

Strength of silty soil treated with cement and reinforced with plastic bottle waste under conventional and wetting-drying conditions

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Article

Keywords

Silty soil
Cement treatment
Water bottle waste
Durability
Compressive and tensile strength

Abstract

This research aims to study the engineering properties of silty soil reinforced with plastic waste fiber (PWF) extruded from water plastic bottles. Other reinforced soil samples have been treated with cement, except for control samples (untreated soil samples). Curing time, length and percentage of fiber are the variables studied in this research. Lab testing results show that adding plastic waste fiber to the silty soil helps to increase the unconfined compressive strength, indirect tensile strength and punching-tensile strength. The results of soil samples treated with 4% cement show that all strength values have increased significantly. These properties also increase with the increase in the curing time. The increase in strength values of natural soil samples compared with cement-treated samples was (91.7 kPa to 1800 kPa), (6.1 kPa to 312 kPa) and (12 kPa to 371 kPa) for the unconfined compressive, indirect tensile and punching-tensile strength for 28 days of curing time. Regarding the effect of wetting-drying cycles on the strength properties, the results show that the natural soil samples fall apart immediately after being soaked in water. However, the results for samples reinforced with plastic waste fiber, treated with 4% cement and cured for 28 days show that the unconfined compressive, indirect tensile and punching-tensile strength decrease with the wetting-drying cycle from (2500 kPa to 1000 kPa), (435 kPa to 189 kPa) and (580 kPa to 448 kPa), respectively.

1. Introduction

The integrity of the roads and pavement structures constructed on weak soil (like silty soil) can easily be affected, due to the low strength and bearing capacity, poor durability, and large deformation (Sagidullina et al., 2022). The problems accompanied by this type of soil are more exacerbated upon wetting, causing greater challenges to geotechnical engineers (Wang et al., 2016; Soldo & Miletic, 2022). The high costs of using good-quality soils in construction have necessitated to use of the local soil in its original location after improvement. However, silty soils with high water content and low strength pose difficulties for construction projects. Various construction engineers are currently forced to build foundations on such soil. The negative effects of weak soil offer no choice other than rejection, replacement excavation, or dumping soil (Alkiki et al., 2021).

Using natural ground with silty or sandy soil for engineering construction purposes requires ground enhancement techniques like soil reinforcement and soil stabilization (Consoli et al., 2017a;

Chenari et al., 2018; Almajed et al., 2021; Yusof et al., 2023). Most of the soils have an acceptable shear strength, good compressive strength, and poor tensile strength (Aldaood et al., 2020). To overcome the weakness in the tensile strength, fiber could be used. The reinforcement within the soil is closely related to the interfacial shear resistance between the fiber and the soil at the interface, which is influenced by four main factors as indicated in (Gelder & Fowmes, 2016). These factors are friction, bond strength, matrix suction, and interface morphologies. These factors, in turn, depend on the moisture content and dry density, as well as the shape and size of the fibers. These factors can act individually or collectively depending on the characteristics of both the fibers and the soil. The presence of fibers among the soil particles forms bridges that transfer the applied forces to the soil particles. Additionally, the fibers help achieve a balance of forces within the soil structure by transferring loads from weaker levels to stronger levels, thereby increasing the shear and tensile resistance of the soil, which is accompanied by an increase in the corresponding strain values of those forces.

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Fiber inclusion in soils brings numerous technical, economic and environmental benefits (Menezes et al., 2019; Hou et al., 2020; Abu Taiyab et al., 2022). In many regions worldwide, PWM use has generated environmental and disposal problems. The use of PWM in engineering construction can resolve disposal problems in an environmentally friendly and cost-effective manner. Peddaiah et al. (2018) mentioned that there is a significant increase in the California bearing ratio and the shear strength parameters of soil samples reinforced with the plastic waste of water bottles. The percentages of enhancement in the soil strengths are ruled by the quantity of these waste materials and their dimensions. Hassan et al. (2021) mentioned that the presence of plastic waste fibers extruded from water bottles improved the compressive strength and CBR results. Further, the greatest values were obtained at 4% fiber with a length of 20 mm. The size of fibers related to soil particle size plays a main role in governing how well the fibers can reinforce the soil. Michalowski (1997) mentioned in his study that to achieve the best interaction between soil and fibers, the fiber length should be no less than one order of magnitude of the sand grains in the soil model used. Therefore, as the length of the fiber increases, resistance also increases up to a certain point, after which it decreases.

