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Studia Geotechnica et Mechanica, 2021; 43(1): 15–21

Original Study **Open Access**

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Influence of Waste Toothbrush Fiber on Strength and Freezing–Thawing Behavior in High Plasticity Clay

https://doi.org/10.2478/sgem-2020-0006
received June 3, 2020; accepted September 15, 2020.

Abstract: The use of waste materials in civil engineering applications has gained importance nowadays. Consuming limited natural resources and increasing waste disposal costs have led researchers to evaluate waste materials for different geotechnical applications. In this respect, some waste materials are used as reinforcement in soils to improve their engineering properties. The main objective of this paper was to investigate the usability of waste polypropylene fiber as a reinforcement material in high plasticity fine-grained soils. For this purpose, waste toothbrush bristle (WTB) was used as a polypropylene fiber reinforcement material and added to fine-grained soil at ratios of 0.2%, 0.4%, 0.6% and 0.8% by dry total weight. The effect of WTB on freezing–thawing behavior and unconfined compression strength of unreinforced and reinforced clayey soil was evaluated. The results indicated that addition of WTB to high plasticity clay improved its behavior against freezing–thawing. Also, undrained shear strength increases with respect to increment in WTB ratio.

Keywords: Waste material, Polypropylene fiber, Toothbrush bristle, Freezing–thawing, Unconfined compression test, Reinforced clay

1 Introduction

In some cases in geotechnical applications, structures must be constructed on problematic soils that may have less bearing capacity or excessive settlements. In order to improve the geotechnical properties of these kinds of soils, waste materials such as borogypsum [1–3], phosphogypsum [4–8], silica fume [9–14], fly ash [15–24] and scrap tire rubber [25,26] have been used.

On the other hand, a wide range of reinforcements has been used to improve soil performance. Increasing the soil strength has caused increased interest in identifying new accessible resources for reinforcement. Due to offering faster, more effective and more economical solutions, these kinds of materials are preferred when compared with conventional methods. In the literature, metal strips [27], metal bars [28], rope fibers [29,30], geotextiles [31,32] and geogrids [33–37] are usually used as soil reinforcement materials.

Economic growth and changes in people's consumption and production patterns are resulting in rapid increase in the generation of solid waste in the world. The storage of these kinds of wastes creates some environmental problems and threatens human health. Recycling of solid waste materials decreases consumption of natural resources and also avoids the environmental problems that occur due to the storage of solid waste materials. Toothbrush is one of the domestic wastes produced by people. Davis and Hudson [38] indicated that approximately 50 million pounds of plastic toothbrushes are discarded each year in the United States. Even the cities with low economic growth have started producing toothbrush waste due to increased use of toothbrushes. As a result of the increasing importance given to oral and dental health all over the world, it is seen that every year millions of tons of waste toothbrushes are produced. This implies that on one hand, more toothbrushes are being used to meet the increased demand of oral and dental health, and on the other hand, more toothbrush waste is being generated.

In this study, the usability of toothbrush bristle, which is a waste material, as a propylene fiber reinforcement material in fine-grained soil was investigated. Therefore, fine-grained soil was mixed with waste toothbrush bristle (WTB) at ratios of 0.2%, 0.4%, 0.6% and 0.8% by dry total weight. The effect of toothbrush bristle on freezing–

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thawing behavior and unconfined compression strength (UCS) of reinforced samples with WTB was evaluated.

2 Materials and Methods

The high plasticity clayey soil used in these experiments was obtained locally from a landfill area, and it has been classified as CH according to the Unified Soil Classification System (USCS) with ASTM D2487 [39]. Some geotechnical properties of this clayey soil are summarized in Table 1. The toothbrush bristle was obtained by cutting from waste toothbrushes using a lancet. The length of bristles was approximately 10 mm (Figure 1a).

The reinforced samples were prepared with WTB at ratios of 0%, 0.2%, 0.4%, 0.6% and 0.8% by weight of dry soil. Waste toothbrush bristle was mixed with soil randomly for unconfined compression and freezing–thawing tests. The dry clay was initially mixed with WTB manually (Figure 1b). After the dry mixing procedure, an appropriate amount of water was added to the WTB–clay mixture in order to get it to optimum water content. Maximum care was taken to ensure a homogeneous distribution of the toothbrush bristle in the clay. The WTB–clay mixtures were stored in a covered container for 24 h (Figure 1c). Mixtures were compacted in three layers into a 38 mm diameter and 76 mm high cylindrical mold at optimum water content. The sample preparation method was adapted from the standard compaction test method (ASTM D-698) [40].

