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Direct and Indirect Tensile Behavior of Cement-Zeolite-amended Sand Reinforced with Kenaf Fiber

I. Mirzadeh[a], R. Shirinabadi*[b,c], G. Mohammadi[b], S. H. Lajevardi[d]

[a] *Department of Civil Engineering, South Tehran Branch, Islamic Azad University, Tehran, Iran*
[b] *Department of Petroleum and Mining Engineering, South Tehran Branch, Islamic Azad University, Tehran, Iran*
[c] *Research Center for Modeling and Optimization in Science and Engineering, South Tehran Branch, Islamic Azad University, Tehran, Iran*
[d] *Department of Civil Engineering, Arak Branch, Islamic Azad University, Arak, Iran*

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A B S T R A C T

Dealing with problematic soils is one of the most challenging parts of geotechnical engineers' careers. Loose sand is one of them due to its low cohesion and can be found worldwide, specifically in coastal regions. Chemical stabilizers like cement are of the prevalent ones among engineers to deal with the weaknesses of loose sand. However, the substitution of these traditional stabilizers with pozzolanic materials like natural zeolite become approved since it helps reduce cement consumption and hence, lower CO_2 emission. Despite all advantages, brittle behavior is an unwelcome consequence of these stabilizers. Therefore, the aim of this study is to reduce the brittleness of the cement-zeolite-stabilized sand employing natural kenaf fibers. To this end, two cement contents, four amounts of zeolite replacement of cement, and three fiber contents in three lengths were adapted in two relative compactions (RC) to investigate the compaction, 8-shape direct tensile strength (DTS), and indirect tensile strength (ITS) behaviors. Experimental efforts revealed that compaction behavior is sensitive to stabilizer contents and fiber content and length. The addition of the 8% cement, increase of the zeolite up to 50%, and fiber increment up to 1.5% led to the reduction of the compaction properties; however, optimum moisture content increased with the rise in kenaf fiber. A notable influence on the DTS and ITS behavior was observed while 30% zeolite replacement in 8%-cemented samples and reinforced with 1% kenaf fiber with 10mm length. Furthermore, a linear relationship was presented between DTS and ITS. In the end, the reinforced sample was analyzed using Scanning Electron Microscope (SEM) images.

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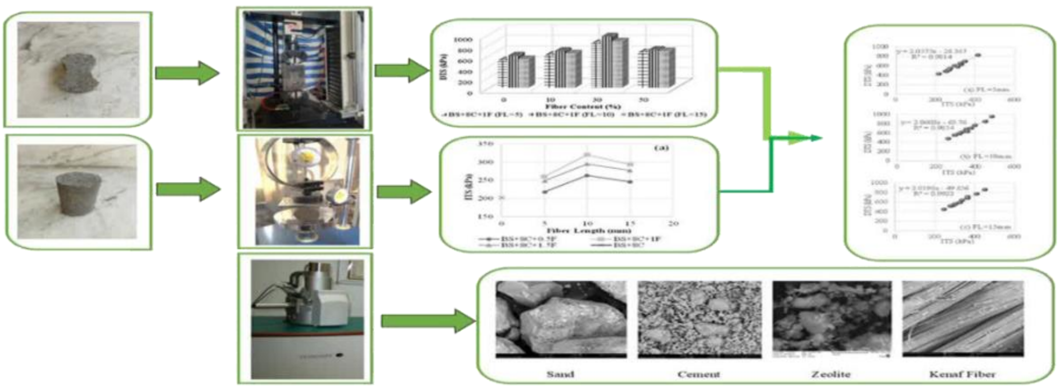
Graphical Abstract



*Corresponding Author Email: R_Shirinabadi@azad.ac.ir (R. Shirinabadi)

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1. INTRODUCTION

Due to population growth of many countries, suitable ground for construction is surprisingly decreasing. Therefore, every remaining local weak land may require to be prepared for constructional practices including building foundations, dams, pavements, excavations, and embankments. Loose sand is one of the problematic soils that, due to its poor cohesion, intensively challenges engineers in many regions, especially coastal areas (1, 2). Construction of various types of structures on these soils usually eventuates in different issues such as lack of shear strength, uneven settlements, foundation failures, internal and surface tunneling erosion, and liquefaction (2, 3).

The stabilization of weak soils through the employment of various additives has been implemented for decades (4). The effect of materials such as cement, lime, fly ash, polymers, resins, acids, and ions has been investigated by researchers for years (2). As one of the conventional and most prevalent soil stabilizers, numerous geotechnical researchers have justified cement to hand over many advantages, including higher strength and stiffenss, liquefaction resistance, lifespan increment, and curbing deformations (2, 5, 6).

Sariosseiri and Muhunthan (7) investigated the effect of cement on the engineering characteristics of several types of soils (sand, silt, and clay). They declared that addition of cement to the soil incremented the plasticity index (PI) at low cement content (about 2.5%); however, higher percentages of cement reduced that index leading to better workability than the base soil. The optimum water content increased by introducing cement to the soils while the maximum dry unit weight was reduced. Stabilization of these soil with cement highly enhanced the unconfined compression strength (UCS); however, leading to a more brittle failure than the base soils. Nguyen and Phan (8)reported that addition of the 8 to 10% cement notably improved the compressive strength, splitting tensile strength, and elastic modulus of stabilized fine-grade soil. Ghanbari et al. (9) stated that introducing cement to the peat soil developed UCS values, diminished strain related to the peak stress, and induced brittle behavior in the amended samples with the increase in curing time. Eme et al. (10) demonstrated that adding 5.5% cement along with 12% water content to the sand enhanced the California Bearing Ratio (CBR) and UCS of the stabilized samples up to 200% and 2500kPa, respectively.

Nevertheless, the cement production process is responsible for a massive amount of greenhouse gases released into the earth's atmosphere, including mainly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (11). Such an indication impelled the researchers to look for substitutions like supplementary cementitious materials (SCMs) that remained from industrial processes, agricultural practices or existed naturally (12-16) with pozzolanic inherent. Natural resources preservation, reduction of the adverse environmental effects of cement production, energy conservation, and also helping waste management are instances of the advantages that the employment of SCMs for cement replacement renders (6). Among those, zeolite as a natural pozzolan notably improves the strength of the cemented soil, reduces undesirable expansion, and decreases the porosity (17). MolaAbasi et al. (18) evaluated the feasibility of employing zeolite as an influential replacement for cement in stabilizing sand. They stated that the replacement of cement with zeolite reduced the UCS of the treated samples in early curing time (7 days). But surprisingly, up to 30% zeolite replacement remarkably enhanced the UCS of the samples in 28 and 90 days of curing time. In another study, MolaAbasi et al. (19)expressed that while 30% zeolite replacement in cemented sand, chemical components of SiO_2 and Al_2O_3 came into a balance with CaO, which resulted in the most desirable pozzolanic reaction, and consequently, the highest UCS and also the tensile strength at 28 days of curing. Kordnaeij et al. (20) evaluated the effect of water on cementitious materials (W/CM) and zeolite replacement on the UCS of the grouted loose sand. They perceived that in all W/CM, up to 30% zeolite replacement was the optimum amount. In an investigation of the cement-zeolite stabilized expansive clay, Ahmadi et al. (11) affirmed that an increase in zeolite replacement of cemented samples led to the decrement and increment of the maximum dry density (MDD) and optimum moisture content (OMC), respectively. They also revealed that raising zeolite replacement up to 30% induced the highest mechanical parameters such as UCS, stiffness (E50), and absorbed energy (AE) in treated samples. Khajeh et al. (21) stated that the incorporation of 30% zeolite replacement satisfyingly compensates the strength reduction caused by employing EPS beads in the cement treatment of loose sand. Another investigation of Khajeh et al. (22) disclosed that the substitution of lime by 25% zeolite resulted in attaining the highest UCS and unconsolidated undrained (UU) triaxial strength, and also the least PI of an amended clayey soil.