Although the PWM addition enhanced the strength properties of soils, their properties are still weak against some of the environmental conditions, like wetting-drying cycles. Thus, chemical stabilization methods using chemical agents (like cement, lime, fly ash, etc.) represent the most important methods to enhance durability and increase soil stability under wetting-drying cycles (Aldaoood et al., 2014; Consoli et al., 2017b; Qureshi et al., 2017; Alkiki et al., 2023). Cement stabilization is widely used for engineering construction purposes, resulting in bearing capacity increase for the soil and enabling a reduction in the pavement layers' thickness. Sariosseiri & Muhunthan (2009) examined the impact of cement percentages (from 2.5% to 10%) on soil engineering properties. The results showed that the engineering properties of cement-treated soils depend not only on the amount of cement but also on the physical and chemical soil properties. Raftari et al. (2014) found that the increment of the cement content led to an increase in the UCS of the improved soil, and it also caused the water content to decrease after curing. Other studies related to the combined effect of fibers and cement illustrate their positive influence on the geotechnical properties of soils (Jassim, 2017; Aldaoood et al., 2021).

It is worth noting that, depending on the nature of the chemical agent used in the treatment, the geotechnical properties of treated soil are mainly affected by the environmental conditions due to cyclic wetting-drying (W-D) (Ashraf et al., 2018; Consoli et al., 2018; Aryal & Kolay, 2020). The variations in soil moisture during seasonal changes cause many geotechnical problems like settlement, cracking and other failures in the soil. According to Stoltz et al. (2014), variations in the engineering properties of soils are attributed to the progressive accretion of permanent strains upon sequential

W-D cycles. The extreme weather in Iraq makes the durability performance of soils under W-D cycles a serious concern. Thus, studying the behavior of cemented reinforced soils in Mosul City under W-D cycles is important. This study aims to evaluate the cement treatment on some engineering properties of silty soil reinforced with plastic waste fiber content (PWF). The durability of cemented reinforced silty soil under W-D cycles was also assessed. The influences of PWF length and percent on the strength properties of natural soil samples were considered. Further, the variations in strength properties of reinforced soil samples before and after W-D cycles were adopted. Loss in weight, pH and electrical conductivity during wetting-drying cycles were also determined.

2. Materials

Three types of materials were used in experimental tests. These materials were silty soil, cement, and plastic waste fiber (PWF). The silty soil samples were collected from a site near Khawaja Khalil regain in Mosul city. The natural soil was a non-plastic soil, with a specific gravity of 2.67% and an organic matter content of 1.37%. The soil consists of 10% gravel, 29% sand, 49% silt, and 12% clay. Based on the grain size analysis and the unified soil classification system, the silty soil was classified as low plasticity silt (ML). The ordinary Portland cement used as a cementing agent in this study was mainly composed of 53.64% tricalcium silicate (C_3S), 18.59% dicalcium silicate (C_2S), 8.58% tricalcium aluminate (C_3A) and 7.92% tetra-calcium aluminoferrite (C_4AF). PWF extracted from water bottles was used as a reinforcement element. These fibers were prepared by shredding the water bottle into sheets and then cutting them into fibers (Figure 1). The fibers were prepared with different



Figure 1. Preparation of PWF from waste plastic water bottles.

length values varying between (10-40 mm) and width values ranging between (2-4 mm). The lengths of the fibers were determined with these values to achieve good interaction and bonding with soil particles compared to the size of the soil samples (especially the unconfined compression test samples). Additionally, these fiber dimensions were chosen to fulfill Michalowski's (1997) assertion that the minimum dimension of the fibers should be at least one order of magnitude larger than the size of the sand particles. The specific gravity of the prepared fiber was 1.26 (ASTM, 2020) and the tensile strength was 345 MPa (ASTM, 2018).

3. Experimental program

3.1 Sample preparation

Silty soil, cement, PWF, and their combination were examined at various laboratory tests. Firstly, the soil samples were oven-dried for 48 hours at 60 °C, then grinded to pass sieve #4. To prepare the soil sample with PWF, a desired quantity of soil was mixed thoroughly with various percentages of PWF (0-2.0% of the dry weight of soil) in a dry state. The PWF was randomly added to the soil to reduce the weak planes that could be expected to develop in the soil-fiber matrix (Aldaood et al., 2021). A fixed quantity of water (equivalent to the optimum moisture content of natural soil) was added to the soil-fiber mixture and mixed thoroughly. The wet mixture was left for about 24 hours in plastic bags to get a uniform moisture distribution in the soil-fiber matrix. At the end of this stage, the soil-fiber mixture was compacted in the desired stainless-steel mold (related to the desired test) to achieve the maximum dry unit weight of natural soil using standard compaction effort. For cemented reinforced soil samples, a desired cement content of 4% was added to the soil sample with varying percentages of PWF ranging from 0.0% to 2.0%. This percentage was chosen (i.e., 4% cement) to satisfy the lower strength value for using soil as a sub-base layer for little traffic (Biswal et al., 2020). Firstly, the cement was mixed with soil in a dry state until a uniform color of the mixture was obtained. Then, the same procedure was adopted to prepare the cemented fiber-reinforced soil, except that the mixtures were left for about 10 minutes for moisture homogeneity before compaction. After compaction, the cemented fiber-reinforced soil samples were enclosed with cling film and covered with many nylon sheets to avoid water loss. Then, these samples were left for curing at 25 °C for 28 days before testing to achieve the minimum strength for use in sub-base or base layers in the case of light traffic. It is worth noting that all soil samples were prepared at an optimum moisture content of about (16%) and a maximum dry density of about 17 kN/m³ of natural soil. Further, the word "samples" mentioned in this paper means composite samples that contain soil, cement, and PWF.

