on cohesive soil–geosynthetic interactions using large direct shear tests. J Mater Civ Eng 19(7):540–549
23. Iyengar SR, Masad E, Rodriguez AK, Bazzi HS, Little D, Hanley HJ (2012) Pavement subgrade stabilization using polymers: characterization and performance. J Mater Civ Eng 25(4):472–483
24. Zhang J, Soltani A, Deng A, Jaksa MB (2019) Mechanical performance of jute fiber-reinforced micaceous clay composites treated with ground-granulated blast-furnace slag. Materials 12(4):576
25. Zhang J, Soltani A, Deng A, Jaksa MB (2019) Mechanical behavior of micaceous clays. J Rock Mech Geotech Eng 11:1044–1054
26. Maher M, Ho Y (1994) Mechanical properties of kaolinite/fiber soil composite. J Geotech Eng 120(8):1381–1393
27. Zaimoglu AS, Yetimoglu T (2012) Strength behavior of fine grained soil reinforced with randomly distributed polypropylene fibers. Geotech Geol Eng 30(1):197–203
28. Hamidi A, Hooresfand M (2013) Effect of fiber reinforcement on triaxial shear behavior of cement treated sand. Geotext Geomembr 36:1–9