Considering the remarkable effectiveness of these cementitious materials on soils' geotechnical properties, they prompt abrupt strength reduction and hence, brittle failure under different types of loadings (23). To ameliorate the deficiencies of those additives, randomly distributed fibers have been investigated by researchers widely in the last several decades. It has been observed that syntactic or natural fiber-reinforced soils demonstrate more desirable engineering behavior like compressive, shear, tensile, strength, California Bearing Ratio (CBR), resistance against wet-dry and freeze-thaw cycles, decreasing the swelling potential, and more importantly, failure strain and flexural performance than unreinforced soils (3, 24-26). Since the production of synthetic fibers induces unfavorable effects on the environment, a promising prospect for pollution decrement is achievable through the adoption of natural fibers (27). These fibers represent acceptable reinforcing influence in addition to their biodegradability and economic availability (26).

Kenaf fiber, as one of the non-wood plant fibers, can be a possible choice for engineers as a reinforcement element of cemented mixtures giving out remarkable tensile strength, Young's modulus, and economical cost. Several investigations have been implemented on the influence of kenaf fiber addition on the engineering properties of different types of soils. Shirvani et al. (28) investigated the influence of the kenaf fiber and clay addition on the mechanical characteristics of sandy soil. Direct shear tests were implemented on the sand samples reinforced with different fiber content and clay. The results showed that 0.75% fiber inclusion with no clay content in the reinforced sample increased the fraction angle by about 13%. In addition, the sample containing 0.75% fiber and 15% clay additive showed a 15% cohesion improvement. Ghadakpour et al. (3) investigated the effect of kenaf fiber content and length on the geotechnical properties of cemented sand samples. The results evaluation indicated that the kenaf fiber reinforcement of cemented sand incremented the UCS, STS, absorbed energy, and reduced the brittle index, elasticity modulus, and ultrasonic pulse velocity.

In the current investigation, the influence of randomly distributed kenaf fiber on the mechanical behavior of cement-zeolite-stabilized sand was evaluated. To that end, standard proctor compaction tests were implemented on designated mixtures of 0%, and 8% cement, replacing cement with 0, 10, 30, and 50% zeolite, the addition of the kenaf fiber in 0, 0.5, 1, and 1.5% with the length of 0.5, 1 and 1.5mm. After that, to analyze the effect of kenaf content and length in the reinforcement effort, 8-shape DTS and ITS experiments were conducted on the samples prepared due to the designed mixtures mentioned earlier and the two relative compaction of 100% and 95%, cured for 28 days.

2. MATERIALS METHOD

2. 1. Materials The base soil (BS) used in this investigation program was a poorly-graded sand (SP) according to the United Soil Classification System (29) collected from the southern coastal regain of the Caspian Sea, Iran. The soil's physical characteristics were measured as presented in Table 1. The particle size distribution of the base sand can be seen in Figure 1.

The base stabilizer of this research opted to be the Portland cement type II. The cement's physical properties were presented by its production factory as demonstrated in Table 1.

The alternative stabilizer of this study was natural zeolite. The employed zeolite is a clinoptilolite type acquired from Semnan Province, Iran. It is a non-plastic material that in accordance with the Unified Soil Classification System (29), is classified as silt (ML) and its specific gravity (Gs) is presented in Table 1. Figure 1 illustrates the particle size analysis results of all three materials utilized in this research. The graphs were obtained in accordance with ASTM D422 (30).

TABLE 1. Specification of materials utilized in this study

Soil			
Maximum Unit Weight	1.58 kN/m^3	Minimum unit weight	1.27 kN/m^3
Uniformity Coefficient (C_U)	4.99	Mean Effective Diameter (D_{60})	2.18 mm
G_S	2.67	Coefficient of Curvature (C_C)	0.99
Cement			
G_S	3.11	Blaine	≥ 2800 (cm^2/g)
Autoclave Expansion	≤ 0.6 (%)	Initial Setting Time	≥ 120 min
Final Setting Time	3:30 (hr)		
Zeolite			
G_S	2.2		
Kenaf Fiber			
G_S	1.32	Diameter	$0.1<d<0.14$ mm
Water Absorption	≤ 2.2% by weight	Tensile Strength	365 MPa
Modulus of Elasticity	17.6 GPa		

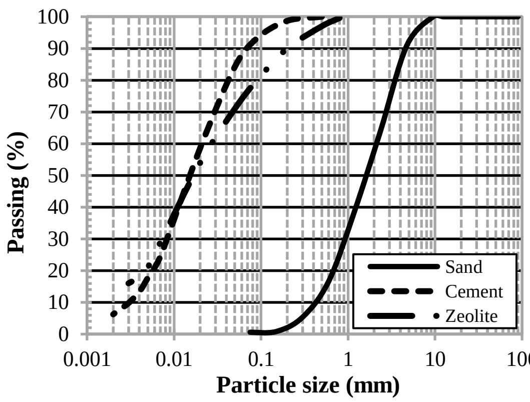


Figure 1. Particle size analysis of the base sand

The reinforcement element of the soil-stabilizer mixtures was determined to be the kenaf fiber. The utilized kenaf fibers had physical properties as presented in Table 1. The fibers were cut in three lengths of 5, 10, and 15 mm to be used for sample preparation.

2. 2. Sample Preparation To conduct experiments, 179 stabilized and reinforced cylindrical samples and 179 8-shaped ones were prepared for the DTS and ITS tests, respectively. The presented values are the average of two measurements. Two percentages of cement (C= 0 and 8%) were adopted as the base stabilizer, and four percentages of cement replacement with zeolite (Z= 0, 10, 30, and 50%) were employed as the pozzolanic alternative to substitute the cement. Kenaf fiber was randomly distributed to the samples in four percentages (F= 0, 0.5, 1, and 1.5%) with three lengths (L= 0.5, 1, and 1.5 mm).

All samples were prepared using the maximum dry density (MDD) and the optimum moisture content (OMC) achieved from the standard proctor compaction test of each designated additive content. The soil and stabilizers were mixed homogeneously, and then the water was added to the soil-stabilizer matrix. After blending the fiber with the mixture, 8-shape DTS samples were cast in an 8-shape metal mold with a thickness of 2.8cm, widest width of 4cm at both sides, middle width of 3cm, and length of 9cm. The ITS samples were also prepared in cylindrical PVC mold with a height of 10 cm a diameter of 5 cm, compacted in three equal layers using a steel rod for the target relative compaction of 95 and 100%. The top of each layer was sacrificed in order to prepare sufficient interlock between the layers. Afterward, samples were cured in sealed plastic bags for 28 at room temperature (21-24ºC) to evaluate the effect of a long curing period on the pozzolanic reaction.

2. 3. Experimental Procedure A series of various tests were implemented to evaluate the effect of different dosages of stabilizers and reinforcement elements on the geotechnical properties of the sandy soil. Standard proctor compaction tests were conducted according to ASTM D698 (31) to obtain the MDD and OMC of the soil-additive mixtures. Afterward, DTS tests were implemented on 8-shape samples in accordance with the reported data by Yao et al. (25). Figure 2a illustrates the direct tensile loading device used in this study. The ITS tests were carried out following ASTM D3967 (32). To do so, the cylindrical samples were positioned horizontally between two hard metal plates, and the load was applied until failure. Both types of loads were applied to the samples at the rate of 0.1mm/min. According to the mentioned standard, the ITS can be calculated as presented below:

$$q_t = \frac{2P}{\pi LD} \tag{1}$$

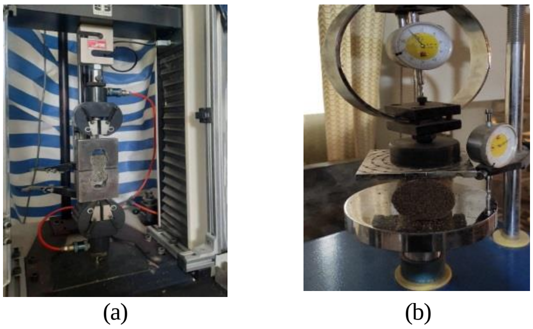
where qt = ITS (kPa), P = applied load at failure (kN), L = height of the cylindrical sample (m), and D = diameter of the sample (m). Figure 2(b) demonstrates the loading instrument employed for ITS tests.