The unconfined compression test was performed according to ASTM D 2166 [43]. Unreinforced and reinforced samples were tested in an unconfined compression machine with 0.8 mm/min loading rate. The UCS ratio was used to examine the effect of WTB with respect to the number of freezing–thawing cycles. The UCS ratio was defined as the ratio of the UCS of reinforced samples to unreinforced samples (Eq.1). The UCS ratio value of unreinforced samples was assumed as 1.00.

$$UCS\ Ratio = \frac{UCS\ of\ Reinforced\ Sample}{UCS\ of\ Unreinforced\ Sample}. \qquad (1)$$

The freezing–thawing tests were conducted in a programmable freezing–thawing cabinet. These tests were carried out on unreinforced and reinforced clay. Samples were wrapped in aluminum foil to prevent changes in their water content [44]. A thin film layer of Vaseline was spread on the foil to prevent samples from sticking to the aluminum foil [45,46]. The prepared samples were placed in the programmable freezing cabinet to remain at –20°C for 6 h and at 25 °C for 6 h (Figure 2). This operation was named as one cycle [47]. Numbers of freeze–thaw cycles were chosen in accordance with the literature as 3, 6, 9 and 12 freezing–thawing cycles [47–49].

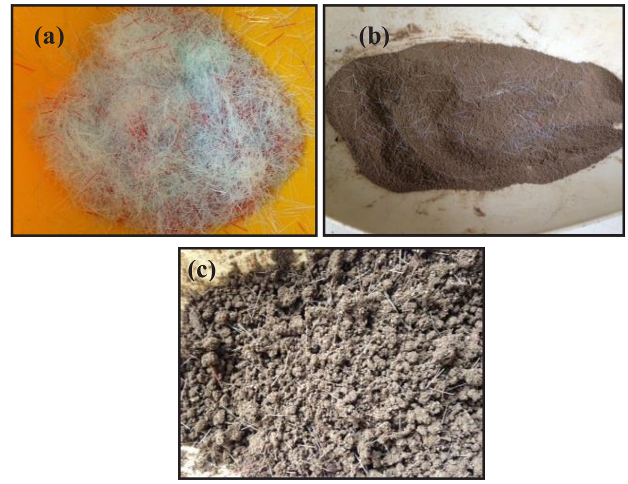


Figure 1: Toothbrush bristles (a) after cutting, (b) after mixing with dry soil, (c) after adding optimum water content.

Table 1: Some properties of clayey soil used in tests.

Properties	Value
Liquid limit[1], w_L (%)	57.8
Plastic limit[2], w_P (%)	24.4
Plasticity index, I_P (%)	33.4
Optimum water content[3], w_{opt} (%)	23.6
Maximum dry unit weight[3], γ_{dmax} (kN/m^3)	15.3
Soil class (USCS)	CH

[1] w_L per BS 1377 (Part 2-1990) [42].
[2] w_P per ASTM D 4318-00 (2000) [41].
[3] Obtained from Standard Proctor Tests [40].

The freezing–thawing mass loss (FTML) of the reinforced and unreinforced samples was also determined. For this reason, the weights of each sample were measured before and after freezing–thawing cycles. In order to calculate the FTML of the samples, Eq. (2) was used [50].

$$FTML\ (\%) = \frac{IW - AW}{IW} \times 100, \qquad (2)$$

where **IW** (i.e., initial weight) is the weight of samples before freezing–thawing cycles and **AW** (i.e., after weight) is the weight of samples after freezing–thawing cycles.

Figure 2: Closed system full automatic freezing–thawing test cabinet.

Table 2: Prepared samples, WTB ratios and number of freezing–thawing cycles.

