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Effect of soil overburden pressure on mechanical properties of carbon FRP strips

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Abstract. Carbon fiber reinforced polymers (CFRPs) have been recently investigated as an alternative material for Geosynthetics to improve soil properties. One of the factors influencing the fiber orientation and mechanical properties of CFRP is the effect of soil overburden pressure. This study investigates the tensile behavior of cast-in-place CFRP. During the curing time of specimens, a wide range of normal stress is applied on specimens sandwiched between the soils. Two different soil types are used to determine the effect of soil grain size on the mechanical properties of CFRP. Specimens are also prepared with different specifications such as curing time and mixing soil in to the epoxy. In this study, tensile tests are conducted to investigate the effect of such parameters on tensile behavior of CFRP. The experimental results indicate that by increasing the normal stress and soil grain size, the ultimate tensile strength and the corresponding strain of CFRP decrease; however, reduction in elastic modulus is not noticeable. It should be noted that, increasing the curing period of epoxy resin and mixing soil in to the epoxy have no significant effect on the tensile properties of CFRP.

Keywords: epoxy resin; geosynthetics; CFRP; soil reinforcement; tensile strength; normal stress

1. Introduction

Soil is one of the oldest construction materials due to its wide applications and great availability in nature. In spite of many advantages, it has many weaknesses such as low tensile and shear strength. Therefore, various methods have been applied to address these shortcomings during the past decades. Soil reinforcement method is used as an effective and successful technique for strengthening and improving the soil. Consequently, materials such as steel and polymers have been used to reinforce soil. This reinforcing improves soils specifications such as drainage, filtration, increasing durability, resistance and decreasing the cost of construction projects (Koerner 1998). However, such materials have significant problems such as creep, low tensile strength, modulus of elasticity and durability. Fiber reinforced polymers (FRP) can solve such flaws by replacing geotextile, geogrid or steel belts in soil.

The development and scientific usage of FRP composites has begun from 1940 (Gibson 1994), initially used for military and aerospace purposes. Nowadays, civil engineers use FRP in construction designs (Ballinger 1990, Triantafillou*et al.* 2001, Wang*et al.* 2015, Ghasemi*et al.* 2015, Saribiyikand Caglar 2016). However, FRP composites are used in few Geotechnical engineering fields their behavior in soil is limited. Advantages of using FRP in geotechnical engineering can be categorized as, high specific strength and modulus, resistance against corrosion, simpler production line and reduction of labor costs. FRP have linear elastic behavior until failure, and all types of its fibers have higher capacity of bearing the stress than steel (Jewell 1980).

Saadatmanesh *et al.* (2010) studied the long-term behavior of different types of FRP. The specimens were exposed to different environments. Uniaxial tension tests were performed on the specimens after 6000, 12,000, and 20,000 hours of exposure; and tensile properties were measured for each specimen. The results indicated that CFRP in an acidic environment (pH=2.5), loses approximately 10% of its strength after 20,000 hours; however, steel will dissolve in such an environment. In an alkaline environment (pH=12.5), CFRP approximately loses 5% of its strength after 20,000 hours; while fiber glass loses 60% of its strength. Narvon *et al.* (2011) by making FRP sample in different temperature conditions (ranging between -15 and +70°C) and doing tensile stress tests on them indicated that different temperature conditions have low influence on elastic modulus and ultimate strain. Toufigh *et al.* (2013) studied the Behavior of FRP bonded to steel under freeze thaw cycles.