Table 2 presented in the following demonstrates the nomenclature used in the figures of this article.

3. RESULTS AND DISCUSSION

3. 1. Compaction Tests To achieve the compaction characteristics of the soil-stabilizer-fiber mixtures, 54 standard proctor compaction tests were implemented on each designed combination. Figures 3, 4, and 5 demonstrate the alteration of MDD and OMC of the samples due to changes in several parameters such as fiber length, fiber content, cement content, and zeolite replacement. It can be deduced from all figures that fiber reinforcement of the base soil and the soil-stabilizer mixtures remarkably reduced the MDD and increased the OMC of the samples.

Figure 3 shows the change in MDD and OMC with respect to the variation of the fiber length and content for base soil, 8% cement-treated sand, and 30% zeolite-replaced-cemented sand as representatives. As shown, it can be perceived that the addition of fiber to the base soil notably decreased the MDD of the sample. Additionally, an increase in fiber content resulted in a severe reduction in MDD. Such an observation is consistent with the investigations of Santoni et al. (33), Tran et al. (34), and Mohamed (35). This behavior is due to the lower unit weight of the fiber than the soil when increment of fiber content reduces the number of soil particles. Nevertheless, such a fiber introduction and content



(a) (b)

Figure 2. Devices used for (a) DTS, and (b) ITS tests

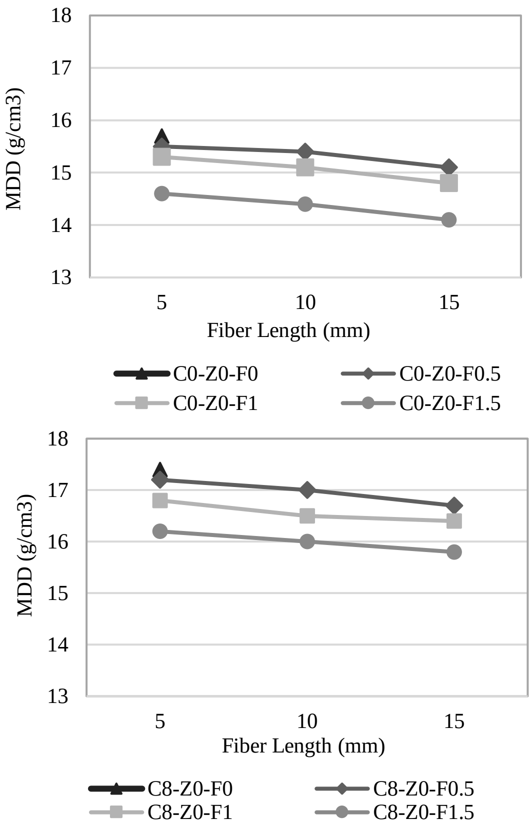
TABLE 2. The nomenclature used for additives of this study

Parameter	Percentage of Cement Content (%)	Percentage of Zeolite Replacement (%)	Percentage of Fiber Content (%)	length of Fiber (mm)
Abbreviation	C (number)	Z (number)	F (number)	F (number)
Example	C8	Z30	F1.5	F15

increment induced an opposite trend in the OMC of the samples, where it rose as the fiber content incremented. A similar trend is reported by Maity et al. (36) and Tran et al. (34) when reinforcing sand with natural fiber. It can be attributed to the water absorption of fibers. Figure 3 also revealed that the more the fibers' length increased, the more the MDD and OMC of the samples diminished. Prabakar and Sridhar (37) reported the same behavior of using sisal fiber as soil reinforcement. Analogous fashion was observed while adding different fiber percentages to the solely-cemented and also 30%-zeolite replaced samples.

Figure 4 illustrates the variation of MDD and OMC of the samples containing 1% fiber due to the change in fiber length and cement content. Analyzing this figure indicated that introducing 8% cement to the base and enhanced the MDD of the sample while decreasing trend of the OMC was observed. Lopez-querol et al. (38) also declared the same trend. Noteworthily, diminishing trends of MDD and OMC were detected when incrementing fiber lengths in samples with 1% fiber content. Such behaviors also were noticed in samples containing 0.5 and 1.5% fiber.

Figure 5 displays the alteration of the MDD and OMC of the 8%-cemented samples containing 1% fiber respecting the variation of zeolite replacement and fiber length. It can be perceived that in a specific fiber length,



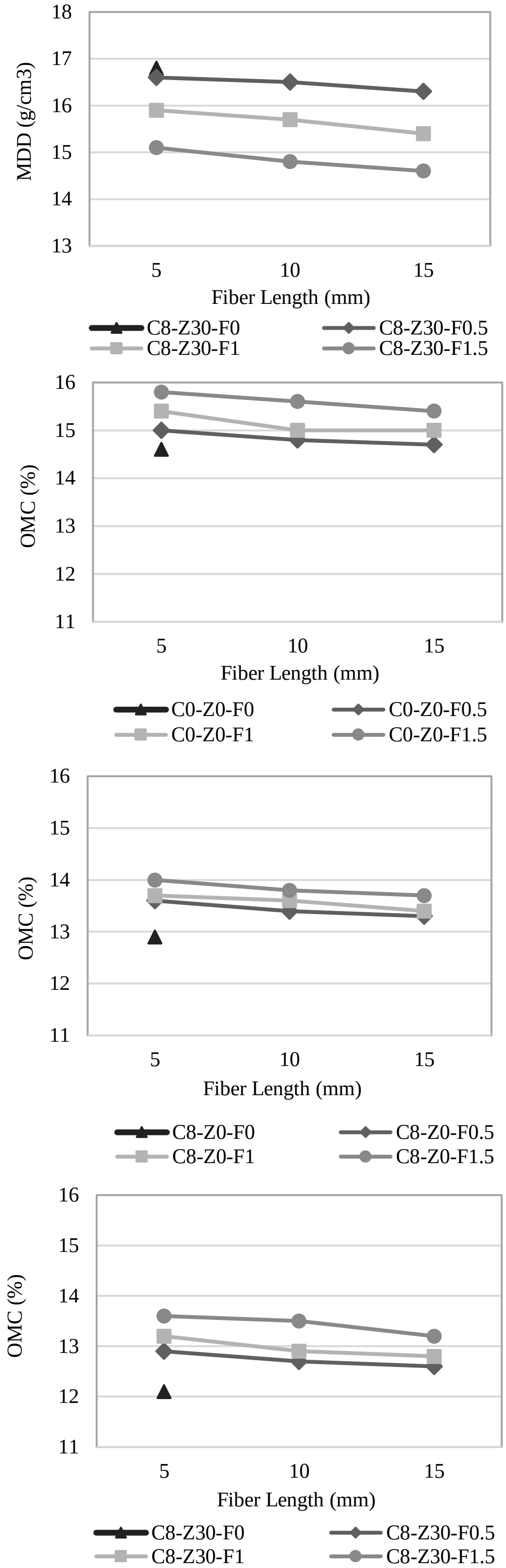


Figure 3. The alteration of MDD and OMC of the base soil, 8% cement-treated sand, and 30% zeolite-replaced-cemented sand due to the change in fiber length and content