Sample Description	WTB Ratio (%)	Number of Cycles
Unreinforced	0.0	0–3–6–9–12
Reinforced-1	0.2	0–3–6–9–12
Reinforced-2	0.4	0–3–6–9–12
Reinforced-3	0.6	0–3–6–9–12
Reinforced-4	0.8	0–3–6–9–12

The prepared reinforced and unreinforced samples and WTB ratios are summarized in Table 2. As can be seen from Table 2, one unreinforced sample and four different reinforced samples were used in this study. For each of the reinforced and unreinforced samples, five different test samples were prepared due to five different freezing–thawing cycles. Also, one more test sample was prepared for each of the unreinforced and reinforced samples and at the end these two test samples' averages were used for calculation. As a result, a total number of 50 test samples were prepared and tested in this study.

3 Results and Discussions

The stress–strain curves of reinforced and unreinforced samples at five different freezing–thawing cycles are given in Figure 3.

It is seen in Figure 3 that an increment in WTB ratio generally increases the peak shear stress at each freezing–thawing cycle. Furthermore, the reinforced samples tend to show higher shear stress than the unreinforced samples, especially at large strains. This behavior was also found by [51,52]. Figure 3 indicates that an increase in freezing–thawing cycles generally leads to a decrease in peak shear stress of reinforced and unreinforced samples. Similar behavior was also observed by [47,51–56].

The photos of reinforced and unreinforced samples after the unconfined compression test are presented in Figure 4. It has been observed in parallel to the findings available in the literature that the reinforced samples exhibit more ductile behavior than the unreinforced samples at each freezing–thawing cycle [57–59], as seen in Figure 4. It is assumed that WTB forms bonds and is randomly distributed into the soil, acting as a bridge between soil particles.

The peak stress values are used to calculate the undrained shear strength (c_u) of the reinforced and unreinforced samples. The relationship between c_u and WTB content is shown in Figure 5. It is clearly seen in Figure 5 that a significant increase is observed in c_u with increasing WTB ratio at 0 and 3 freezing–thawing cycles. The increment in c_u values is approximately 63% and 42% at 0 and 3 cycles, respectively. On the other hand, an increase in freezing–thawing cycles causes a decrease in c_u values at high freezing–thawing cycles (i.e., 6–9 and 12). It may be attributed to the fact that pore water freezes and forms ice lenses in the pore space between the soil particles; then these ice lenses expand in volume and push particles of the soil and act like springs, increasing gaps among soil particles [60].

The UCS ratios for peak strengths are shown in Figure 6a. It can be seen from Figure 6a that the peak UCS ratios of all reinforced samples are higher than the unreinforced sample at zero cycle. However, the UCS ratio values start to decrease steadily between 0 and 9 cycles while there is an increase between 9 and 12 cycles. The relationship between the ultimate UCS ratio and freezing–thawing cycles is illustrated in Figure 6b. The ultimate UCS ratio values of all reinforced samples are generally higher than the unreinforced samples at all freezing–thawing cycles. It is seen that the ultimate UCS ratio values of reinforced samples are higher than the peak UCS values when Figures 6a and 6b are compared. This situation does not mean that the UCS of reinforced samples of ultimate strain is higher than the peak ones. This means that the strength loss of unreinforced samples at large strains is more pronounced than those at the peak strains.

The relationship of FTML with freezing–thawing cycles is shown in Figure 7. It should be noted that the lower the