Frost and Han (1999) investigated the interface behavior of fiber-reinforced polymer and sand using direct shear test. Based on this investigation, the interface shear behavior between FRP composites and granular materials depends on the relative roughness, normal stress level, and initial density of soil mass, angularity of particles. Conversely, the rate of shearing, thickness of the soil specimen and soil

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Table 1 Mechanical properties of soils

Description	Standard	Fine soil	Coarse soil
Natural water content (W)	ASTM D2216-10	0.0%	0.0%
W opt	ASTM D698- 12	15%	18%
Soil gravity (Gs).	ASTM C128- 12	2.64	2.73
Minimum of void ratio.	ASTM D698- 12	0.6	0.6
Maximum of void ratio	ASTM D2216-10	0.64	0.64
D10	ASTM D422- 07	120 μm	600 μm
D30	ASTM D422-07	220 μm	1300 μm
D60	ASTM D422-07	410 μm	2200 μm
Uniformity coefficient(Cu)	ASTM D422-07	3.4	3.7
Curvature coefficient(Cc)	ASTM D422-07	1	1.35
Angle of internal friction	ASTM D3080-11	35	0.0
Cohesion coefficient	ASTM D3080-11	0.0	16.40 kN/m^3
Maximum dry density	ASTM D698-12	16.18 kN/m^3	15.95 kN/m^3

specimen preparation method has low effect on the interface friction coefficients.

Toufigh *et al.* (2013) studied the interface behavior of CFRP-sand and fine sand by using pull-out test. They reported that increasing the normal stress during the curing time increases the interface friction angle between sand and CFRP-Sand by approximately 20%. A range of 25 to 100 kPa normal stress was used in this research. Based on these results, the cast-in-place CFRP-sand specimens provide higher pull-out resistance than precast specimens under low normal pressure Later, Toufigh *et al.* (2013) investigated the interface properties of the CFRP and backfill soil, experimentally using the cyclic multi-degree-of-freedom (CMDOF) device. A range of 17.5 to 1050 kPa normal stress was applied. Based on results, the friction angle between CFRP with soil on the surface and backfill soil is 44.68°, and without soil on the surface, it decreases to 41.45°. In the other research, Desai and El-Hoseiny (2005) reported that the interface friction angle between Tensar SR2 and backfill must be 34°. Then, constitutive model was used to characterize the behavior of the interface between the CFRP and backfill soil. Javid (2011) by laboratory studies on the behavior interface soil and FRP stated that ratio of soil and FRP-sand interface friction angle to soil friction angle is more than 1/2. This amount represents the high friction between soil and FRP-sand.

An experimental and modeling study of the interface behavior between carbon/glass FRP bar/strip and sand was carried out by Zhang *et al.* (2014) using pull-out test. The results reveal that the GFRP reinforcement has a more non-linear and non-uniform distribution of interface shear stress as compared to CFRP and steel reinforcements. Furthermore, the differences in elastic modulus and interface shear coefficient influence the pull-out performances.

In the previous researches, the initial normal stress was studied as an impact factor in the interface behavior.

Table 2 Physical properties of fiber

Description	Properties
Fiber thickness (mm)	0.166
Fiber strength (MPa)	4900
Fiber stiffness (GPa)	230
Weight per unit area of woven fiber (gr/m2)	300

Accordingly, during curing process normal stress causes the epoxy to permeate in the soil voids. Then, the epoxy sticks soil particles to carbon fibers resulting in a rough surface. However, this normal stress enhances the interface behavior but it can change orientation of fibers: which leads to destructive effects on tensile properties of carbon fibers.

CFRP is a new material for reinforcing soil which can be used instead of geosynthetics and geotextiles. The main goal of this research is to investigate the effect of the normal stress on the tensile properties of CFRP. For this purpose, different normal stresses (0, 50, 100, 200 and 400 kPa) were applied during the curing time. After curing the specimens, tensile strength, corresponding strain and elastic modulus of all specimens were determined by tensile test. CFRP specimens were also prepared with different specifications such as soil type (fine and curse soil), curing time and mixing soil in to epoxy resin. It should be noted that normal stress throughout the paper is referred to normal stress applied at curing time of epoxy.

2. Test materials

Main materials used in this study are as follow:

2.1 Soil

The soils used in this study are quicksand and washed sand. Soils are classified as SP and GP according to the Unified Soil Classification (USCS). Sieve gradation was operated according to ASTM-D422-2007. The mechanical properties of soils and their relevant ASTM standard test methods are given in Table 1.

