# Strength development and freeze–thaw behavior of fiber reinforced cemented sand

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ABSTRACT: In the last decade, ground improvement by using polypropylene fibers has gained popularity. In this study, different sets of specimens were constituted according to the fiber ratios and unconfined compressive testing was applied to the fiber reinforced cement admixed sand specimens to evaluate their strength development. Lightly cemented sand specimens were prepared by adding 2, 4, and 6% of cement to the dry soil. The fibers used in this study had a length of 6 mm and added to the soils in percentages of 0, 0.3, 0.6, and 0.9. The results of this study indicated that fiber addition to the cemented sand improved the unconfined compressive strength of the medium. It was seen that both cement ratio and fiber ratio must be considered as separate components of the mixture. Although the specimens that had 2% cement ratio and %0.9 fiber ratio combinations resulted in the highest values of unconfined compressive strength in its experimental set, the highest values of unconfined compressive strength was obtained for the specimens with 4% and 6% cement ratios which had 0.6% of fibers. Freeze-thaw tests were applied in a conventional manner, therefore the freezing period lasted one day and thawing period was the next day, each cycle completed in two days. Number of cycles was 0, 1 and 3. Increment of cycles resulted in the strength loss of the specimens, but the loss of strength was partially prevented by using fiber reinforcement confirming that fiber reinforcement may provide a good solution for soils under freeze-thaw effects.

*Keywords: Fiber, cement, sand, unconfined compressive strength, freeze-thaw*

## 1 INTRODUCTION

Soil treatment using cement is a popular improvement technique and its advantages have been observed among geotechnical engineers in recent years. Cement admixed soils have been used increasingly to construct stabilized bases under concrete pavements and to strengthen slopes in slope stability problems. Cement addition to soil contributes to settlement reduction and bearing capacity increase, which are preferable in overcoming geotechnical problems. Cement addition to soils increase the elastic modulus and the peak strength, treated soils exhibit more brittle stress–strain behavior at lower initial mean effective stresses or higher cement contents. This issue could be overcome with fibers and fiber inclusion could be an alternative solution. Fiber inclusion to cement admixed soil provides a bridging effect and friction between the soil and the fibers. A fiber reinforced cemented soil can support the applied load even after the failure occurred and significantly change the soil behavior from brittle to a more ductile one (Eskisar et al. 2015; Eskisar and Altun, 2015).

Consoli et al. (2004) examined the effect of three kinds of fibers on the mechanical behavior of fiber-reinforced cemented soils. Their results showed that the inclusion of PP fiber significantly improved the brittle behavior of cemented soils, whereas the deviatoric stresses at failure slightly decreased. In the study of Kumar et al. (2006), polyester fibers were mixed with soft clay soil to investigate the relative strength gain in terms of unconfined compression. They observed that unconfined compressive strength of clay increased with the addition of fibers and it further increased when fibers were mixed in clay sand mixture. Park (2011) indicated that the inclusion of PVA fibers has a significant effect on both the unconfined compressive strength and the axial strain at peak strength. The increase in the unconfined compressive strength was most apparent in the 2% cemented specimen wherein the unconfined compressive strength increased more than three times as the fiber ratio increased up to 1%. Sadek et al. (2013) reported that at cement content of 0.5%, as the fiber length increased, the unconfined compressive strength increased and the strain at failure increased, indicating improved ductility, with the effect of fiber length being evident at higher fiber contents compared to lower fiber contents.

The purpose of this paper is to present the results of unconfined compression tests on fiber reinforced cemented sand specimens. The effect of the inclusion of fibers in cemented sand was evaluated in terms of strength and ductility of cemented sand. Furthermore, freeze-thaw tests were applied in a conventional manner in different cycles. Increment of cycles resulted in the strength loss of the specimens, but the loss of strength was partially prevented by using fiber reinforcement confirming that fiber reinforcement may provide a good solution for soils under freeze-thaw effects.