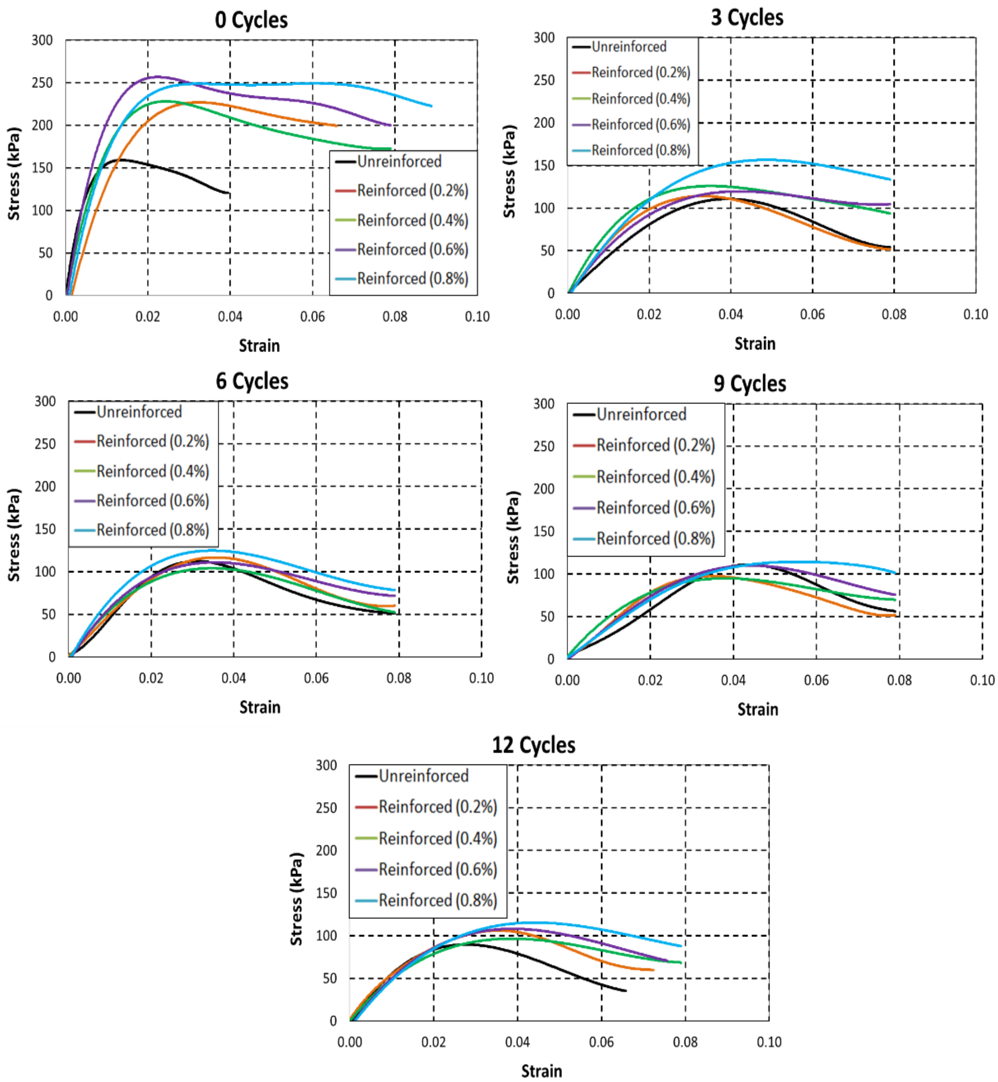


Figure 3: Stress–strain curves of samples at (a) 0 cycle, (b) 3 cycles, (c) 6 cycles, (d) 9 cycles, (e)12 cycles.

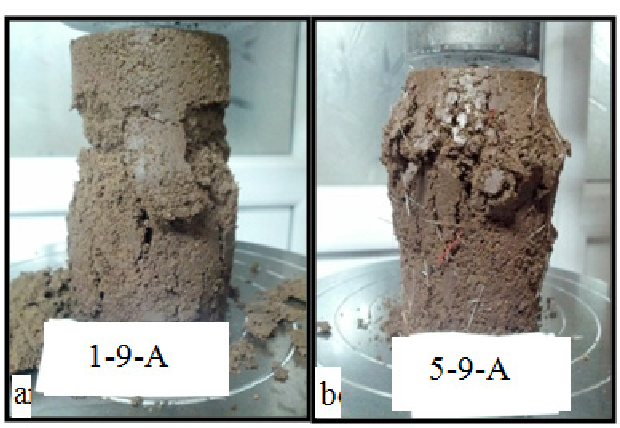
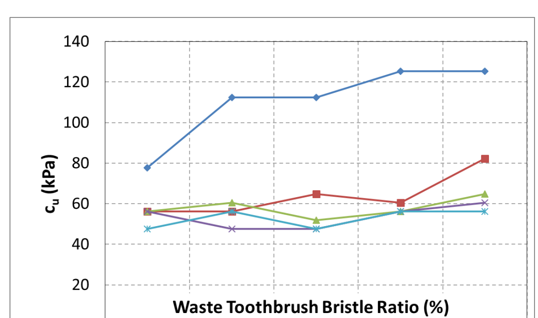


Figure 4: Unconfined compression test: (a) unreinforced sample (9 cycles), (b) reinforced sample (toothbrush bristles 0.8% ratio, 9 cycles).