3.2. Laboratory tests

Different laboratory tests were adopted in this study to examine the behavior of uncemented and cemented silty soil reinforced with PWF and exposed to many wetting-drying cycles. These tests include unconfined compression, indirect tensile, punching tensile, pH, electrical conductivity, and wetting-drying tests. The unconfined and indirect tensile tests were carried out on cylindrical samples (50 mm × 100 mm) following the ASTM D2166 (ASTM, 2010). In these tests, the rate of loading was 1.27 mm/min.

For the punching tensile test, the procedure suggested by Kim et al. (2012) and Hasan & Rashid (2017) was used, which employs small disks to determine soil mechanical and tensile properties. The punching tensile test was used in this study because it represents an intermediate case between both the unconfined compression and the indirect tensile tests, which fixes the laboratory results that will be obtained. This test was conducted on uncemented and cemented reinforced samples prepared in a Proctor compaction mold (101.6 mm in diameter and 116.8 mm in height). Two loading discs with a diameter of 25.4 mm were used at the top and bottom of the sample (see Figure 2). The loading rate was also 1.27 mm/min and the load increased till failure occurred. The punching tensile strength (PTS) was determined using the equation below (Equation 1):

$$\sigma_t = \frac{P_{max}}{\pi kbH - a^2} \times 100 \quad (1)$$

where: σ_t = punching tensile strength; P_{max} = maximum applied compressive load; b = radius of soil sample; H = height of soil sample; a = radius of loading disc; and k = factor governed by the angle of friction, sample dimensions, loading discs, cone failure angle and the compressive to tensile strength ratio. The k -value in the above equation is equal to 1.0.

The pH and electrical conductivity (EC) values were determined for the cemented soil before and after the wetting-drying cycle, following the procedure mentioned by Aldaood et al. (2014). After a curing period of 28 days, the cement-treated soil samples were exposed to numerous W-D cycles following the procedure mentioned by Aldaood et al. (2014). In this study, eight W-D cycles were used. Every cycle involved 48 hours of wetting by submerging the samples in water at room temperature (25 °C) and then drying the samples at 60 °C for another 48 hours. The variation in *weight*, *pH* and *EC* values was measured during W-D cycles. Also, the compressive, indirect tensile and punching tensile strength values of the soil samples were measured in the drying state of the 2nd, 4th, 6th, and 8th cycles.



Figure 2. Punching test: (A) sample with metal rings to align loading discs; (B) fixing the sample for test; (C) sample under testing.

4. Results and discussion

4.1 Characteristics of PWF-reinforced natural soil

The variations of unconfined compressive strength (UCS), indirect tensile (ITS) and punching tensile strength (PTS) values are shown in Figures 3-5. As can be seen, all strength values increased with the increase in PWF up to a certain limit, then gradually decreased. Also, there was a difference in the optimum PWF content, which gives the maximum strength value of the adopted tests. In all strength tests, the optimal PWF content was noted to be dependent on the sample size. The maximum PTS values were observed with 1.5% of PWF, while the maximum strength values in other tests were recorded with 1.0% of PWF. This behavior could be attributed to the larger size of the PTS samples as compared with those in other tests. Moreover, in the PTS test, there is further PWF, so the tensile stress in the fiber can be induced due to its packaging around the soil particles. It is worth noting that all strength values of reinforced soil samples were greater than those of unreinforced ones. The increase in the strength values with PWF addition could be due to the: (1) the non-uniform distribution of PWF within the soil matrix can reduce the weak planes between PWF

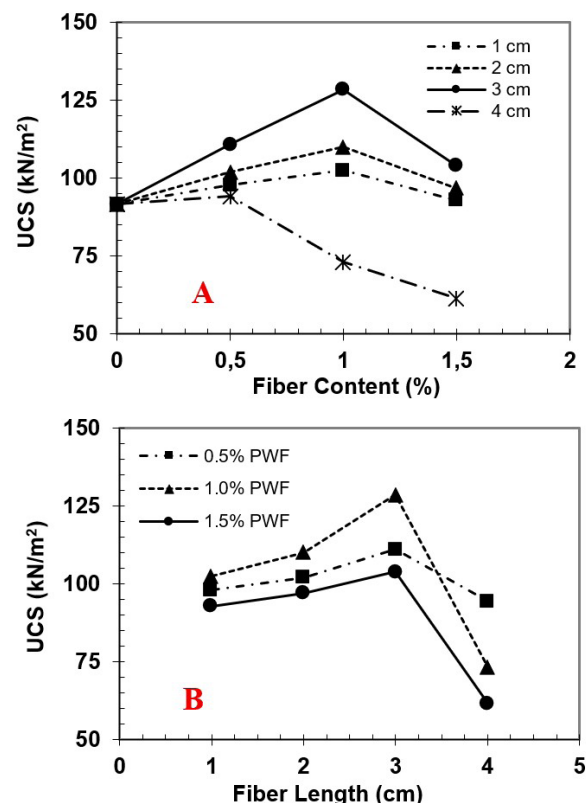


Figure 3. UCS variations with: (A) PWF content; and (B) PWF length.

