Compressive Strength of Fiber-Reinforced Lightly-Cement Stabilized Sand

Résistance à la compression des sables renforcées par fibres et ciment

Sadek S., Najjar S., Abboud A.
Department of Civil and Environmental Engineering, American University of Beirut

ABSTRACT: The stabilization of soils using cementing agents has long gained acceptance and is well established in geotechnical engineering practice. Furthermore, adding discrete fibers to the cement-treated soil has been shown to improve the soil's response to loading and its overall engineering behavior. Limited studies of the behavior of fiber-reinforced cemented sand in the laboratory indicated that the addition of cement and fibers results in an increase in the strength of the composite, especially at high fiber contents and lengths. Cemented sands were found to be brittle compared to un-cemented sands, with the brittleness decreasing with the inclusion of fibers. The objective of this paper is to investigate the effect of randomly distributed fiber reinforcements and cement addition on the response of sandy soils. To achieve this objective, the behavior of cement/fiber-reinforced sands was studied using unconfined compression tests. The parameters that were varied are [1] the cement content (0.5% and 1%), [2] the fiber content (0%, 0.25%, 0.5%, and 1.0%), and [3] fiber lengths (6, 12 and 20 mm). The results of the tests were used to quantify the degree of improvement in strength and stiffness due to the addition of fibers and cement to the cohesionless sand.

RÉSUMÉ: La stabilisation des sols en utilisant des agents de cimentation a longtemps été accepté et est bien établie dans la pratique de la géotechnique. De plus, l'ajout de fibres discrètes au sol-ciment a été demontré effectif pour améliorer la réponse du sol au chargement et son comportement mécanique global. Seules quelques études éxistent où le comportement des sols renforcés par des fibres et ciment a été é tudie au laboratoire. Elles ont indiqué que l'addition de ciment et de fibres engendrent une augmentation de la résistance du composite, en particulier à des teneurs en fibres et des longueurs élevées. Les sables cimentés ont été jugés fragiles par rapport aux sables non cimentés; cette fragilité diminue avec l'inclusion de fibres. L'objectif de cet article est d'étudier l'effet de renforts en fibres distribuées de façon aléatoire et l'ajout de ciment sur la réponse des sols sableux. Pour atteindre cet objectif, le comportement de sables enforcés par ajout de ciment / fibres r a été étudiée par des essais de compression non confinée. Les paramètres qui ont été variées sont [1] la teneur en ciment (0,5% et 1%), [2] la teneur en fibres (0%, 0,25%, 0,5%, et 1,0%), et la longueur des fibres [3] (6, 12 et 20 mm). Les résultats des tests ont été utilisés pour quantifier le degré d'amélioration de la résistance et de rigidité due à l'ajout de fibres et de ciment au sable pulvérulent.

KEYWORDS: fiber-reinforced sand, cement stabilized sands, fibers, cement, unconfined compressive strength.

1 INTRODUCTION

The geotechnical and materials/pavement engineering fields are witnessing an increasing interest in exploring soil improvement schemes that are based on the addition of stabilizing agents such as synthetic or natural fibers and/or cementing agents for various applications. The objective is to produce a composite material with improved engineering properties that could be used in lieu of good quality construction material that is typically obtained through non-sustainable and environmentally problematic activities such as quarrying. The composite material with its improved engineering properties could be used to replace conventional base and sub-base material under pavements, or to support foundations of "light" structures or infrastructure, which otherwise could not be adequately supported by the natural soil. The improved material could also be used as backfill behind earth retaining walls and reinforced or stabilized slopes.