2.2 Carbon fiber reinforced polymer

In this study, unidirectional carbon fiber with a density of 300 gr/m^2 was used. Carbon fibers were saturated with epoxy resin. Epoxy resin was used to bind fibers together, and transmit a uniformly distributed stress to fibers. It also protects fibers against physical damage and chemical attack (Fib 2001 and Sika 2013). The physical properties of carbon fiber are shown in Table 2.

3. Testing program

Effects of various parameters on the tensile strength of CFRP sheets which have been evaluated are as follows:

- Normal stress applied during the curing time of CFRP specimens
- Soil particle size

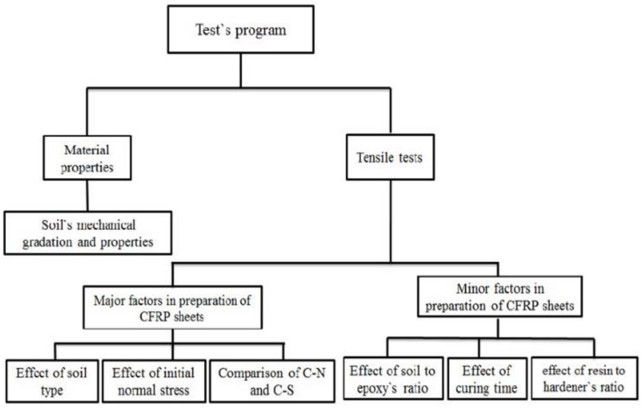


Fig. 1 Chart of testing program

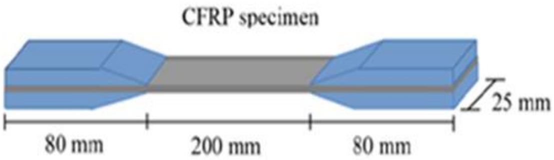


Fig. 3 Specimens dimension and geometry (mm)

- The mixing ratio of resin and hardener
- Curing of epoxy in presence of soil
- Curing time of the specimens

Fig. 1 illustrates the test program of this study.

3.1 Testing equipment

A Zoeik Universal Testing Machine (UTM) was used in this research to determine the mechanical properties of CFRP as shown in Figs. 2(a)-(b).

3.2 Testing conditions

ASTM-D3039 standard was used to determine tensile properties of CFRP sheets. Tensile tests were done in a room temperature, with displacement control by the rate of 0.033 mm/s. In order to increase the accuracy of results, five specimens were tested in each individual condition.

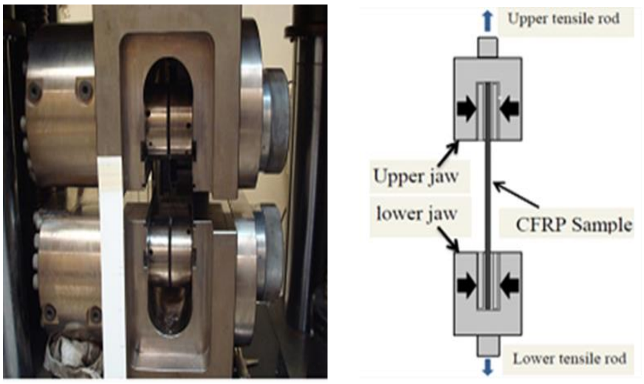
3.3 Specimens geometry

Specimen's dimensions according to ASTM-D3039 are shown in Fig. 3.