themselves, and make these fibers act as filaments that intertwine with the soil particles leading to restricts deformation upon

loading; (2) the non-uniform distribution of PWF make these fibers to share the tensile stresses which were developed among soil particles due to the sliding restriction of PWF in the soil mixtures (Menezes et al., 2019); (3) increasing both cohesion and friction between soil particles and PWF, which resulted in the redistribution of the internal stresses through soil and PWF.

The reduction in strength values of reinforced samples with increasing PWF might be due to the poor mixing with higher PWF content, which leads to fewer contact points with soil particles. Also, the higher PWF content, more than the optimal value, caused fibers to clump over each other, leading to the development of a weak plane and forming voids between PWF and soil particles (Aldaood et al., 2021; Correia & Rocha, 2021).

To highlight the influence of fiber length on the strength properties of PWF-reinforced samples, various fiber lengths (ranging from 10 mm to 40 mm) were used. It is observed that fiber length plays an important role in soil strength improvement. All soil samples reinforced with 30 mm long PWF had the maximum values of UCS, ITS and PTS, respectively.

The increase in strength values with the increase in fiber length may be due to the increase in the tensile strength of the longer fibers. In addition to that, as the fiber length increases, the growing friction between fibers and soil increases and absorbs the extra tensile stress. Similar results have been mentioned by Sai & Srinivas (2019) and Louzada et al. (2019).

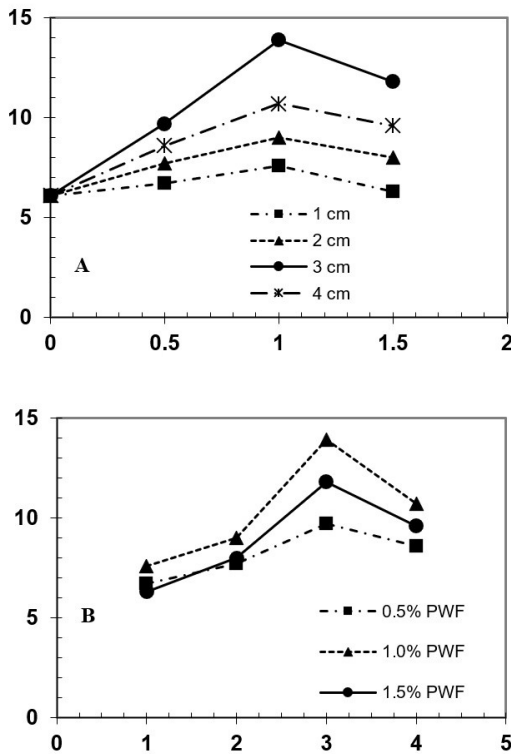


Figure 4. ITS variations with: (A) PWF content; and (B) PWF length.

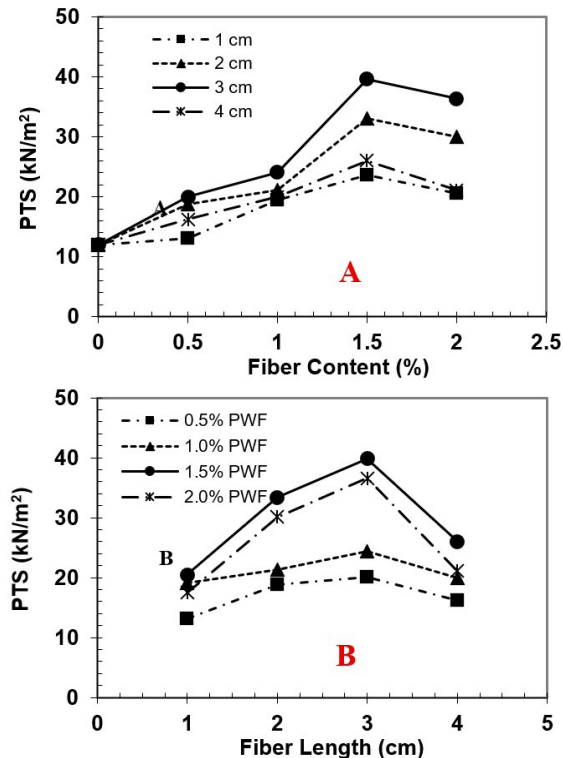


Figure 5. PTS variations with: (A) PWF content; and (B) PWF length.

4.2 Characteristics of PWF-reinforced cemented soil

To study the behavior of cemented reinforced soil samples, the soil samples were reinforced with various percentages (0.0-2.0%) of PWF having 30 mm long (this length value gave maximum strength values as mentioned previously).