The experimental data that is available in the literature for fiber/cement reinforced sands is relatively limited (Maher and Ho 1993, Consoli et al. 1998, Kaniraj and Havanagi 2001, Sobhan and Mashnad 2002, and Consoli et al. 2002). There is a need for designing and implementing a comprehensive experimental testing program that is aimed at investigating the behavior of fiber/cement reinforced sands systematically. To achieve this objective, the behavior of cement/fiber reinforced sands was studied in the laboratory using unconfined compression tests. The parameters that were varied in this study are [1] the cement content (0.5% and 1%), [2] the fiber content (0%, 0.25%, 0.5%, and 1.0%), and [3] fiber lengths (6, 12 and 20 mm). The results of the tests were used to quantify the degree of improvement in strength, stiffness, and ductility due to the addition of fibers and cement to the cohesionless sand.

2 EXPERIMENTAL PROGRAM

Twenty unconfined compression tests on fiber/cement reinforced sands were conducted as part of this study.

2.1 *Material Properties*

The sand used in this study is Ottawa Sand with the properties shown in Table 1. The sand classifies as a *poorly graded sand (SP)* according to the Unified Soil Classification System.

The fibers (Fig. 1) chosen for the reinforcement are polypropylene fibers, typically used as secondary reinforcement of lightweight concrete and mortar mix designs. They were adopted because they are available in several lengths, they can be mixed with soil-cement mixtures and satisfy efficiently the intended role of reinforcement. The fibers have a specific gravity of 0.91 g/ml, a tensile strength of 0.38 kN/mm^2 and a young modulus of 3.5 kN/mm^2. Fiber lengths of 6 mm ±1, 12 mm ±1 and 20 mm ±1 were used in the testing program. The nominal diameter of the fibers was determined in the lab under an electronic microscope to be in the order of 0.1mm.

Table 1. Table caption (TNR 8), numbered consecutively. Tables placed below caption. TNR 8 for text and numbers in Table.

Soil Property	Value
D_{10} (mm)	0.22
D_{30} (mm)	0.31
D_{60} (mm)	0.42
Coefficient of uniformity (D_{60}/D_{10})	1.95
Coefficient of curvature $(D_{30})^2/(D_{60}*D_{10})$	1.04
Maximum and minimum void ratios (e_{max},e_{min})	(0.75,0.49)
Specific gravity	2.65

The cement used in this study is normal Portland cement type I. The same sources of cement and sand were used for all the specimens to eliminate all risk of material discrepancy.

2.2 *Sample Preparation*

The specimens used in the UCS tests were prepared in cylindrical PVC split molds to facilitate the extraction of the sample after formation. For a given test, the material quantities were determined based on the target fiber content, cement content, and sand density. Initially, the sand and cement were mixed in dry conditions before adding 5% by weight of water necessary for the hydration of the cement and blending of the mixture. The fibers were then mixed thoroughly with the sand-cement to obtain a final homogenous mix with well-distributed and untangled fibers. It is to be noted that all the mixing was done manually since the use of a mechanical mixer could result in tangling and clodding of the fibers and their segregation from the soil mixture. Each layer was then compacted into the mold to the required height under the effect of a compaction tool which was specifically designed for the purpose. The top surfaces of the 1^{st} and 2^{nd} layers were scratched prior to putting the new material for the subsequent layer in order to obtain, to the extent possible, a homogenous specimen and eliminate the risk of weak shear planes at the contact surface between two layers.

A curing time of 8 ± 1 days was chosen to allow the cement enough to time to set. Since the curing time is not a parameter which was studied in the testing program, the period of 8 days was chosen as an average time which provides a significant period for curing without unduly prolonging the overall time needed for each test.

2.3 *Unconfined Compression Strength Tests*

The UCS tests were performed according to ASTM D2166 with specimens having a diameter of 5.5 cm and a height of 11 cm giving an acceptable height to diameter ratio of 2. The machine used in the tests is a HUMBOLDT HM-3000 loading frame fully automated and computer software-controlled. The vertical deformation is recorded by an LVDT, while the resisting axial load is recorded by load cells of different capacities. The rate of application of the strain is 0.05 cm/min. The data were recorded automatically every 4 seconds and the test was continued until failure occurred or when the axial strain exceeded 15%.