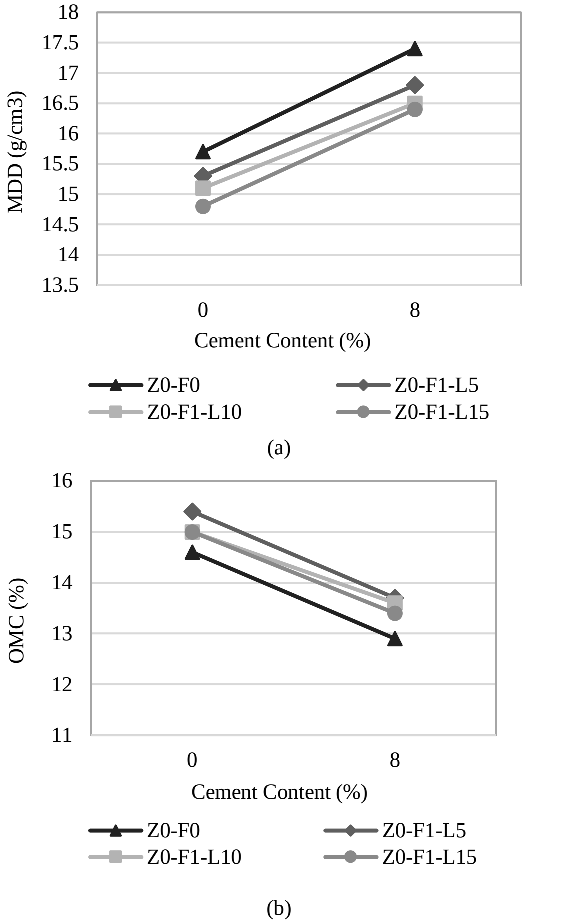


Figure 4. The alteration of MDD and OMC of the samples containing 1% fiber due to the change in cement content and fiber length

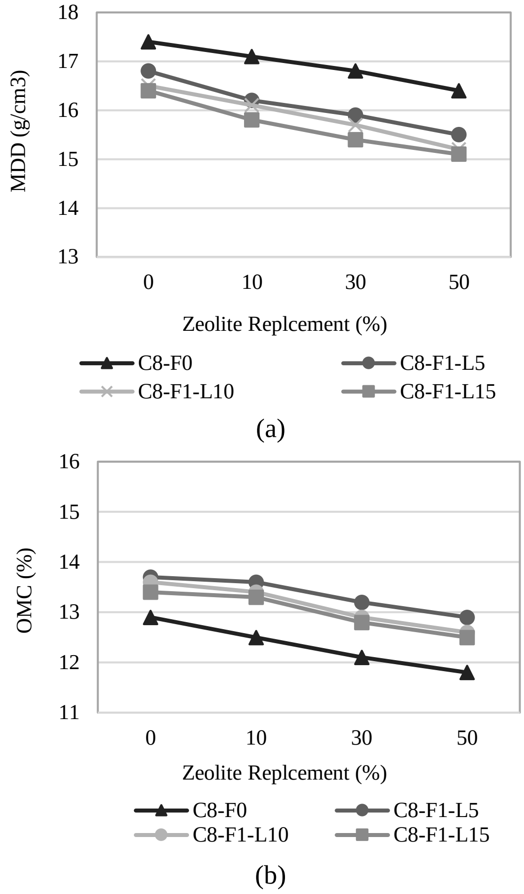


Figure 5. The alteration of MDD and OMC of the samples containing 1% fiber due to the change in zeolite replacement and fiber length

an increase in zeolite replacement led to the decrement of both MDD and OMC of the samples. Ahmadi et al. (11)observed analogous behavior in their research. The lower specific gravity of the zeolite than the cement prompted MDD reduction. In addition, larger particle size of the zeolite than cement decreased the OMC. Similar to what occurred earlier, in a specific zeolite replacement (in a single binder content), the increment of fiber length had a reducing effect on both the MDD and OMC of the samples.

3. 2. Direct Tensile Strength (DTS) Tables 3 and 4 present the conducted DTS test results of 8-shape samples with Rc=100% and Rc=95%, respectively, for 28 days of curing. The strength of each sample specified with the designated cement and fiber contents, zeolite replacement, and fiber length can be found in these tables. To demonstrate the alteration of DTS concerning the aforementioned parameters, several figures have been presented as representatives of the whole.

Figure 6 shows the change of DTS in the samples containing 8% cement, different zeolite replacements, and 10mm fiber length due to the variation of fiber length. It is perceivable that the introduction of kenaf fiber to the cement-treated sand in any amount effectively enhanced the DTS of the samples. The increment of fiber content from 0.5% to 1% led to a striking rise in the DTS of reinforced samples. The addition of fiber further to 1.5%, however, induced a deteriorating effect on the strength. Such trends were observed for added fibers with lengths of 5mm and 15mm. The behavior noticed at 1% fiber content could be ascribed to the optimum interaction of fibers, sand, and cementitious materials, which could not be achieved in the other fiber content statements. Yao et al. (25) reported 1% polyvinyl alcohol fiber content as the percentage resulting in the maximum DTS of silty soil.

Figure 7(a) and (b) illustrate the DTS variation of the samples treated with 8% cement, 0%, and 30% zeolite replacements for different fiber contents due to the change in fiber length. As can be seen, an increase in fiber

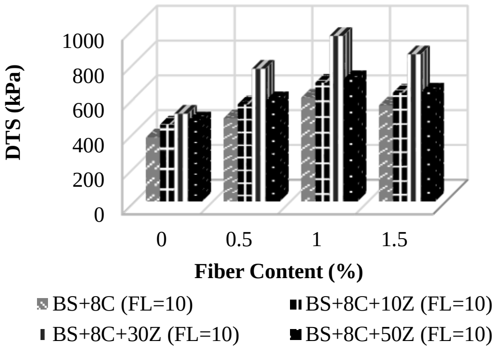


Figure 6. The alteration DTS of the samples containing 8% cement and different zeolite replacement due to the change in fiber content

TABLE 3. The UCS tests results of the samples with Rc=100% cured for 28 days

28 curing days			DTS (kPa)				
F.C (%)	F.L (mm)	%C	0	8			
		%Z	0	0	10	30	50
0	0		23.4	368.2	441.8	504.3	466.2
	5		27.6	430.2	486.5	630.7	513
0.5	10		35.8	477.5	557.8	763	582.5
	15		34.2	449.2	519.1	711.8	563.9
	5		36.7	508	605.6	828	654.2
1	10		44.1	596.5	682.9	951.4	703.5
	15		40.4	530.3	636.3	860.4	680.1
	5		31.5	485.7	548.1	695.2	582.1
1.5	10		39.9	551.7	625.3	845.9	631.5
	15		35	513.9	550.8	770.1	590.4

TABLE 4. The UCS tests results of the samples with Rc=95% cured for 28 days

28 curing days			DTS (kPa)				
F.C (%)	F.L (mm)	%C	0	8			
		%Z	0	0	10	30	50
0	0		20.4	311.2	385.6	446.3	415.4
	5		24	353.9	431	532.8	446.1
0.5	10		32.8	404.2	515.8	662.7	522.8
	15		28.5	382	451.2	602	450.4
	5		33.6	467.1	525.6	671.4	522.6
1	10		38.9	536.1	602.4	777.3	641
	15		35.2	480.2	540.3	730.9	567.2
	5		28.7	406.4	495.1	621.4	484.3
1.5	10		35.1	503	561.4	736	570.9
	15		31.9	450.1	512.6	645.2	521.5

length from 5mm to 10mm remarkably improved the DTS of the cement-treated samples and with 30% zeolite replacement ones. But a further increase from 10mm to 15mm reduced the DTS of the samples. Nevertheless, samples containing 15mm fibers showed a higher DTS than the 5mm ones. Similar behavior was observed for zeolite replacements. Such an enhancement at reinforced samples with 10mm fibers can be attributed to the better distribution condition and hence, better interaction of the sand and cementitious materia along the body of the fiber. The fiber length of 10mm was also reported as optimum by Li et al. (39) while the addition of syntactic fiber for soil reinforcement.