## 2 MATERIALS AND EXPERIMENTAL PROGRAM

### *2.1 Materials*

Sand is obtained from a construction work site in Izmir, Turkey. The sand is classified as SP in Unified Soil Classification System (USCS). The effective particle size of the sand ($D_{10}$) is 0.14 mm, the average particle size ($D_{50}$) is 0.19 mm, the uniformity coefficient is 2.33 and the specific gravity of the sand is 2.65. The grain size distribution of the sand is given in Figure 1. The fiber materials used in this study are also produced in Turkey by a local company. Their composition is 100% virgin polypropylene. The fibers are fibrillated type with a rectangular cross section and with a length of 6 mm (Figure 2). Tensile strength and Young’s modulus of the fibers are 300 MPa and 1000 MPa, respectively.

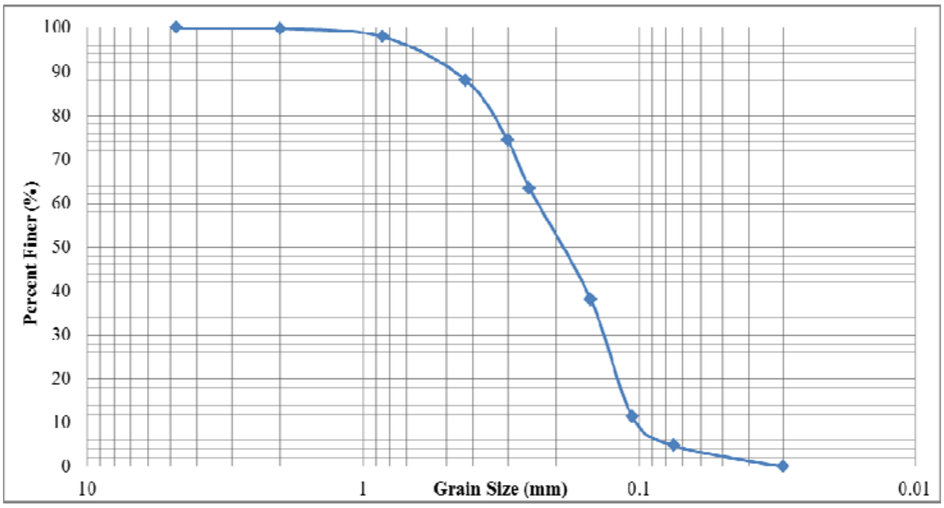

Figure 1: Grain size distribution of the sand


Figure 2: 6 mm long fibers used in this study

Portland cement (CEM 42.5 type of cement) that has a specific density of 3.08 g/cm$^3$ and a specific area of 3960 cm$^2$/g is chosen for this study as it could be easily provided for stabilization works in the field.

### *2.2 Specimen preparation*

Sand - cement mixture was prepared by mixing dry sand and cement with an optimum water content of 20%. The optimum moisture content was determined as a result of standard Proctor tests previously. The cement ratio and the fiber ratio of the specimens were calculated as a percentage of the dry mass of the sand. Cement ratios of 2%, 4%, and 6% and fiber ratios of 0, 0.3%, 0.6% and 0.9% were used when preparing the specimens with all possible combinations of these variables. Cement was mixed with sand by hand with a predetermined amount of fiber to obtain a uniform fiber distribution throughout the entire specimen. Cemented sand mixed with fibers was compacted in three equal layers and then cured for 28 days. It was carefully checked that a uniform distribution of fibers throughout the specimen was achieved for laboratory testing.

Specimens that have 50 mm diameter and 100 mm length were compacted directly into a custom made mold by applying an energy level of a standard Proctor test. The specimens were wrapped air tight with LLDPE film and placed in a moisture room (at 25°C and r.h. 97%) for 28 days. In the context of this study, specimens are named with cement content (C), fiber content (F), and freeze – thaw cycles (FT), respectively. As an example, C4F0.6FT3 describes a specimen with cement content of 4%, fiber content of 0.6%, and then subjected to 3 freeze - thaw cycles. In this study, at least 3 specimens were prepared in each group with same cement and fiber contents and subjected to same amount of freeze-thaw cycles to check the repeatability of the test results.