3 TEST RESULTS AND ANALYSIS

Results from twenty unconfined compression tests on fiber/cement reinforced sands are presented in this paper. The tests were restricted to lightly cemented sands (cement content = 0.5% and 1.0%) that were reinforced with fibers of different lengths (6mm, 12mm, and 20mm) at different fiber contents (0%, 0.25%, 0.5%, and 1.0%). The analysis of the tests includes an assessment of the stress-strain behavior and the dependency of the unconfined compressive strength on the reinforcement parameters (fiber content, fiber length, and cement content).

Figure 1. Polypropylene fibers used in the experiments.

3.1 *Stress-Strain Response*

The stress-strain response of specimens that were stabilized with a cement content of 0.5% is presented in Figs. 2a, 2b, and 2c for fiber contents of 0.25%, 0.5%, and 1.0%, respectively. The response of specimens that were reinforced with a cement content of 1.0% is similarly presented in Figs. 3a, 3b, and 3c. On each of the plots, stress-strain curves are presented for different fiber lengths (6mm, 12mm, and 20mm) and for the specimen that was prepared with no fibers.

For specimens that were reinforced with a cement content of 0.5% (Fig. 2), the stress strain curves indicate a consistent increase in stress with strain up to a maximum peak stress value at which failure occurs. The value of the peak and the post peak behavior are a function of the cement content, fiber content, and fiber length. The failure mode as indicated by the value of the strain at failure and by the post peak response is found to be more ductile as the fiber content increased from 0% to 1.0%. In addition, for a given fiber content, ductility was found to improve as the length of fibers increased from 6mm to 20mm.

For the higher cement content of 1.0% (Fig. 3), the behavior of the composite specimens was found to be more brittle compared to their lightly cemented counterparts. The inclusion of fibers added some ductility to the mode of failure, but this effect was minor for the smaller fiber contents (0.25% and 0.50%). The improvement in the mode of failure was only evident in the higher fiber content of 1.0% at all fiber lengths and for the intermediate fiber content of 0.5%, but only at the larger fiber length of 20mm.

3.2 *Effect of Fiber/Cement on Stiffness*

The stress-strain response at the onset of loading in Figs. 2 and 3 could be used as a measure of stiffness for the fiber/cement reinforced specimens. For the smaller cement content, results on Fig. 2 indicate that the stiffness of the specimens was not affected by the addition of fibers except for cases involving the longest fibers (20mm) with fiber contents of 0.25% and 0.50% where the stiffness was found to be improved. For cases involving fibers with a high fiber content of 1.0%, no improvements were observed in the stiffness, irrespective of the fiber length.

A slightly different behavior was observed for the higher cement content of 1.0% where slight improvement in stiffness were observed for the shorter fibers at the smaller fiber contents, with the improvements in stiffness vanishing for the longest fiber and the highest fiber contents, where slight reduction in stiffness was actually observed. This indicates that fibers could result in a softer initial response for higher cement contents, higher fiber content, and longer fibers.