4.2.1 Variation of pH, EC and residual moisture values

The pH, EC, and residual moisture content (RMC) values of reinforced soil samples treated with 4% cement and cured for 7, 14 and 28 days were determined. As is well known, PWF is a chemically inactive and hydrophobic material that does not react with cement and/or soil particles. Moreover, PWF materials do not absorb soil moisture. Thus, the pH, EC and RMC are not influenced by the addition of these materials. It is observed that both pH and EC values increased initially with cement addition. These values increased from 9.8 and 720 $\mu\text{S}/\text{cm}$ for natural soil to 12.9 and 1962 $\mu\text{S}/\text{cm}$ for cemented soil samples, respectively. The increase in these values with cement addition could be attributed to the increase in calcium ions (Ca^{2+}). The pH and EC values showed a continuous reduction with curing time. The pH value decreased from 12.9 to 11.78, 11.35 and 11.06, when the soil samples were cured for 7, 14 and 28

days, respectively. At this level of pH value, the pozzolanic reaction products (such as calcium silicate hydrate, CSH, and calcium aluminate hydrate, CAH) continue to form, leading to an increase in the soil strength. The EC values showed the same trend as pH values with curing time; these values decreased from 1962 $\mu\text{S}/\text{cm}$ to 1762 $\mu\text{S}/\text{cm}$, 1563 $\mu\text{S}/\text{cm}$ and 1378 $\mu\text{S}/\text{cm}$ when the soil samples were cured for 7, 14 and 28 days, respectively. The reduction in pH and EC values of cemented soil samples is connected to the reduction in the Ca^{2+} and OH^- ions consumed during pozzolanic reactions. The continuous decrease in moisture content through curing times might affect the pozzolanic reactions. Great attention has been given to estimating the RMC of the cemented soil samples. It was noticed that the RMC decreased with the increase in curing times. Most reduction in moisture content occurred during the first 7 days of curing times; thereafter the reduction in RMC continued slightly. The RMC values decreased from 16% to 12.7%, 12.3% and 11.8% when the soil samples were cured for 7, 14 and 28 days, respectively. The reduction in the RMC could be attributed to cement hydration and the completion of the pozzolanic reactions.

4.2.2 Variation of strength properties value

Figures 6-8 illustrate the variations of UCS, ITS and PTS values of cemented reinforced soil samples cured for 7, 14 and 28 days. As expected, cement addition enhanced the strength values of soil samples. The UCS increased from 91.7 kN/m^2 of natural soil to 1208 kN/m^2 , 1427 kN/m^2 and 1800 kN/m^2 for cemented soil samples cured for 7, 14 and 28 days, respectively. In the same sequences, the ITS increased from 6.1 kN/m^2 to 113 kN/m^2 , 245 kN/m^2 and 312 kN/m^2 respectively. While the PTS increased from 12 kN/m^2 to 125 kN/m^2 , 258 kN/m^2 and 371 kN/m^2 respectively. For cemented reinforced soil samples, it can be seen that all strength values of cemented reinforced samples were increased linearly with increasing curing times. It is also clear that cement addition did not affect the PWF percentage, which gave the maximum values of strength. This means that both maximum values of UCS and ITS remain at 1.0% of PWF, while 1.5% of PWF remains to give the maximum value of PTS (as mentioned previously). The increase in the strength values of reinforced soil samples with both cement addition and curing times was related to the two actions. The first action is cement hydration, which is necessary to provide calcium ions for ion exchange. The second one is the pozzolanic reaction products, such as calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) (Etim et al., 2021). Many studies associated with cement stabilization revealed that the strength characteristics of various types of soils improved with cement addition (Safdar et al., 2020).

The more interesting results observed in Figures 6-8 are that the strength values of cemented reinforced soil samples were larger than the strength of unreinforced cemented samples. This behavior was due to the contribution action of

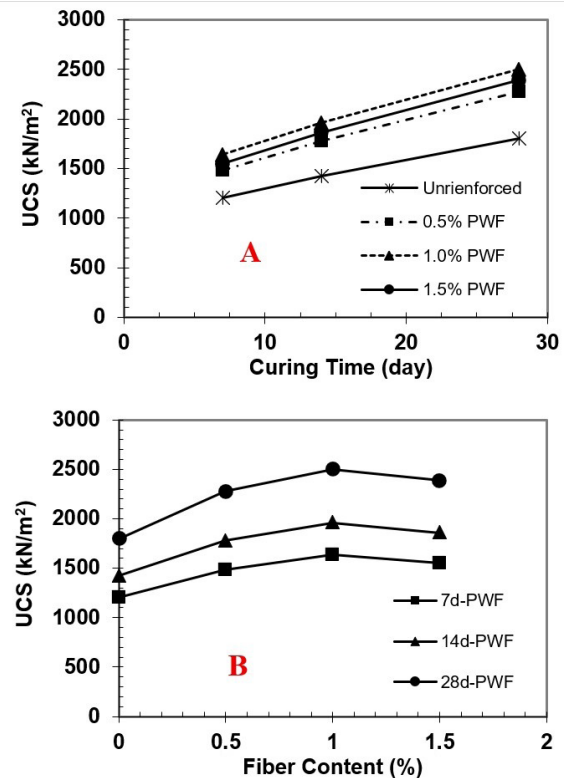


Figure 6. Variations of UCS: curing time (A); and fiber percent (B).