4. Specimen preparation

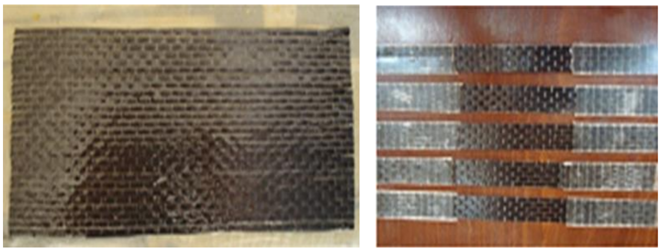
Three types of specimens are categorized below:
- CFRP sheets with no soil (C-N; case1)
- CFRP sheets covered with fine grain soil on top and bottom (C-S1; case 2)
- CFRP sheets covered with coarse grain soil on top and bottom (C-S2; case 3).

4.1 Epoxy preparation methods



(a) Grips on the UTM (b) Schematic pictures

Fig. 2 Performing FRP on the universal testing machine



(a) Before cutting (b) After cutting

Fig. 4 Preparation of C-N sheets

Epoxy is generally obtained by mixing resin and hardener with ratio of 2:1 (except for section 6.4 where effect of this ratio is investigated) (Toufigh *et al*. 2016, Toufigh *et al*. 2013 and Toufigh *et al*. 2013). These substances were mixed for three minutes and then fibers were saturated by epoxy resin.

4.2 Preparation methods of C-N specimens

Carbon fiber sheets with dimensions of 150 mm × 360 mm were saturated with epoxy resin. Initial normal stresses (σ=0, 50, 100, 200 and 400 kPa) were applied on the socked fibers, placed between two steel plates for 48 hours. CFRP sheets were cut to 25 mm×360 mm strips according to ASTM D3039 (Figs. 4(a)-(b)). Shi *et al*. (2014) investigated the tensile behavior of FRP. They acted in a similar way to prepare and cutting samples.

4.3 Preparation methods of C-S1 specimens

First, a steel box with dimensions of 370 mm×160 mm×40 mm was filled with 2 cm height of loose and dry, fine-grained soil (Fig. 5).

Then, saturated fiber sheets were placed on the soil. The remaining volume of the box was filled by the same soil. Different initial normal stresses (σ=50, 100, 200 and 400 kPa) were applied to each specimen by steel ingots for 48 hours. Finally, prepared laminates (C-S1) were cut to 360 mm×25 mm dimensions as shown in Figs. 6(a)-(b), (total of 20 specimens).

4.4 Preparation methods of C-S2 specimens

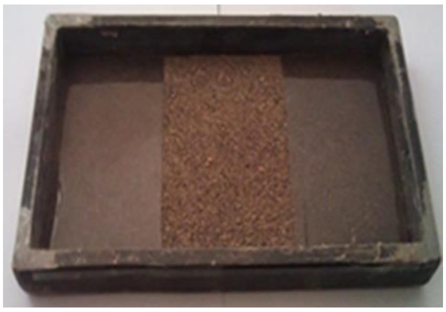
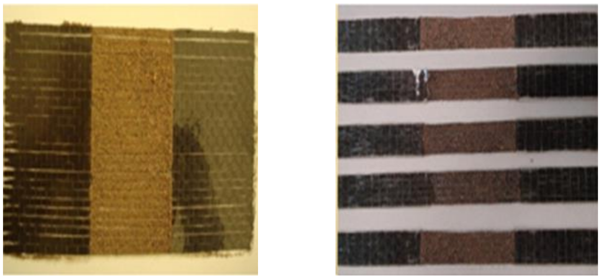