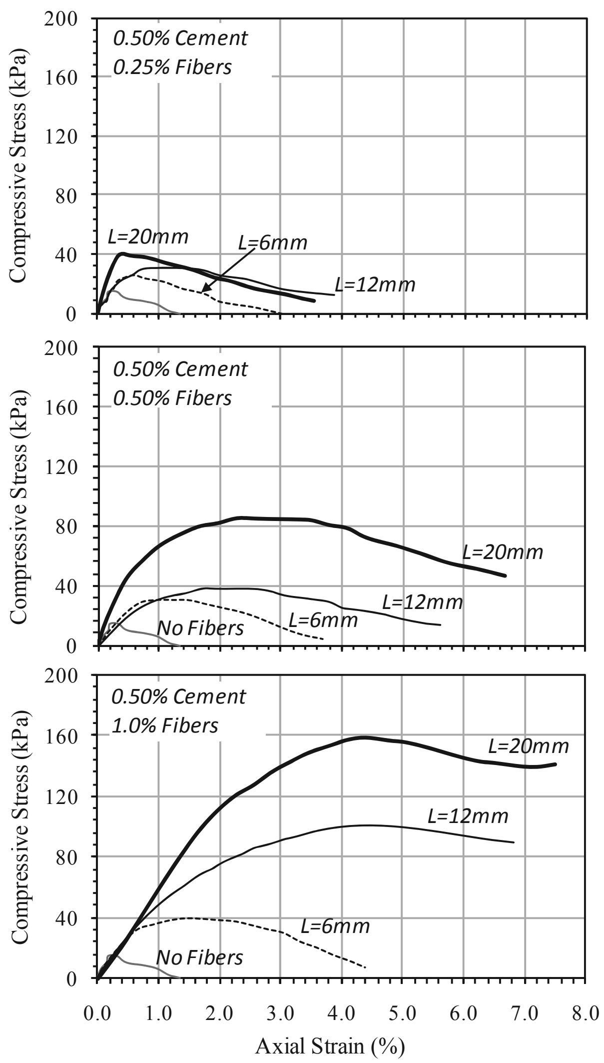

Figure 2. Stress-strain response for cement content of 0.5%.

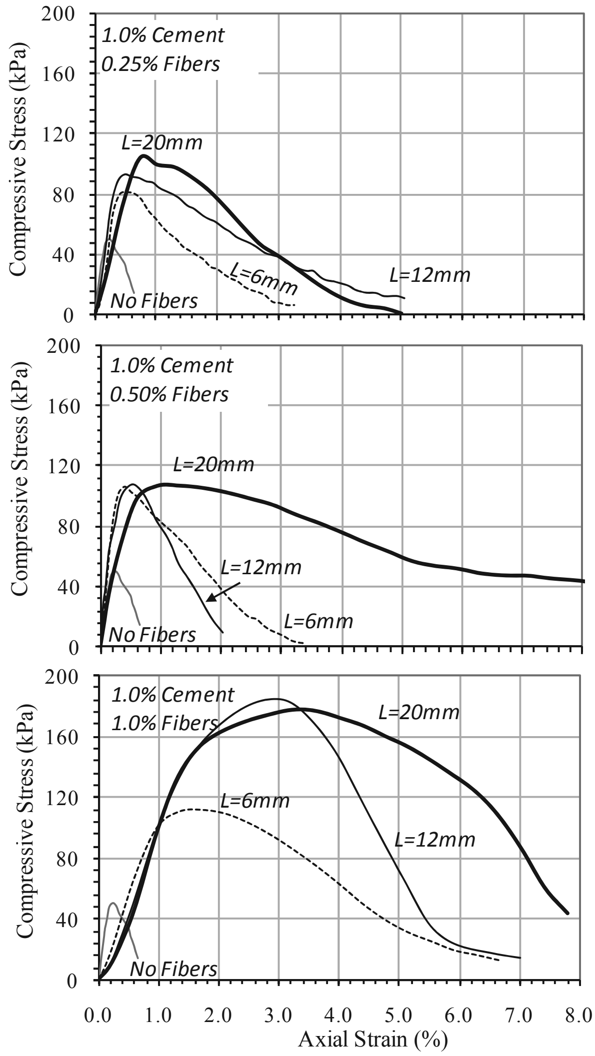

Figure 3. Stress-strain response for cement content of 1.0%.