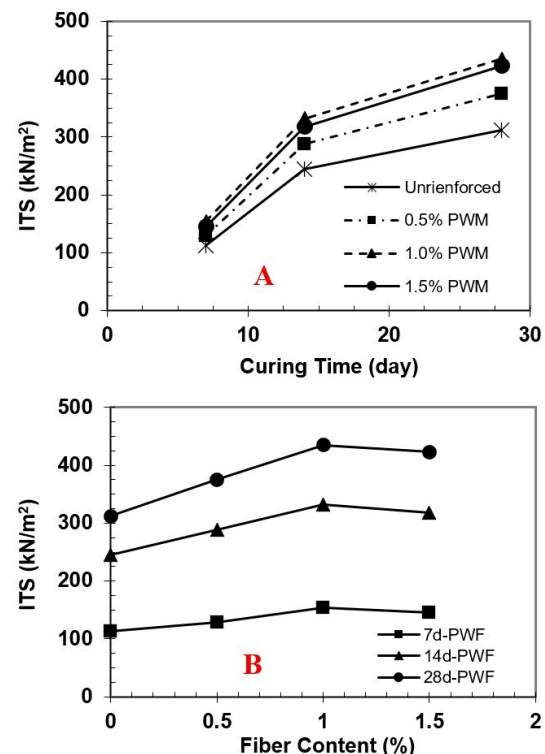


Figure 7. Variations of ITS: curing time (A); and fiber percent (B).

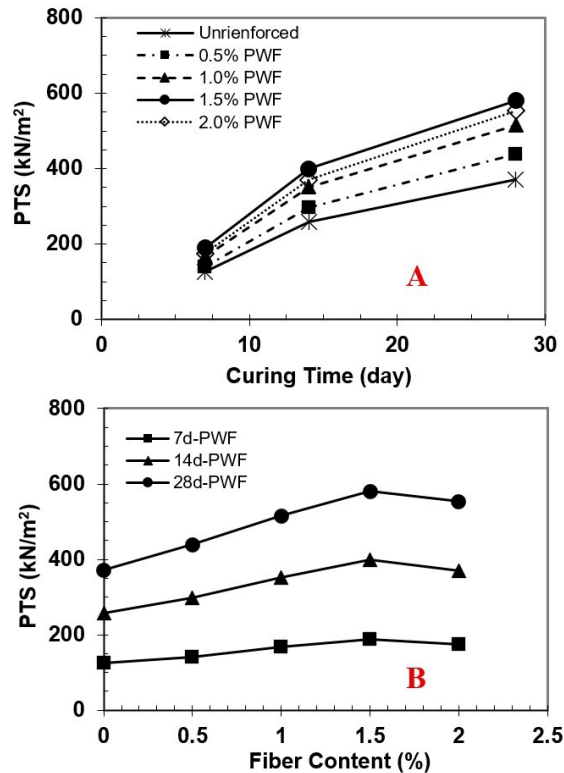


Figure 8. Variations of PTS: curing time (A); and fiber percent (B).



Figure 9. PWF along tension cracks (bridge action of PWF).

both cement and PWF to increase strength. During the curing period, some soil particles may be attached to PWF, resulting in to increase in friction and the bonding strength between them (the soil and the PWF). Furthermore, the sand particles could impact and abrade the PWF surface forming many grooves on the PWF surface and leading to the enhancement of the interlocking between them. Qu et al. (2013) mentioned that the increase in shear strength of the reinforced soil is related to the roughness of fiber and the interface between fiber and soil.

The UCS of cemented soil samples cured for 28 days increased from 1800 kN/m² to 2275 kN/m², 2500 kN/m² and 2390 kN/m² for cemented soil samples reinforced with 0.5%, 1.0% and 1.5% PWF, respectively. In the same manner and for similar samples, the ITS increased from 312 kN/m² to 375 kN/m², 435 kN/m², and 423 kN/m², respectively. Moreover, the PTS increased from 371 kN/m² to 439 kN/m², 515 kN/m², 580 kN/m², and 553 kN/m² for soil samples reinforced with 0.5%, 1.0%, 1.5%, and 2.0% of PWF, respectively. This behavior refers to the positive action of cement and PWF together in enhancing the strengths values, rather than the action of cement and/or PWF alone. The increase in strength value of cemented reinforced soil samples could be attributed to that: (1) the adhesion between PWF and cemented soil particles is further than that between PWF and un-cemented ones; (2) the bonding strength and the friction were also higher in cemented reinforced samples as compared with those in unreinforced cemented ones (Aldaood et al., 2021); (3) the small pores in cemented soil samples lead to more contact zones with PWF; (4) as soon as cracks propagate in soil samples, the PWF across these cracks will be responsible to resist the tension forces in the soil by bridge action of PWF (see Figure 9); (5) visual observation of cemented reinforced samples illustrated that, the surface of PWF became rougher than uncemented samples, thus the friction between PWF and cemented soil particles will be increased.