	0.00	0.20	0.40	0.60	0.80
0 Cycles	77.8	112.4	112.4	125.4	125.4
3 Cycles	56.2	56.2	64.9	60.5	82.1
6 Cycles	56.2	60.5	51.9	56.2	64.9
9 Cycles	56.2	47.6	47.6	56.2	60.5
12 Cycles	47.6	56.2	47.6	56.2	56.2

Figure 5: Waste toothbrush bristle ratio vs. undrained shear strength.

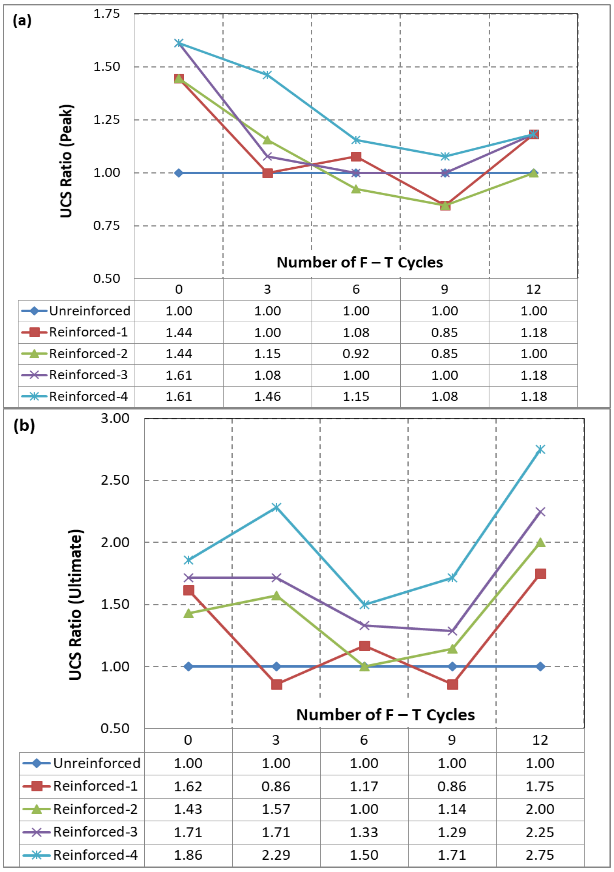


Figure 6: Relationship between (a) the peak UCS ratio, (b) the ultimate UCS ratio and freezing–thawing cycles.

Figure 7: Relationship between FTML and freezing–thawing cycles.

FTML value, the better the durability to freezing–thawing effect. Experimental results show that the FTML values of reinforced samples are generally lower than unreinforced samples (Figure 7). This means that the reinforced samples are more durable than the unreinforced samples.

4 Conclusions

In this study, a series of unconfined compression and freezing–thawing experiments were conducted in the laboratory in order to observe the freezing–thawing behavior of fine-grained soils reinforced with WTB in different ratios. The general results from the experiments are as follows:

– The results indicate that WTB mixed with clayey soils can be used as a reinforcement fiber material.
– Increment in toothbrush bristle ratio generally increases the peak shear stress at all freezing–thawing cycles.
– The reinforced samples tend to exhibit higher shear stress at large strains when compared with the unreinforced samples.
– An increase in freezing–thawing cycles generally leads to a decrease in peak shear stress of reinforced and unreinforced samples.
– The reinforced samples exhibit more ductile behavior than unreinforced samples at each freezing–thawing cycle.
– A significant increase is observed in c_u with increasing toothbrush bristle ratio at 0 and 3 freezing–thawing cycles.
– The FTML values of reinforced samples are generally lower than unreinforced samples.

In order to achieve more realistic judgments on the subject, experiments are recommended to be continued for further studies with different soil types, numbers of freezing–thawing cycles and WTB contents.

Acknowledgments: Support has been provided for this research work from the funds of the Scientific Research Project of Ataturk University. The authors express their gratitude to Ataturk University for this support.

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