3.3 *Effect of Fiber Content on UCS*

For a given cement content, the stress-strain curves in Figs. 2 and 3 indicate that the unconfined compressive strength increases as the fiber content increases. The unconfined compressive strength for each test was computed and plotted as a function of the fiber content in Figs. 4a and 5a for cement contents of 0.5% and 1.0%, respectively. For the two cement contents and for all fiber lengths, results indicate a consistent increase in the unconfined compressive strength with fiber content. For a cement content of 0.5%, the UCS increased from about 15 kPa (no fibers) to about 40 kPa (1.0% fibers) for the shortest fiber length of 6mm, and from 15 kPa (no fibers) to about 160 kPa (1.0% fibers) for the longest fiber length of 20mm. For the larger cement content of 1.0%, the UCS increased from about 50 kPa (no fibers) to about 112 kPa and 178 kPa, for the shortest and longest fibers at 1.0% fiber content, respectively.

In order to obtain a quantitative measure of the degree of improvement in the unconfined compressive strength, the ratio of the UCS with fibers to the UCS without fibers was computed and plotted versus the fiber content in Figs. 4b and 5b. These results indicate that the cement content played a significant role in defining the improvement ratio, with the ratio varying from 2 (smallest fiber content and fiber length) to 10 (largest fiber content and fiber length) for a cement ratio of 0.5%, and from about 2 to 4 for the larger cement ratio of 1.0%.

3.4 *Effect of Fiber Length on UCS*

The effect of the fiber length on the stress-strain response and on the improvement in the UCS is evident in Figs. 2 to 5 and is found to be dependent on the cement content. For a cement content of 0.5%, as the fiber length increases, the unconfined compressive strength increases and the strain at failure increases, indicating improved ductility. The effect of fiber length was found to be more evident at higher fiber contents compared to lower fiber contents. For example, for the small fiber content of 0.25%, the improvement ratio in the UCS increased slightly from 1.7 to 2.6 (for fiber length of 6mm and 20mm) compared to the dramatic increase from 2.6 to 10.6 (for fiber length of 6mm and 20mm) for the larger fiber content of 1.0%.

For the larger cement content of 1.0%, the effect of fiber length on the unconfined compressive strength becomes smaller. For the smaller fiber contents of 0.25% and 0.5%, the difference in the measured values of the UCS is relatively insignificant, with improvement ratios varying in the narrow range of 1.6 to 2.0 (fiber content of 0.25%) and 2.1 to 2.15 (fiber content of 0.50%) for the shortest and longest fibers, respectively. For the largest fiber content of 1.0%, the improvement ratio increases from 2.2 to 3.7, as the fiber length increases from 6mm to 20mm.

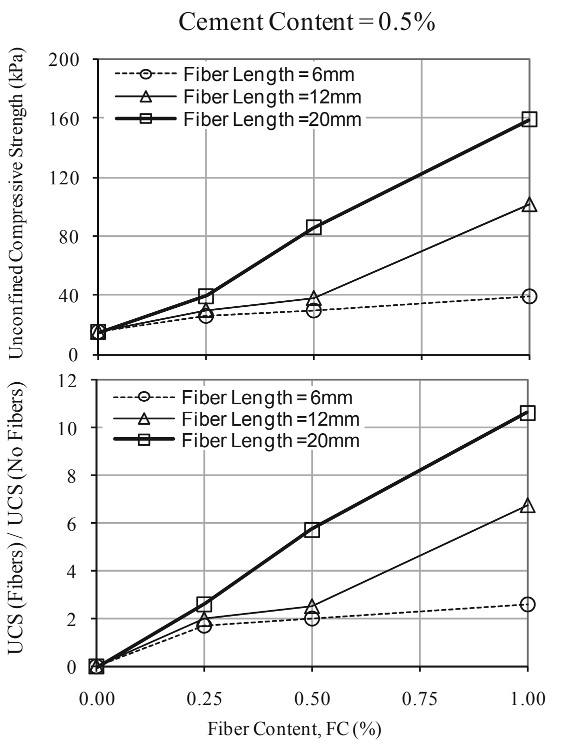

Figure 4. Improvement in UCS for cement content of 0.5%.