### *2.3 Unconfined compression tests*

Unconfined compression tests were used to determine the effect of fiber reinforcement on strength behavior of cemented sand specimens. Unconfined compression tests were performed according to ASTM D 2166. The load was applied so as to produce an axial strain at a rate of 1 %/min. The rate of strain was chosen so that the time to failure did not exceed 15 min. The loading continued until the load values decreased with increasing strain, or until 15 % strain was reached.

### *2.4 Freezing–thawing tests*

After curing period of a sample group was completed, the protective film surrounding the specimens was removed and freeze–thaw tests were conducted. The freeze–thaw temperatures used were −20 °C and 20 °C. During freezing, the samples were placed in a conventional freezer at −20 °C for 24 h. During thawing, the samples were placed in a room with a stable temperature of 20 °C for 24 h. This procedure was repeated until the samples had undergone the required cycles of freezing and thawing. All these stages were regarded as 1 cycle.

## 3 RESULTS AND DISCUSSION

### *3.1 Evaluation of unconfined compression tests*

Figure 3 (a-c) shows the stress–strain behavior of fiber-reinforced cemented sand specimens prepared with different cement ratios, namely, 2, 4, and 6%, respectively. The curing time of the presented specimens is 28 days. The unconfined compressive strength (UCS) increases steadily for soils with 2% cement ratio as the fiber ratio increase to 0.9%, but a different trend was observed for soils that contain 4% and 6% cement. The upper limit of fiber ratio that contributes to the UCS was found to be 0.6% and further addition of fibers (0.9%) decreased the UCS of the specimens. In general, fiber addition to the cemented specimens increased the UCS 102%-200% depending on the fiber content. Table 1 gives a summary of the peak strength and the axial strain at peak strength.

Studies of Consoli et al. (2003) and Tang (2007) reported that inclusion of fibers to the cemented soils could increase the UCS. However, the extent of the increase that was due to the inclusion of fibers was not determined. The increase in the UCS that is due to the inclusion of fibers can be quantified by defining an unconfined compressive strength ratio (UCSR) which is given in Equation 1. It is the ratio of the UCS of fiber-reinforced cemented specimens to that of the non-fiber reinforced specimens:

$$UCSR = UCS_{\text{with fibers}} / UCS_{\text{without fibers}} \quad (1)$$

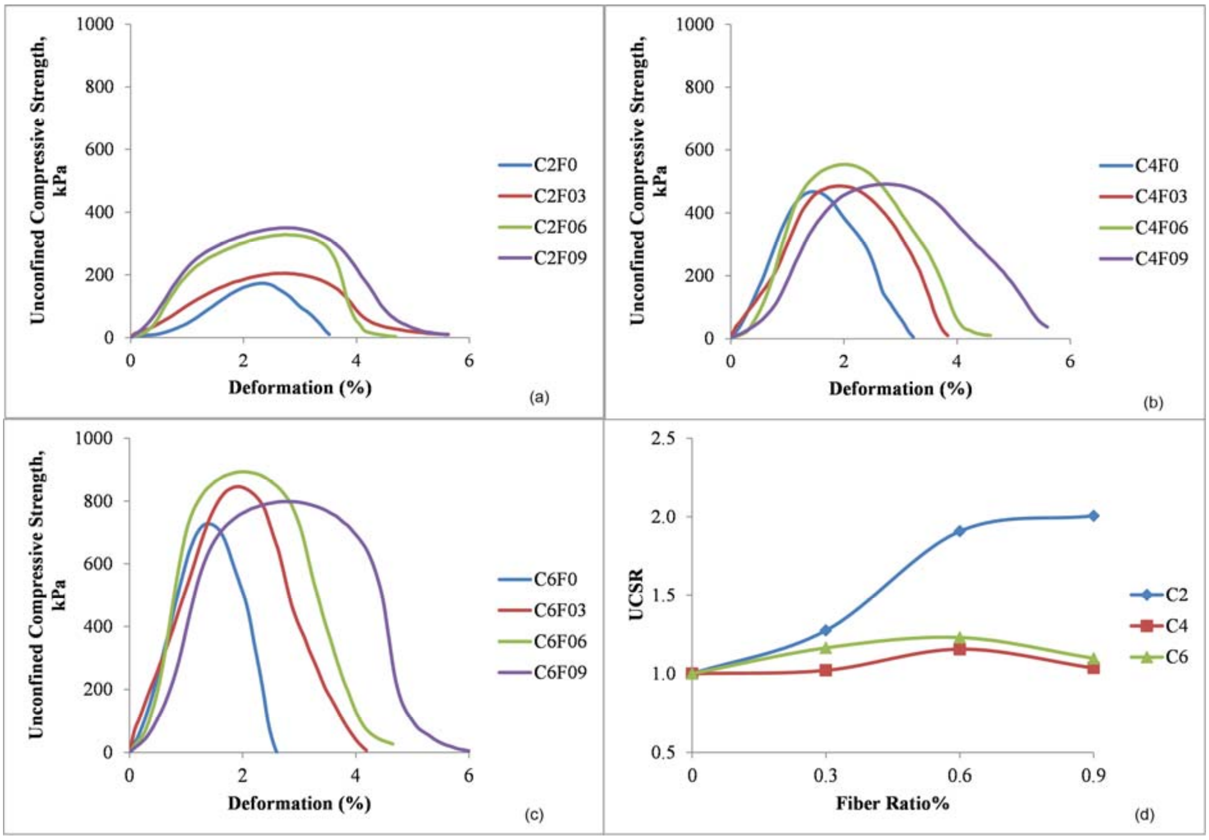


Figure 3: Stress-strain curves of specimens with (a) 2% cement, (b) 4% cement, (c) 6% cement reinforced with varying fiber ratios, (d) strength increase (UCSR) due to increment of fiber ratio

The values of UCSR for three different cement ratios are compared in Figure 3 (d). The highest UCSR value is calculated for the specimens that contain 2% cement and 0.9% fibers. Maher and Ho (1993) tested a specimen of 1% glass fiber that was mixed with 4% cemented Ottawa sand, and found that UCSR was approximately 1.5. Kumar et al. (2006) mixed 1% fiber and clay with 10% sand, and found that UCSR was approximately 1.2. Park (2011) obtained a value of UCSR of 3.5 was obtained for the case with 1% fiber ratio and 2% cement ratio. The UCSR ratio of specimens in this study is obtained as 2.01 being in the range of the previously mentioned studies. Reaching to a higher UCSR could be explained by the good adhesion formed by the addition of 2% cement and the fibers; therefore sufficient friction was sustained during the unconfined compression tests.

Table 1. Summary of test results

| Cement Ratio % | Fiber Ratio % | UCS kPa | Def. % | UCSR | D |
|---|---|---|---|---|---|
| 2 | 0 | 172 | 2.30 | 1.00 | 1.00 |
| | 0.3 | 219 | 2.65 | 1.27 | 1.15 |
| | 0.6 | 328 | 2.80 | 1.91 | 1.22 |
| | 0.9 | 345 | 2.89 | 2.01 | 1.26 |
| 4 | 0 | 473 | 1.42 | 1.00 | 1.00 |
| | 0.3 | 490 | 1.80 | 1.04 | 1.27 |
| | 0.6 | 547 | 2.00 | 1.16 | 1.40 |
| | 0.9 | 483 | 2.75 | 1.02 | 1.93 |

| | | | | | |
|---|---|---|---|---|---|
| 6 | 0 | 727 | 1.42 | 1.00 | 1.00 |
| | 0.3 | 846 | 1.94 | 1.16 | 1.36 |
| | 0.6 | 894 | 1.97 | 1.23 | 1.38 |
| | 0.9 | 798 | 2.74 | 1.10 | 1.92 |