4.3 Characteristics of PWF-reinforced cemented soil with W-D cycles

The results of the durability test (i.e., wetting-drying test) are presented in terms of variations in pH, electrical conductivity (EC), and percent weight loss for cemented reinforced and unreinforced soil samples subjected to 8 cycles. Further, the UCS, ITS and PTS were also determined at the end of 2nd, 4th, 6th, and 8th cycles of wetting-drying. It is worth noting that natural soil samples (both unreinforced and reinforced samples) did not sustain the durability test. These soil samples failed after 5-15 minutes of soaking in water due to the nonexistent cohesion required to strengthen them against W-D cycles. Thus, all results discussed in the next sections were related to the cemented soil samples.

4.3.1 Variation of pH and EC values with W-D cycles

The variations in pH and EC values of cemented reinforced soil samples with W-D cycles are measured.

These values decreased in the same trend as W-D cycles increased. More reduction in the pH and EC values occurs during the 2nd cycle. At this cycle, the pH values decreased from 11.06 to 9.4, while the EC values decreased from 1378 $\mu\text{S}/\text{cm}$ to 680 $\mu\text{S}/\text{cm}$. After that, a slight reduction in pH and EC values occurs to reach 9 and 545 $\mu\text{S}/\text{cm}$, at the last W-D cycle, respectively.

The reduction in pH and EC values with W-D cycles is expected and was attributed to the reduction in the Ca^{2+} and OH^- ions, which are necessary to complete the pozzolanic reactions. Moreover, cement leaching during W-D cycles led to a reduction in the Ca^{2+} ions and resulted in a decrease in both pH and EC values.

4.3.2 Variation of loss in weight and strength properties with W-D cycles

The durability behavior of the soil could be detected from the weight loss value and the variation of strength properties during the W-D cyclic. Figure 10A shows the cumulative loss in weight of different soil samples for soil samples tested in UCS, ITS, and PTS, during W-D cycles. These values were presented for the dry state only. The results from Figure 10A show that the presence of PWF affects the

degradation process of soil samples. This figure also shows that the value of loss in weight of the soil samples during W-D cycles depends on the size of the soil samples. Different soil sample sizes illustrate different values of weight loss, which affects the strength values of soil samples when exposed to W-D cycles. With the increase in W-D cycle numbers, it was noticed that the loss in weight of soil samples increased at a fairly constant rate, especially in the first cycles. After the fourth cycle of W-D, the rate of loss in weight was increased. This behavior is attributed to the crack propagation, which increased with increasing W-D cycles.

Interestingly, the soil samples tested for PTS showed smaller values for loss in weight, as compared with other soil samples. In other words, PTS samples illustrated a good resistance for W-D cycles. This behavior could be attributed to the larger size of PTS samples, which contained more PWF. Thus, the reason that leads to more interaction between soil and PWF, which gave more resistance under W-D cycles. The loss in weight for UCS and ITS samples was more noticeable and approximately equal. Cement and PWF addition significantly reduced the values of weight losses as compared with natural soil samples (having fragile particle bonds, which was the cause of their failure after 5-15 minutes of soaking in water). The cementing materials (CSH and CAH) and the bonding between PWF and soil particles made the soil samples more durable than the natural soil against W-D cycles. Finally, a visual observation of soil samples, during W-D cycles, illustrated that there were a few cracks that propagated in these samples. Although these cracks affect the strength properties of soil samples (as will be discussed later), the samples kept their shapes till the last cycle of W-D (i.e., all soil samples could be tested in the planned experiment).

Figure 10B illustrates the variations in strength values of cemented reinforced soil samples against W-D cycles. It is observed that all strength values decreased linearly with increasing W-D cycles. The UCS of soil samples decreased from 2500 kN/m^2 to 1000 kN/m^2 , when subjected to eight cycles of W-D. At the same time, the ITS and PTS decreased from 434 kN/m^2 and 580 kN/m^2 to 189 kN/m^2 and 448 kN/m^2 , respectively. The reduction in strength values with W-D cycles could be attributed to the degradation of cementing bonds and a change in the soil microstructure, resulting in a greater loss of strength. Another possible reason for decreasing strength was the formation of cracks that could be created during the W-D cyclic. These cracks weakened the interaction matrix and therefore reduced the strength values. Similar observations were noticed by (Sun & Cui, 2018; Cuisinier et al., 2020; Nabil et al., 2020). Also, it shows that the resistance of the soil to cyclic W-D depends on the size of the soil samples. The highest loss percentages in strength values occurred for unconfined compression samples and indirect tensile samples. The punching-tensile samples illustrate the lowest reduction in strength. It is worth noting that, even after three cycles of W-D, the UCS and ITS