Fig. 5Test box filled with 2-cm of soil



(a) Before cutting (b) After cutting

Fig. 6 Preparation of C-S1 sheets

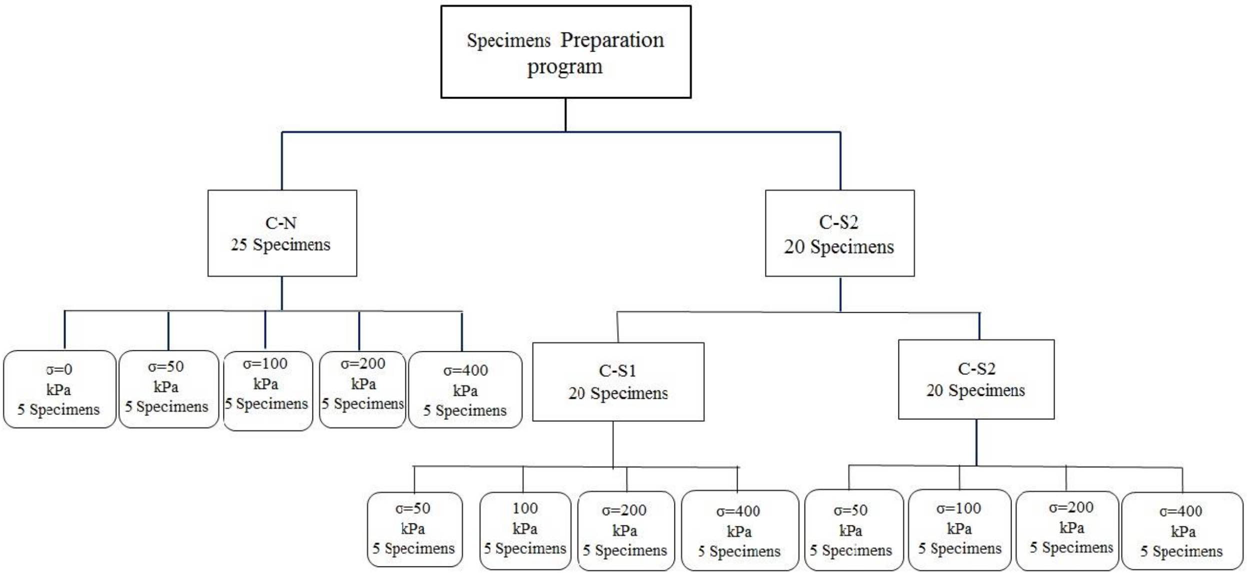


Fig. 7 Specimen preparation char

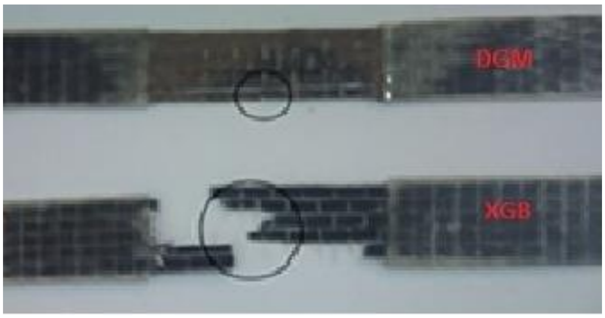


Fig. 8 Failure mode of specimens

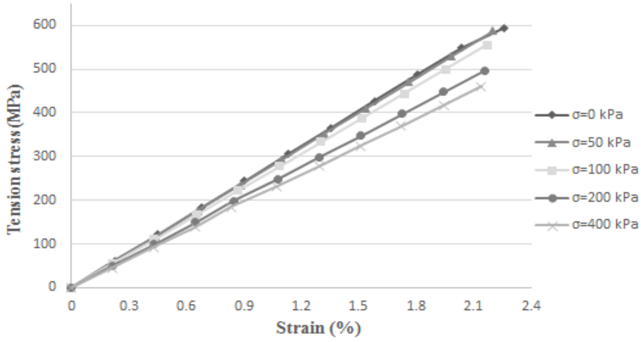


Fig. 9 Stress-Strain relation for C-N specimens under different normal stresses

All the aforementioned steps were repeated except coarse soil used instead of fine soil. A summary of the specimen preparation procedure is shown in Fig. 7.