The secant elastic modulus ($E_{50}$) was calculated from one half of the axial strain at peak strength and was then compared against the cement ratio in Figure 4. The secant elastic modulus depends on the cement ratio rather than on the fiber ratio. For a constant cement ratio, the secant elastic modulus of each specimen, each with a different fiber ratio, falls within a narrow band of values as shown in Figure 4, whereas the axial strain associated with peak strength gradually increases with increasing fiber ratio as shown in Figure 3. This kind of increasing stress–strain behavior has been similarly observed in the results of triaxial compression tests on cemented specimens with increasing confining stress (Clough et al., 1981; Abdulla and Kiousis, 1997). From these experimental results, it can be inferred that in terms of an increase in strength, an increase in the fiber ratio in fiber-reinforced cemented sand has the same effect as an increase in the confining stress in non-fiber-reinforced cemented sand. The horizontal deformation of fiber-reinforced samples was restrained by the included fibers. The increase in the confining stress can also restrain the horizontal deformation of the samples. This result has been ascertained by Yang (1972) who pointed out that the increase in the maximum principal stress at failure in the fiber-reinforced sample was attributable to the increase in the confining stress.

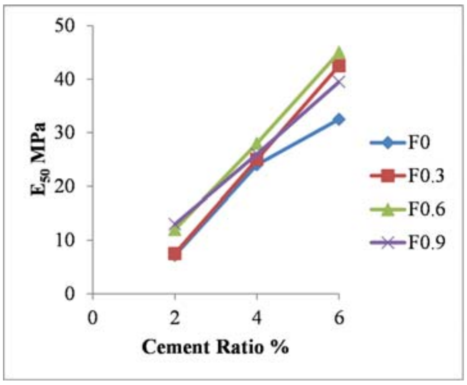

Figure 4: Variation of secant modulus with cement ratios.

The cement addition to soil improves the brittle behavior as a result of the hardening characteristic of the cement. However, the addition of fibers delays failure and changes the brittle behavior to a ductile one. The concept of ductility could be used to determine the performance of fiber-reinforced cemented soils. If Figure 3 (a-c) is reviewed, the change of behavior with the addition and increment of fibers could be observed. Ductility can be defined as the ratio of the final deformation or deflection at the ultimate state to that at the yield state. There are some cases in soil-based inelastic materials, unlike the elastic materials mentioned earlier, where no such clear distinction appears between the yield and ultimate states. The term deformability index (D) was proposed (Equation 2) and defined to describe the ductility of fiber reinforced cemented sand specimens by Park (2011):

D = Axial deformation at peak strength of fiber reinforced soil / Axial deformation at peak strength of unreinforced soil (2)

It should be emphasized that deformability index uses two stress–strain curves, one each from unreinforced and fiber-reinforced cemented specimens. The index is useful when either a peak stress or a residual stress state is not clearly observed. However, its applications are limited to the cemented specimens that have the same cement ratio. Deformability index values of the specimens are calculated and summarized in Table 1.

If the cement ratio is kept constant it is seen that specimens with 2% cement constitutes a group and another group gathers for specimens with 4% and 6% cement. The frictional resistance is more pronounced between the fibers and the sand for the specimens with 2% cement. For this reason axial deformation is around 2.89% for the specimens with 0.9% fiber content. In the second group it is seen that deformation levels are close regardless of the cement ratio. During the tests failure was observed due to the detachment of fibers and the soil. As a result, the deformation was around 2.75%. The unreinforced specimens showed an axial deformation of 1.42%, being 1.5 times less in deformation values.

### *3.2 Evaluation of freeze-thaw tests*

The effect of freeze-thaw cycles on the unconfined compressive strength is determined by freeze - thaw tests. Hori and Morihiro (1998) stated that degree of deterioration is dependent on the properties of the soils. When cement treated sands were left to freeze – thaw cycles, due to the change of cemented structure, damage may be observed. In this study 1 and 3 freeze – thaw cycles were applied to see the effects of freeze – thaw. The loss of strength was observed in the unreinforced and reinforced specimens (Figure 5).