Figure 8 indicates the variation of DTS in the samples containing 8% cement and 1% fiber content at three specified fiber lengths concerning the change in zeolite replacement. As can be deduced, in each specific fiber length, zeolite replacement induced an enhancing effect on the DTS of the reinforced samples. The rise of zeolite replacement from 10% up to 30% prompted an increment in DTS to the highest level and any further increase of zeolite replacement up to 50% resulted in a detrimental effect on DTS compared with 30%. Cement triggers a chemical reaction called hydration, as the water is added to the mixture, which has two main products. The cementitious material that emerges when the hydration reaction is calcium-silicate-hydrate (C-S-H) gel and the

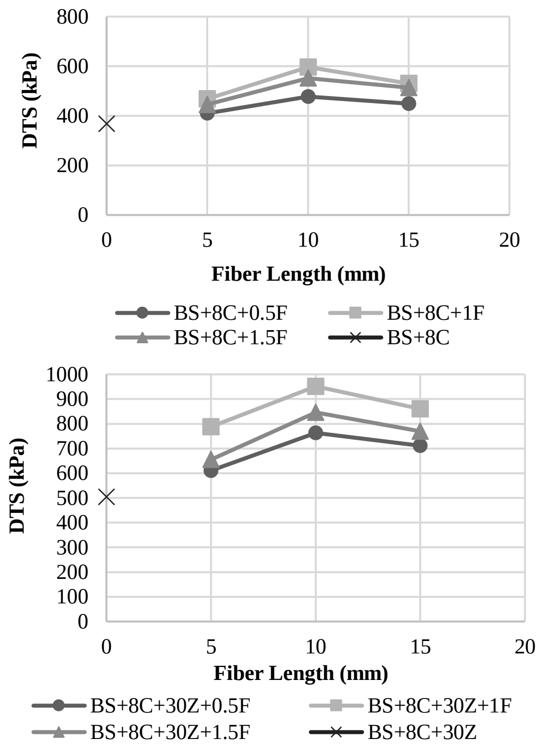


Figure 7. The alteration DTS of the samples containing 8% cement due to the change in fiber length for (a) 0%, and (b) 30% zeolite replacement

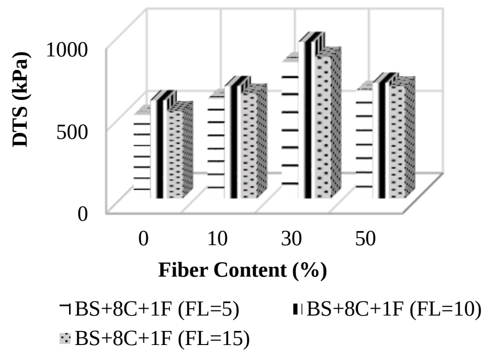


Figure 8. The alteration DTS of the samples containing 8% cement and 1% fiber content at different fiber lengths due to the change in zeolite replacement

other by-product is calcium hydroxide ($Ca(OH)_2$). When cement gets replaced by zeolite, SiO_2 and Al_2O_3 offered by zeolite react with $Ca(OH)_2$ (pozzolanic reaction) and produce more C-S-H gel (11). The reason that 30% zeolite replacement handed the best strength performance is that the amount of $Ca(OH)_2$, SiO_2, and Al_2O_3 came into a balanced situation, leading to the optimum pozzolanic reaction.

3. 3. Indirect Tensile Strength (ITS) Tables 5 and 6 represent the ITS of the cement-zeolite-stabilized and also reinforced samples cured for 28 days and cast in two RC of 100% and 95%, respectively. Using these Tables, the exact value of each test according to the stabilizers' dosages, kenaf fiber content, and fiber length can be determined. In the following, several graphs have been presented to elucidate the changing trend of the ITS values due to the existing variable.

Figure 9 shows the ITS alteration of the samples containing 8% cement with different proportion of zeolite as cement replacement along with changes of fiber content.

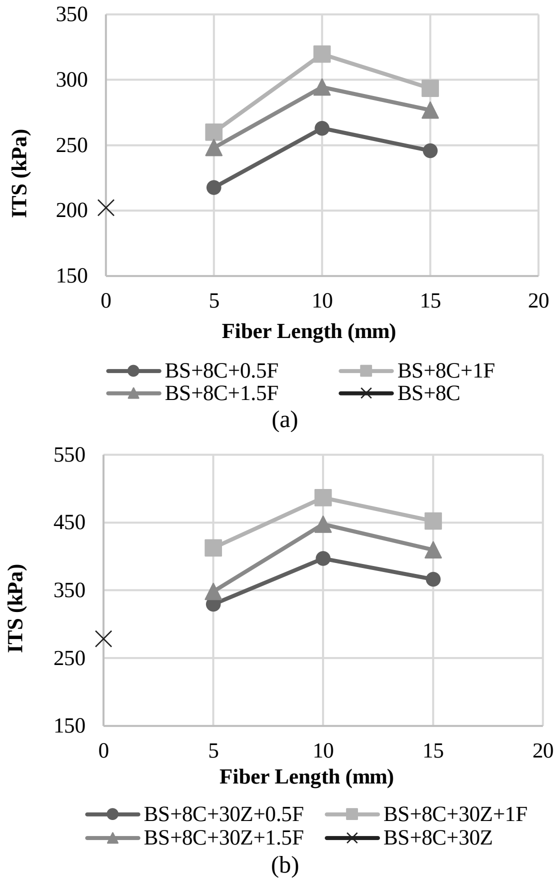


Figure 10. The alteration ITS of the samples containing 8% cement due to the change in fiber length for a) 0%, and b) 30% zeolite replacement

Figure 10 shows the ITS alteration of the samples containing 8% cement with different fiber length for 0% and 30% zeolite as cement.

Figure 11 depicts the ITS alteration of the samples containing 8% cement and 1% fiber at different fiber lengths for the variation of zeolite as cement replacement.

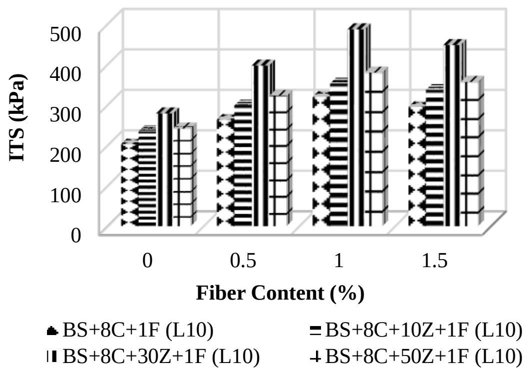


Figure 9. The alteration ITS of the samples containing 8% cement and different zeolite replacement due to the change in fiber content

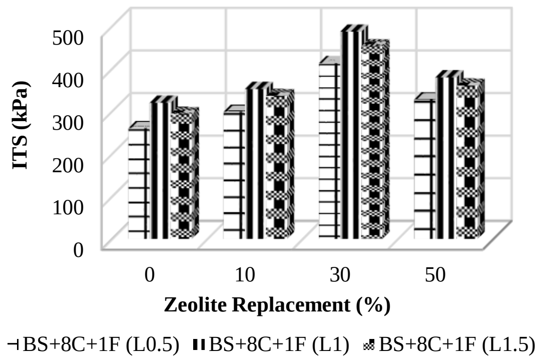


Figure 11. The alteration ITS of the samples containing 8% cement and 1% fiber content at different fiber lengths due to the change in zeolite replacement

TABLE 5. ITS tests results of the samples with Rc=100% cured for 28 days

F (%)	L (mm)	%C	0	8			
		%Z	0	0	10	30	50
0	0		13.2	202.2	233.7	278.6	241.2
	5		15.6	217.7	258.7	329.4	267.4
0.5	10		20.1	263	297.8	396.9	321.3
	15		18.9	245.8	279.3	366.1	303.2
	5		21.1	260	298.4	412.6	327.5
1	10		25.3	319.6	352.1	486.6	379.3
	15		22.8	293.4	335.6	452	359.9
	5		17.7	248.1	272.9	348.3	310.8
1.5	10		23.1	294.4	336.3	447.6	356.3
	15		21.7	276.8	300.6	409.6	326.2

TABLE 6. ITS tests results of the samples with Rc=100% cured for 28 days

F (%)	L (mm)	%C	0	8			
		%Z	0	0	10	30	50
0	0		12.1	178.2	219.3	262.1	235.8
	5		14.3	192.7	242.3	305.7	247.4
0.5	10		18.5	239.9	293.2	373	301.5
	15		17.2	219.3	262.6	348.1	283
	5		20.1	241.3	287.4	360.8	300.5
1	10		24	310.2	347.2	460	364.3
	15		21	276.7	314.9	426.4	330.2
	5		16.8	214.7	266.4	338.3	282.5
1.5	10		21.1	288	321	415.9	334.1
	15		19.7	261.7	296.4	380.5	313.9

Analyzing Figure 12 reveals that in a single fiber length, for example, 10mm, ITS enhanced remarkably with direct addition of fiber and incrementing it up to 1%. The reason is attributed to the better performance of fibers at this content, presenting the best distribution in the mixture, hence, the optimum interaction between cemented particles and fibers. Further increase in fiber content negatively affected the ITS of the reinforcement samples, which is a direct consequence of inappropriate distribution and flocculation of the fibers while mixing. Such behavior was observable in samples reinforced with other fiber contents. However, the effect of fibers on ITS was more pronounced in 1% fiber content. Analogous fashion has been reported by Rabab'ah et al. (40), reinforcing clay with glass fibers.