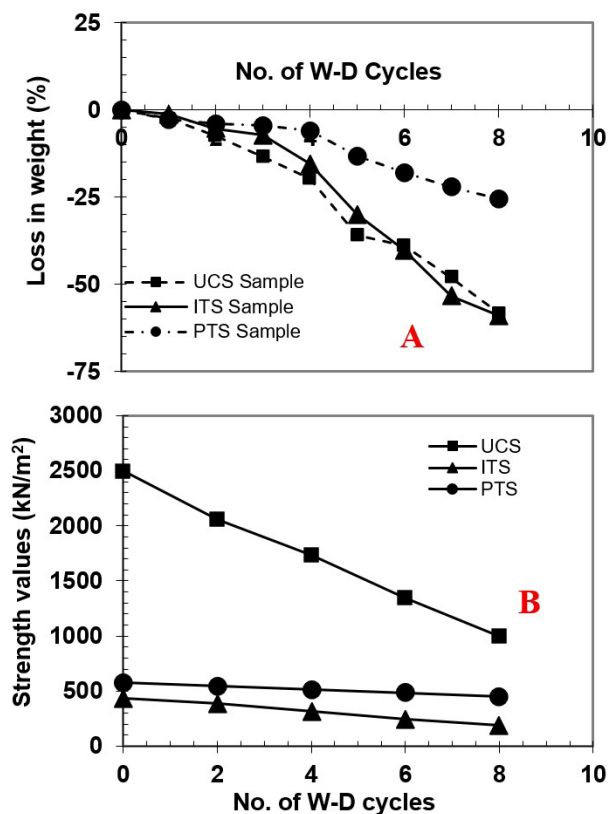


Figure 10. (A) loss of weight of soil samples; and (B) strength variations, with W-D cycles.

of cemented soil samples have not lowered below that of the cemented unreinforced one. While the PTS of the same samples remained higher than the cemented unreinforced even at the end of W-D cycles. Generally, this behavior shows good resistance to W-D due to the reinforcement of the soil samples with PWF. An additional benefit of PWF is the restraint of crack propagation in soil samples during W-D cycles and after initial formation. Before cracking, the PWF looked to have no noticeable effect on the soil behavior. While during W-D cycles, the existence of PWF modifies the mechanism of failure by preventing crack propagation. Further, the results show that the existence of PWF slowed the degradation process for reinforced soil samples during W-D cycles. This means that all soil samples survived for all W-D cycles.

5. Conclusions

Silty soil represents one of the problematic soil types due to its significant susceptibility to water. Therefore, improving the properties of this soil is necessary for its use in engineering projects. Reinforcing the soil using recycled materials, such as waste plastic water bottles, is important in geotechnical engineering applications. Using such materials has considerable economic benefits. Incorporating binding materials like cement with these waste materials greatly enhances the silty soil's properties, particularly under the influence of climatic conditions. The following conclusions can be deduced:

- o Using recycled PWF as reinforcement fibers for silty soil increases compressive and punching tensile strength. The strength values increase with increasing PWF percentage and fiber length up to a certain limit.
- o The combined effects of cement and fiber were better than their effects alone. Meaning that the strength of the soil samples treated with cement and reinforced with PWF was better than those treated only with cement and/or only with reinforcement.
- o The results of the UCS for all study variables illustrated the same trend as the ITS and PTS tests.
- o For all lengths of PWF used, there is an increase in strength values. The maximum increase in strength was noted in soil samples reinforced with PWF with 30 mm long.
- o Irrespective of combinations, all tested samples decreased in strength after W-D cycling, which confirms the negative effect of water during these cycles.
- o The PWF reinforcement of cement-treated soil resulted in good resistance to W-D cycles even up to three cycles. Thus, the choice of increasing cement content can be certain according to the expected severity of the cyclic W-D scenario.

Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper, and there is no financial interest in reporting.

Authors' contributions

Farah Zaal Mishaal: methodology, investigation. Abdulrahman Aldaood: writing, original draft preparation, reviewing, and editing.

Data availability

Enquiries about data availability should be directed to the authors.

Declaration of use of generative artificial intelligence

This work was done with minimal assistance from GenAI (ChatGPT), less than 20%, to improve readability and language. other aspects of the paper were developed solely by the authors, who take full responsibility for the content of this publication.

List of symbols and abbreviations

pH	Potential of hydrogen
CSH	Calcium silicate hydrate
CAH	Calcium aluminate hydrate
EC	Electrical conductivity
ITS	Indirect tensile strength
ML	Low plasticity silt
NP	non-plastic
OH ⁻	Hydroxyl ion
OMC	Optimum moisture content
PTS	Punching-tensile strength
RMC	Residual moisture content
UCS	Unconfined compressive strength
USCS	Unified Soil Classification System
W-D	Wetting-drying

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