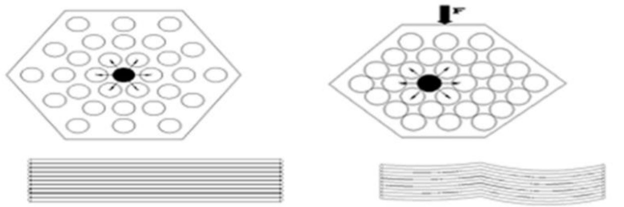
5. Determining the failure mode

The mode and location of failure of the specimens are provided in Fig. 8 according to ASTM D3039. The first character (*D* and *X* stand for edge Delamination and eXplosive respectively) represents the failure type, the second character (*G* for Gage) represents the failure area and the third character (*B* and *M* stand for Bottom and Middle, respectively) represents the failure location.

6. Experimental results and discussion

Various factors in preparation phases may change the mechanical properties of CFRP. Effect of these factors was investigated in this research. Average results for C-N, C-S1 and C-S2 specimens are shown in Tables 3 to 5, respectively. These tables represent a collection of ultimate tensile strength ($F_{T.U}$), corresponding tensile strain ($\varepsilon_{T.U}$), elastic modulus (E) and dominant failure mod.

6.1 The effect of the normal stress on mechanical properties of CFRP specimens



(a) Before applying normal stress (b) After applying normal stress

Fig. 10 Fiber arrangement and orientation

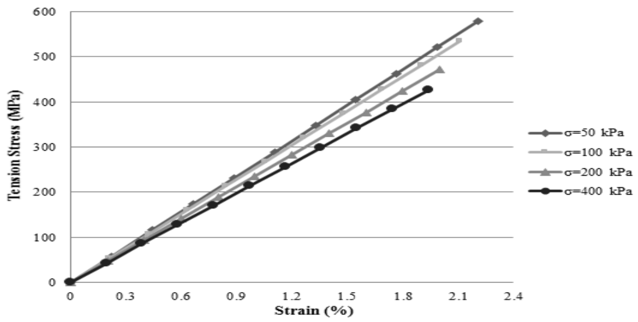


Fig. 11 Stress-Strain relation for C-S1 specimens under different normal stresses

Table 3 Average results for C-N specimens

	σ (kPa)	$F_{T.U}$ (MPa)	CV *(%)	Reduction in tensile strength (%)	$\varepsilon_{T.U}$	CV (%)	Dominant failure mod
C-N	0	594	2.2	0	2.26	2.8	XGB
	50	587	1.9	1.18	2.2	4.5	DGM
	100	555	4.2	6.6	2.17	11.2	DGM
	200	497	4.7	16.32	2.16	7.5	DGM
	400	460	4.8	22.55	2.14	6.6	DGM

*Coefficient of variation

To study the effect of normal stress on the mechanical properties of CFRP, 25 C-N specimens were tested with UTM. Average results and stress-strain relation with different initial normal stresses are shown in Table 3 and Fig. 9, respectively.

According to Fig. 9 by increasing normal stress, reduction in mechanical properties such as the ultimate tensile strength and ultimate strain can be inferred. However, at normal stresses between 0 to 50 kPa, there is no significant effect on the elastic modulus. At higher normal stresses, as normal stresses increase, the elastic modulus decreases.

The main reason for this reduction based on the observation can be explained as:

• Increasing the initial normal stress on CFRP can disturb the performance of epoxy resin; therefore, it cannot bind fibers together and transmit a uniformly distributed stress to fibers.

• Initial normal stresses distort fiber layers. That causes weakness in fiber's performance (Figs. 10(a)-(b)).

Similarly, for the 20 C-S1 specimens, stress-strain diagram for four various loadings (σ=50, 100, 200 and 400 kPa) is plotted in Fig. 11. Table 4 shows average tensile strength and corresponding strain of C-S1 for each loading.It should be noted that by increasing the normal stress in C-S1 specimens, the tensile strength and ultimate strain decrease. The elastic modulus is the same as part C-N.