Figure 13(a) and (b) demonstrate the change in ITS of the samples stabilized with 8% cement and also having 30% of cement replaced with zeolite, respectively, for all fiber contents due to the variation of fiber length. These figures have been chosen as representatives of all samples since similar trends were observed for other series. It can be deduced from Figure 13(a) that in 8% of cemented samples, increasing the fiber length up to 10mm induced an increasing behavior of the ITS resulting in the peak tensile strength in reinforced samples. For the addition of fibers longer than 10mm up to 15mm, a reduction of the ITS was noticed; however, the ITS values were still larger than the ones for samples reinforced with 5mm fibers. Such a trend was noticed by Yang et al. (41) when using polypropylene fiber to reinforce loess.

Figure 14 demonstrates the alteration of ITS against the change in zeolite replacement considering samples reinforced with 1% fiber. It is transparent that conducting zeolite replacement and increases up to 30% improved

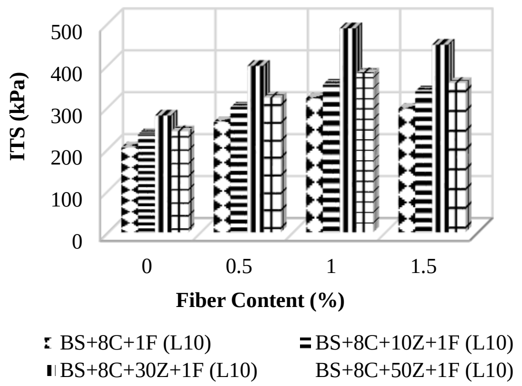
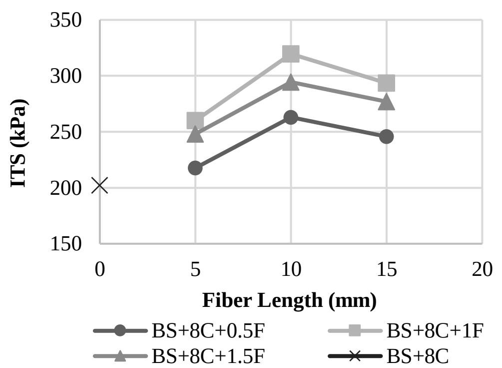
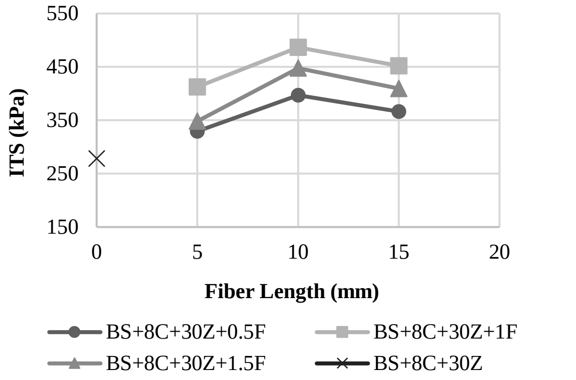


Figure 12. The alteration ITS of the samples containing 8% cement and different zeolite replacement due to the change in fiber content



(a)



(b)

Figure 13. The alteration ITS of the samples containing 8% cement due to the change in fiber length for a) 0%, and b) 30% zeolite replacement

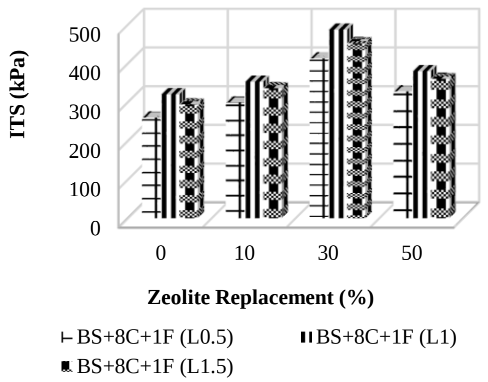


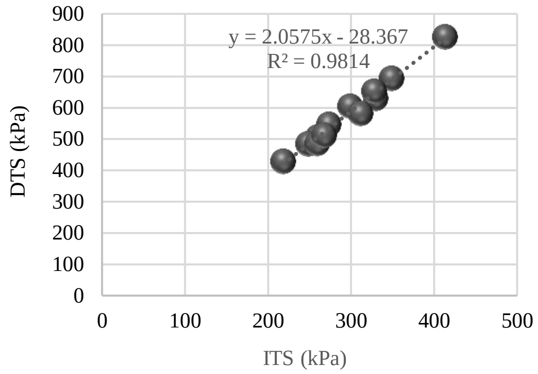
Figure 14. The alteration ITS of the samples containing 8% cement and 1% fiber content at different fiber lengths due to the change in zeolite replacement

the ITS substantially. For further zeolite replacement up to 50%, an STS-reducing fashion was distinguished. The improvement of ITS is attributed to the pozzolanic reaction intensified at 28 days of curing, resulting in more C-S-H gel rather than only-cemented samples (42).

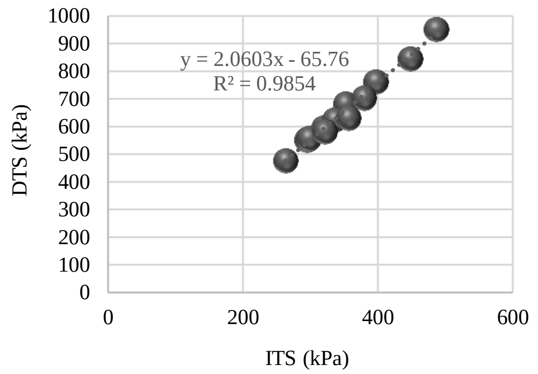
3. RELATIONSHIP BETWEEN DTS AND ITS

3. 1. Linear Regression A few relationships have yet to be presented by researchers correlating DTS to the ITS of the fiber-reinforced soils (43). In this section, the results of 80 DTS and 80 ITS tests conducted on samples stabilized with 8% cement, 0, 10, 30, and 50% zeolite replacement, and also the ones reinforced with 0.5, 1, and 1.5% kenaf fiber in three lengths of 5, 10, and 15mm were considered. Half of the samples were cast with RC=100% and the other half with RC=95%, and all samples were cured for 28 days. Conducting linear regression, the results of these tests demonstrated that linear relationships with acceptable correlation coefficients equal to R^2=0.9814, 0.9923, and 0.9923 for FL=5mm, FL=10mm, and FL=15mm, respectively, are definable for samples with RC=100% and to R^2=0.9598, 0.9895, and 0.985 for FL=5mm, FL=10mm, and FL=15mm, respectively, can be presented for RC=95%. The functions and the coefficient of correlations are presented in Figure 15. Evaluating these figures can reveal that the ITS alters with the same trend in which DTS changes irrelevant to the stabilizers and reinforcing elements.