Attenuation in strength decrement was achieved with the addition of fibers. When the UCS of the unreinforced specimens were compared with the specimens reinforced with 0.6% fibers, the UCS values are 40% and 37% higher after 1 cycle and 3 cycles, respectively. Also, every specimen was weighed before and after freeze-thaw tests to evaluate the mass loss, it is seen that loss of mass is between 0.08% and 0.1% after 3 cycles of freeze - thaw.

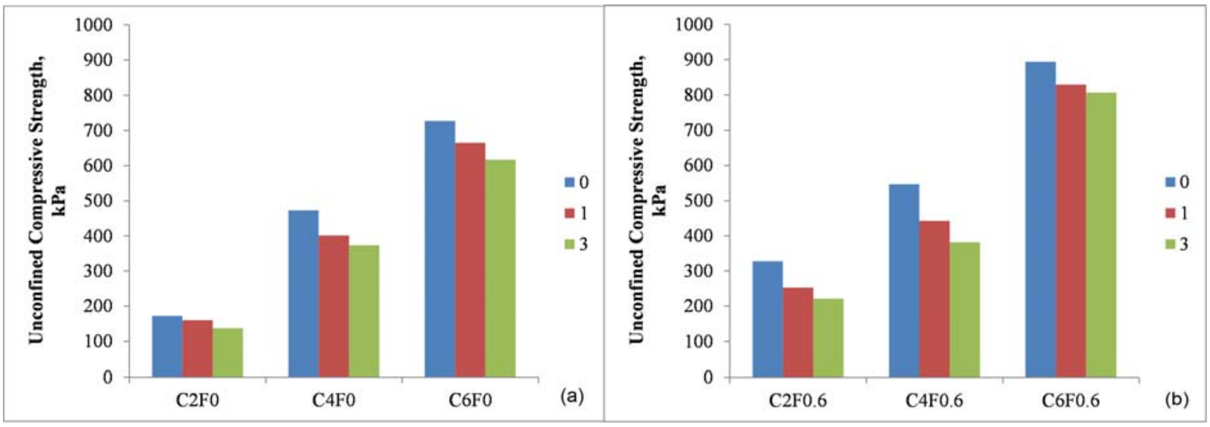


Figure 5: UCS of specimens after 0, 1, and 3 cycles of freeze – thaw (a) unreinforced specimens (b) specimens reinforced with 0.6% fibers

## 4 CONCLUSIONS

In this study, a series of unconfined compression tests were carried out on fiber reinforced cemented specimens. The effect of the fiber ratio and the cement ratio on the strength and the ductility of cemented sand were investigated. To see the effects of freeze – thaw, freeze - thaw tests were performed and the changes in the UCS were evaluated. The conclusions could be summarized as follows:

- The fiber-reinforced sand with 2% cement and 0.9% fibers showed the maximum unconfined compressive strength ratio of 2.01. The effect of fiber inclusion was most apparent in the 2% cemented samples.
- The highest UCS values were obtained for a fiber ratio of 0.6% for the specimens treated with 4% and 6% cement. This condition is attributed to the inclusion of more fibers partially preventing the development of chemical reactions taking place in the cementitious medium, resulting in lower strength values.

- Ductile behavior was observed in the fiber-reinforced specimens. The ductility was quantified through the term of deformability index and it was seen that the axial strain at peak strength of specimens with 4% and 6% cement increased up to 1.5 times as the fiber ratio increased.
- Freeze – thaw cycles caused a strength loss in the specimens but the UCS values were higher in the specimens compared with the same type of specimen without fibers. The specimens reinforced with 0.6% fibers, the UCS values were 40% and 37% higher after 1 cycle and 3 cycles, respectively. Therefore, fiber reinforcement may provide a good solution for soils under freeze-thaw effects.
- Mass loss after 3 cycles of freeze – thaw was between 0.08% and 0.1%.

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