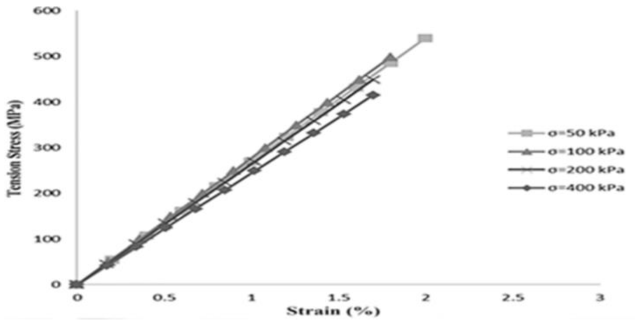


Fig. 12 Stress-Strain relation for C-S2 specimens under different normal stresses

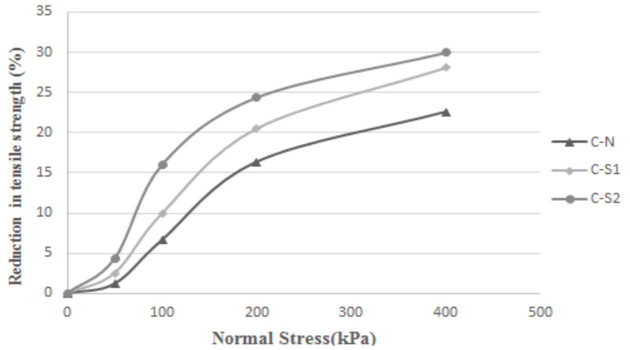


Fig. 13 Normal Stress-Reduction in tensile strength

Table 4 Average results for C-S1 specimens

	σ (kPa)	$F_{T.U}$ (MPa)	CV (%)	Reduction in tensile strength (%)	$\varepsilon_{T.U}$	CV (%)	Dominant failure mod
C-S1	50	579	1.3	2.5	2.21	3.5	DGM
	100	535	6.3	9.93	2.11	8.6	DGM
	200	472	14.6	20.5	2	6.1	DGM
	400	427	5.6	28.1	1.94	5.8	DGM

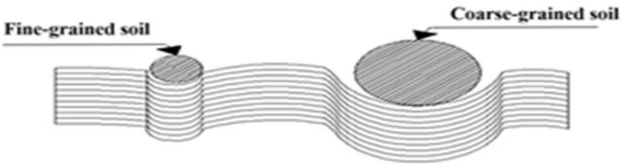
Table 5 Average results for C-S2 specimens

	σ (kPa)	$F_{T.U}$ (MPa)	CV (%)	Reduction in tensile strength (%)	$\varepsilon_{T.U}$	CV (%)	Dominant failure mod
C-S2	50	568.4	2.53	4.3	2.06	2.1	DGM
	100	499	2.5	16	1.8	8.6	DGM
	200	449	4	24.4	1.76	8.1	DGM
	400	415	2.2	30	1.76	5.9	DGM

The effect of the normal stress on mechanical properties of C-S2 is similar to C-S1 specimens. These results are shown in Table 5 and Fig. 12. It can be noticed that by increasing normal stress, the tensile strength and the corresponding strain decrease. The elastic modulus of C-S2 is the same as part C-N.

The effect of soil particle's diameter on the tensile strength for all specimens is shown in Fig. 13 (form 0 kPa normal stress of C-N). Based on these results, it can be inferred that by applying normal stress of 50 kPa on C-N,

(a) Before applying normal stress



(b) After applying normal stress

Fig. 14 Schematic shape of fiber’s orientation

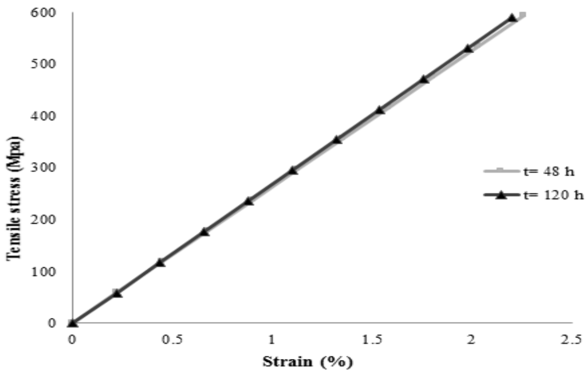


Fig. 15Stress-Strain relations for CFRP specimens under the effect of curing time