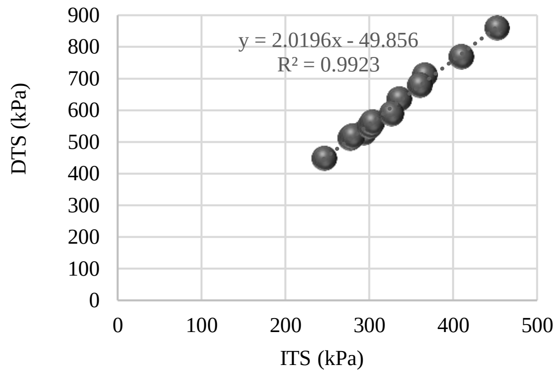
The significance of the ITS on changes in DTS values was investigated employing an ANOVA analysis of variance in Microsoft Excel area; the results are shown in



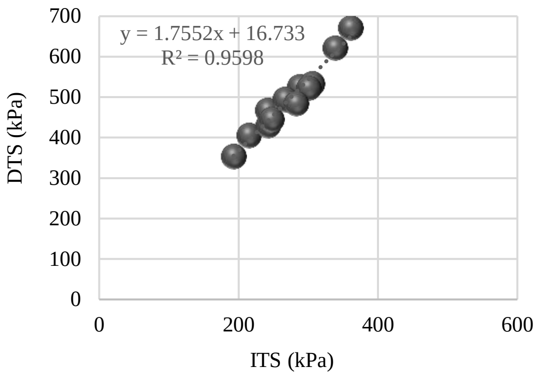
(a) FL=5mm



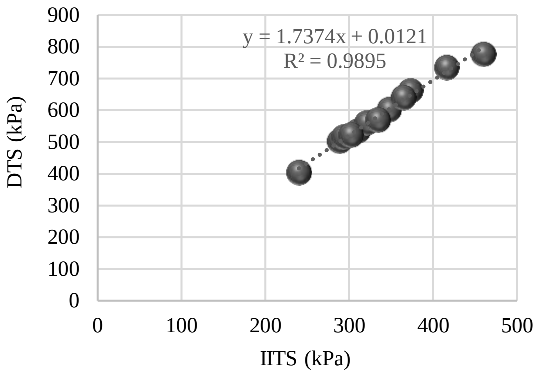
(b) FL=10mm



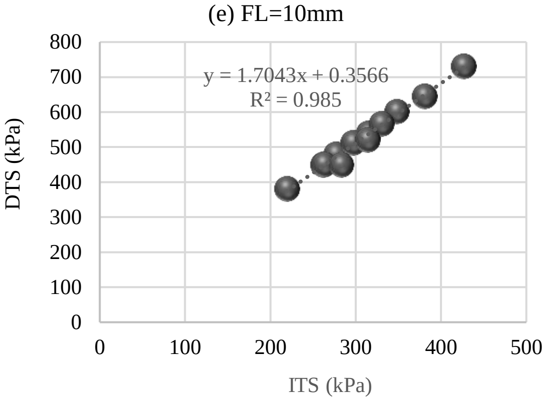
(c) FL=15mm



(d) FL=5mm



(e) FL=10mm



(f) FL=15mm

Figure 15. Correlation between DTS and ITS of the cement-zeolite-stabilized samples reinforced with kenaf fiber at (a),(b), and (c) for Rc=100%, and (d), (e), and (f) for RC=95%

Table 7. When the corresponding p-value is lower than 5%, it can be stated with 95% confidence that the observed alteration is due to the different levels of the investigated factor and not just a random error that happens through the test's implementations. This is when a factor's influence is typically accounted for significantly. According to the findings of this study as presented in Table 7, the alteration of investigated DTS values was significantly in relation to ITS values (with p-values very much lower than 5%). Therefore, the

TABLE 7. P-values of the equations presented in Figure 14-b

Equation	a	b	c	d	e	f
p-value	$5.58E^{-10}$	$1.64E^{-10}$	$6.67E^{-12}$	$2.61E^{-08}$	$3.10E^{-11}$	$1.91E^{-10}$

presented relationships are statistically significant and it can be stated that the DTS alters in a definable relationship with ITS.

4. MICROSTRUCTURAL ANALYSIS

In this study, Scanning Electron Microscope (SEM) images were utilized to investigate the soil microstructure of stabilized samples, as well as stabilized fiber-reinforced samples at the optimal amount of binder and fiber content. Investigating the microstructural behavior of soil dominates in understanding the behavior of soil since the shear strength of soil mass is transferred from the contact surface of its solid elements. In fact, the weakest area in the limiting factors of soil resistance is the transition area (empty spaces between solid elements).

According to the type of binders and reinforcing elements employed in soil stabilization, the resistance of the transition areas may be higher than the base soil mass. During the hydration reaction, at the beginning of the processing time, the size of the voids is large and the transfer areas have a larger volume, which causes the sample to show a lower resistance. However, with time, the hydration reaction products diminish the volume of these areas. Also, hydration reaction products are generally more resistant than the soil mass. Production of new binding materials in transition areas is from the reaction of the cement and zeolite, which leads to the formation of the calcium-silicate-hydrate gel.

To demonstrate the alteration happening after soil stabilization and also reinforcement, a failed sample's picture is illustrated in Figure 16, and the pure image of the solid constituents of the samples is depicted in Figure 17. In addition, the microstructural view of the optimally-stabilized samples without and with kenaf fiber is illustrated in Figure 18 considering the sand sample images in Figures 17 and 18. It is perceivable that adding cement and zeolite resulted in the formation of binding gel and the reduction of the transition areas.

In the images of Figure 19, it is clearly displayed that the fiber is imbedded between sand and cementitious material and has a proper interaction with them on the failure surface. Due to having a relatively significant tensile strength, the fibers have been stretched but not torn, and this has a great contribution to the cohesion of the particles at the moment of rupture, keeping the particles interlocked and increasing the tensile and shear strength. As can be seen in Figure 20 (a), after the indirect

Figure 16. A fractured 8-shaped sample tested in this investigation

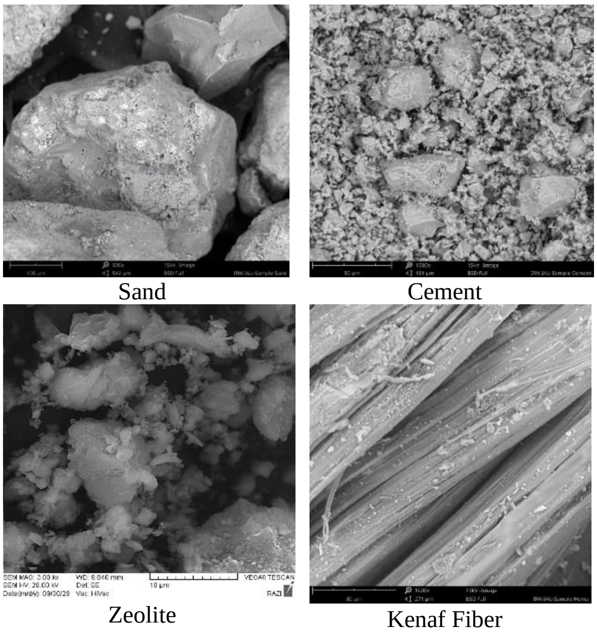
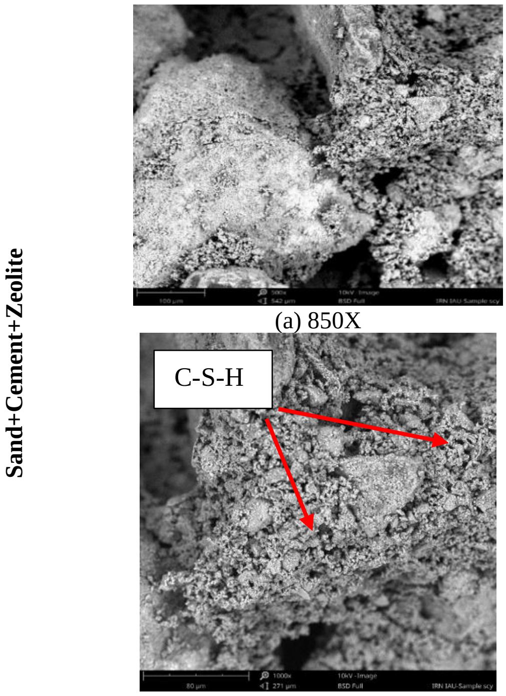


Figure 17. The SEM view of the materials used in this study

tensile test, it was observed that the unreinforced samples have wider cracks from the fractured cross-section, which are caused by the force applied in the direction of sample failure and the joining of microcracks with each other. However, Figure 20 (b) demonstrates that the fibers help uniformity of the samples and fewer cracks appeared.