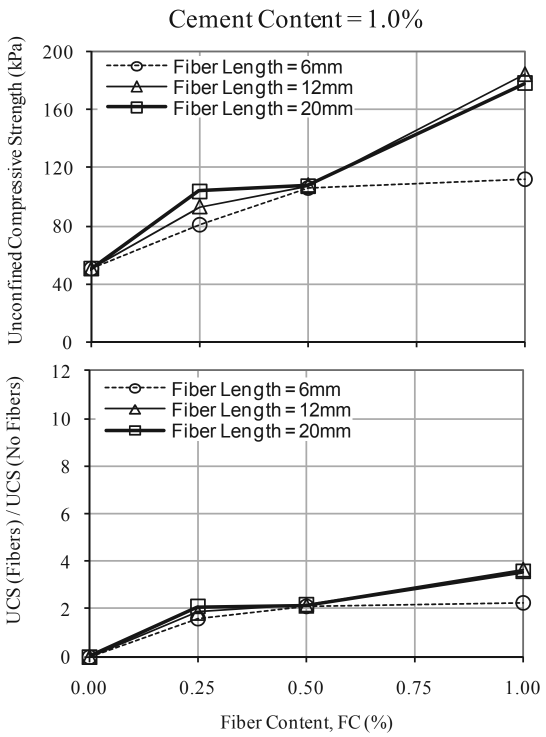

Figure 5. Improvement in UCS for cement content of 1.0%.

3.5 *Effect of Cement Content on UCS*

The range of the cement content that was chosen in this study (0.5% to 1.0%) is indicative of lightly-cemented sands. However, the results presented in Figs. 2 to 5 indicate a clear difference in the performance of the composite specimens that were stabilized with 0.5% cement and specimens stabilized with 1.0%, particularly with regards to the contribution of the fibers to the improved compressive strength.

For specimens that were not reinforced with fibers, the increase in cement content from 0.5% to 1.0% increased the unconfined compressive strength from 15 kPa to 50 kPa. With the addition of fibers, results showed that the UCS could be improved by more than 10 times for a cement content of 0.5% but only to 3.7 times for the cement content of 1.0%, indicating a decreased relative efficiency of the fibers at improving the compressive strength as the cement ratio increases.

It should be noted however that the actual maximum value (largest fiber content and fiber length) of the unconfined compressive strength was still higher (about 185 kPa) for the cement content of 1.0% compared to the maximum value (159 kPa) measured for the cement content of 0.5%. For the smaller fiber contents and fiber lengths, the values of the UCS for the cement content of 1% were all higher than those of the 0.5% at the same fiber content and fiber length, indicating that the magnitude of the improved UCS was larger for the higher cement content.

4 CONCLUSION

Based on the results of 20 unconfined compression tests that were conducted in this study on fiber-reinforced lightly-cemented sands, the following conclusions can be drawn:

1. The behavior of specimens with higher cement contents is more brittle compared to specimens with lower cement contents. However, brittleness decreased with the inclusion of fibers and the energy absorption capacity increased as the fiber content and length increased.
2. For the smaller cement content, the stiffness of the specimens was not affected by the addition of fibers, except for the cases of 20mm fibers with fiber contents of 0.25% and 0.50%, where the stiffness was found to be improved. For the higher cement content fibers could result in a softer initial response particularly for higher fiber contents and longer fibers.
3. For the both cement contents used, results indicated a consistent increase in the unconfined compressive strength with fiber content. The cement content played a significant role in defining the improvement ratio of the UCS, with the ratio varying from 2 (smallest fiber content and fiber length) to 10 (largest fiber content and fiber length) for a cement ratio of 0.5%, and from about 2 to 4 for the larger cement ratio of 1.0%.
4. For a cement content of 0.5%, as the fiber length increased, the UCS 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. For the larger cement content of 1.0%, the effect of fiber length on the unconfined compressive strength was less significant.

5 ACKNOWLEDGEMENTS

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