C-S1 and C-S2 specimens the tensile strength decreases about 1.2%, 2.5% and 4.3%, respectively. By applying 100 kPa normal stress on C-N, C-S1 and C-S2 specimens, the tensile strength decreases about 6.6%, 9.9% and 16%, respectively. Similarly, by applying 200 kPa normal stress on C-N, C-S1 and C-S2 specimens, the tensile strength decreases about 16.3%, 20.5 % and 24.4%, respectively. By applying 400 kPa normal stress on C-N, C-S1 and C-S2 specimens, the tensile strength decreases about 23%, 28% and 30% respectively.

The results also indicate that the degradation for C-S2 specimen is even more considerable because larger diameter of soil particles initiates larger penetration in fiber structures as shown in Figs. 14(a)-(b). Therefore, the reduction in tensile strength is significant.

6.2 The effects of the curing time and mixing ratio of soil / epoxy

The curing time of epoxy may affect the tensile properties of CFRP. 10 specimens were prepared and tested, after two set of curing time 48 and 120 hours (each set includes five specimens). These periods of time are required until a sufficient number of polymer chains are formed. However, the results show no significant change in tensile strength. CFRP specimens that have been prepared for 48 hours, acquired satisfying strength. Fig. 15 shows the average results of stress-strain relation with curing time of 48 and 120 hours.

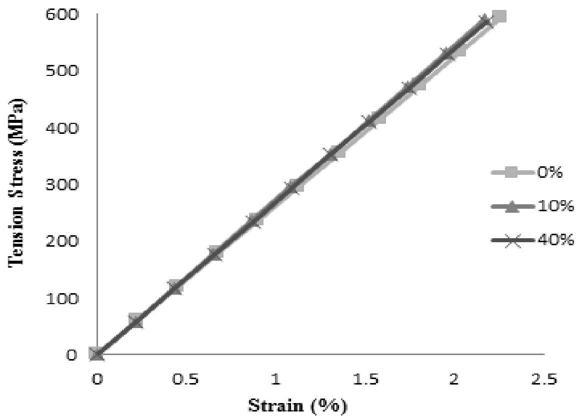


Fig. 16 Stress-Strain relations for CFRP specimens under the different mixing ratio of Soil in Epoxy

Generally, mixing soil and epoxy then making FRP specimens with this mixture can lead to profound effect on interface friction angle of soil and FRP (Toufigh 2012). However, it may cause detrimental effect on mechanical properties of FRP composites. To investigate this effect, three series of specimens were prepared by adding fine-grained soil equal to 0%, 10% and 40% of epoxy’s weight. Then specimens were tested similar to the previous parts. Based on the obtained results, increasing ratio of soil to epoxy has no significant effect on the tensile strength (less than 1%) as show in Fig. 16. Therefore, such reduction can be neglected.

7. Conclusions

In this research, the effect of soil and the normal stress on the mechanical properties of CFRP composites is studied; therefore, a comprehensive series of tensile tests were performed. The following conclusions are the results of this study:

- Results for C-N specimens indicate that by increasing the normal stress during the curing time, fiber orientation changes and the tensile strength decreases.
- Elastic modulus is subjected to a minor reduction, while normal stress is increased.
- Soil’s existence and increasing of its particles size (C-S1 and C-S2) cause negative effects on the tensile strength of CFRP. It means, the tensile strength reduction in C-S1 and C-S2 is more considerable.
- Increasing the curing time of epoxy resin and mixing soil in to epoxy have no significant effect on the tensile properties of CFRP.
- Based on the obtained results, increasing ratio of soil to epoxy has no significant effect on the tensile strength (less than 1%).

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