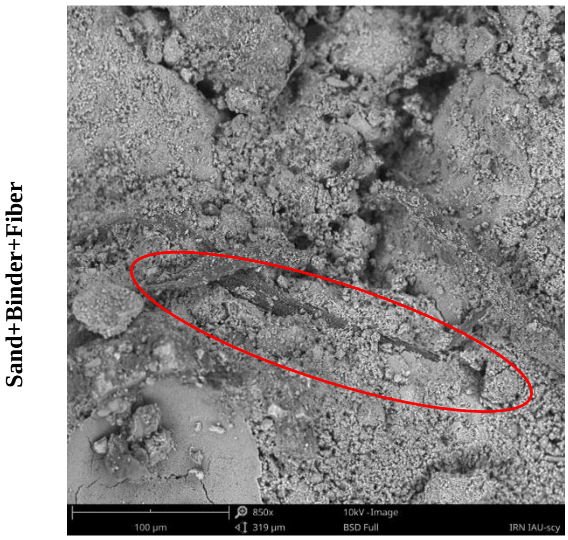
Microcracks form at the transition zone of the aggregate-paste. Brittle materials, such as friable soil, fail through crack propagation, which ultimately joins together to create arrays of continuous fracture surfaces, and the deformation commences to intensify along with that. Loose particles may exist on the surface, and a fracture surface represents a weak plane through the cementitious paste rather than material failure. Additionally, the mobilized shear strength can be lower than the fully softened shear strength along the failure surface. Meanwhile, the bonding strength between cemented matrix and fiber constrains the occurrence and development of microcracks all over the matrix, curbing the creation of macrocracks, and the peak tensile strength happens at higher strain deformation. The occurrence of microcracks induces an abrupt breakage of unreinforced specimens, while the fiber addition in the specimen, on the other hand, has a significant influence on the post-cracking behavior.



(a) 850X

(b)1700X

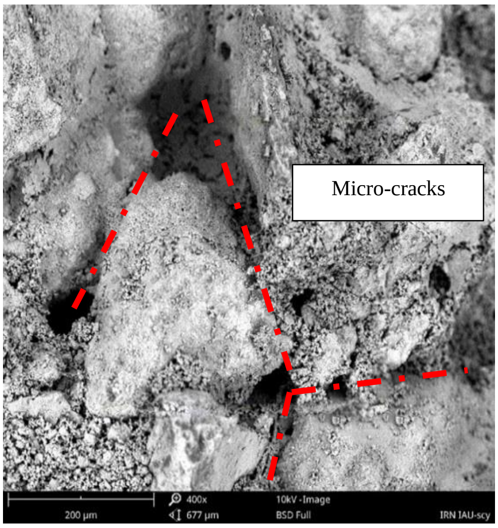
Figure 18. Microstructural view of the stabilized samples without and with kenaf fiber



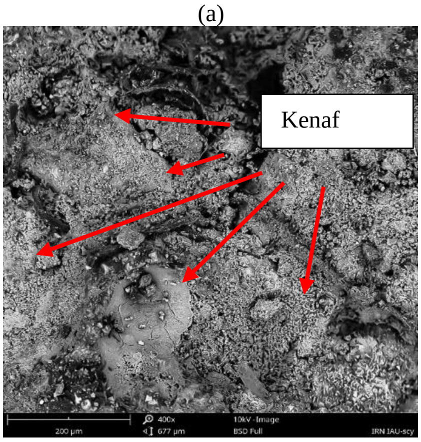
(c) 850X

(d) 1700X

Figure 19. Microstructural view of the stabilized samples with kenaf fiber



(a)



(b)

Figure 20. Micro-cracks created during failure, and (b) Kenaf fiber interaction with cementitious materials in the reinforced sample

5. CONCLUSIONS

The aim of this study is to investigate the effect of kenaf fiber on the mechanical behavior of sand, such as compaction, direct tensile strength (DTS), and indirect tensile strength (ITS). To this end, laboratory experiments were conducted on various mixtures of cement, zeolite, kenaf fiber, and sand, and their results are presented in the following:

- Increasing the fiber content diminished the MDD; on the other hand, it raised the OMC of the mixture.
- The increment in fiber length resulted in the reduction of the MDD and OMC of the mixtures.
- Cement addition increased the MDD and decreased OMC of the mixtures.
- Conducting zeolite replacement reduced the MDD and OMC of the reinforced mixtures.
- Adding kenaf fiber up to 1% resulted in the highest DTS and ITS of the fiber-reinforced samples. Further fiber addition negatively influenced the mentioned parameters compared to the samples with 1% kenaf fiber content.
- Fibers with a length of 10mm resulted in the highest DTS and ITS of the reinforced samples.
- Zeolite replacement of up to 30% resulted in the best DTS and ITS performance of the reinforced samples in comparison with the only-cement-stabilized fiber-reinforced samples. However, further zeolite replacement induced a weakening effect on the mentioned parameters.
- A linear relationship was presented correlating DTS to ITS with acceptable accuracy.
- Through SEM images, it was shown that kenaf fibers properly helped keeping the uniformity of the samples and diminished the transition areas.

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Persian Abstract

چکیده

مقابله با خاک های مشکل‌دار یکی از چالش‌برانگیزترین بخش‌های شغلی مهندسان ژئوتکنیک است. یکی از آنها ماسه سست با چسبندگی کم است و در سرتاسر جهان به ویژه در مناطق ساحلی یافت می‌شود. تثبیت‌کننده‌های شیمیایی مانند سیمان از جمله موارد رایج در میان مهندسان برای مقابله با نقاط ضعف ماسه سست هستند. با این‌حال، جایگزینی این تثبیت‌کننده‌های سنتی با مواد پوزولانی مانند زئولیت طبیعی تایید شده است زیرا به کاهش مصرف سیمان و در نتیجه کاهش انتشار CO2 کمک می‌کند. با وجود تمام مزایا، رفتار شکننده پیامد ناخوشایند این تثبیت‌کننده‌ها است. بنابراین، هدف از این مطالعه کاهش شکنندگی ماسه تثبیت‌شده با سیمان–زئولیت با استفاده از الیاف کناف طبیعی است. برای این منظور، دو مقدار سیمان، چهار مقدار سیمان جایگزین‌شده با زئولیت، و سه مقدار الیاف در سه طول در دو تراکم نسبی خاک (Rc) برای بررسی تراکم، مقاومت کششی مستقیم 8–شکل (DTS) و کشش غیرمستقیم تطبیق داده شد. رفتارهای قدرتی (ITS) تلاش‌های تجربی نشان داد که رفتار تراکم به محتویات پایدارکننده و محتوای فیبر و طول حساس است. افزودن ۸ درصد سیمان، افزایش زئولیت تا ۵۰ درصد و افزایش الیاف تا ۱.۵ درصد منجر به کاهش خواص تراکم شد. با این حال، رطوبت بهینه با افزایش فیبر کناف افزایش یافت. تأثیر قابل‌توجهی بر رفتار DTS و ITS در حالی که ۳۰ درصد جایگزینی زئولیت در نمونه‌های سیمانی ۸ درصد و تقویت شده با ۱ درصد الیاف کناف با طول ۱۰ میلی‌متر مشاهده شد. علاوه بر این، یک رابطه خطی بین DTS و ITS ارائه شد. در پایان، نمونه تقویت شده با استفاده از تصاویر میکروسکوپ الکترونی روبشی (SEM) مورد تجزیه و تحلیل قرار گرفت.