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ORIGINAL PAPER

Problematic Soft Soil Improvement with Both Polypropylene Fiber and Polyvinyl Acetate Resin

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Abstract Several methods are used to improve mechanical properties of loose soils including rewetting, soil replacement, compaction control, chemical additives, moisture control, thermal methods, and more recently, discrete fibers. All the methods are applied to soft soil to increase load bearing capacity and to improve other properties such as prevention of erosion and dust generation. In the present study, a new method of soil improvement using both discrete polypropylene (PP) fibers and polyvinyl acetate (PVAc) is introduced. The method is applied to improve load bearing capacity of a problematic sandy soil in both dry and saturated states. Based on the results from CBR tests on various specimens, it has been revealed that the combination of PP fiber and PVAc resin with weight percentages of 0.1 and 0.6 %, respectively, had the optimum effect in increasing the CBR value in both saturated and dry soil specimens. It should be mentioned that this method has caused a great increase in the CBR value in the saturated soil.

Keywords Soil improvement · Polypropylene fiber (PP) · Polyvinyl acetate resin (PVAc)

1 Introduction

Soil improvement is used to increase bearing capacity, reduce settlement, prevent erosion, and dust generation in problematic soils. Basically, some properties of soft soil such as compressibility and permeability are improved in order to have higher shear strength, compressibility, density and hydraulic conductivity (Kazemian and Barghchi 2010). Application of stabilizing agents on soil has a long history, for example in the application of fiber in the Great Wall of China, 2000 years ago (Hongu and Philips 1990). When stabilizing agents are added to soil, a series of reactions take place. These processes cause stronger bonds between grains, fill up voids, and consequently cause higher load bearing capacity in soil. Several improvement methods such as chemical additives, rewetting, soil replacement, compaction control, moisture control, and thermal methods are applied by engineers. All these methods, however, have some drawbacks such as being costly, ineffective and of a low durability. Chemical stabilization by cement or lime is a proven technique (Ismail et al. 2002; Basha et al. 2005); these technique, nevertheless, cause high stiffness and brittleness in soil (Hongu and Philips 1990).

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In contrast to other methods, soil improvement with discrete fibers would be a better choice based on the following factors:

- Discrete fibers are simply added and mixed into the soil, in much the same way as cement, lime, or other common additives (Yetimoglu and Salbas 2003).
- Randomly discrete fibers limit potential planes of weakness that can develop parallel to oriented reinforcement (Yetimoglu and Salbas 2003; Kumar et al. 2006; Maher and Gray 1990).
- This method also causes less brittleness and it is more durable in soil (Yetimoglu and Salbas 2003; Marandi et al. 2008).
- In contrast to lime, cement and other chemicals stabilization methods, fiber reinforced soil is not dramatically affected by weather conditions.
- Fiber inclusion soils prevent the formation of tension crack in soil (Marandi et al. 2008; Consoli et al. 2009).

In recent years, many researches were done to study the behavior of fibers to evaluate their effects in soil. Park (2008) figured out a significant increase in the strength of the FRCS (fiber reinforced cemented sand) by adding randomly PVA fibers with cement to soil. Consoli et al. (2009) compared the performance of discrete fiber with cement in soil. They reached better qualities in soil using discrete fibers, more peak and ultimate strength, less brittleness and stiffness (Consoli et al. 2009). It seems that polypropylene fiber is employed in soil improvement because of its excellent acid and alkali resistance. Moreover, it is founded that interfacial shear strength between soil and PP fibers depends on soil particles, effective interface contact area, and fiber surface roughness (Tang et al. 2010).

PP fibers, used in this study are more interested by researchers these days. They are used to increase soil strength properties and unconfined compressive strength UCS, and to reduce soil shrinkage, volumetric shrinkage and swelling (Khattak and Alrashidi 2006; Yetimoglu et al. 2005; Vasudev 2007; Puppala and Musenda 2000; Tang et al. 2006). PP fibers harden soft soils. They could be used in shallow foundations, embankments and in other earthworks that may suffer excessive deformation in order to reduce settlements. It has been investigated that PP fiber reinforced compacted sandy soil had an acceptable hardening even at 20 % strain increase (Puppala and Musenda 2000). PP reinforced specimens demonstrate higher ductility during triaxial or UCS tests. The effect of fiber inclusion on soil could be seen in Fig. 1. The reinforced specimen bulged, indicating an increase in the ductility; while, axial deformation of the unreinforced specimen resulted in the development of a failure plane (Freilich et al. 2010).

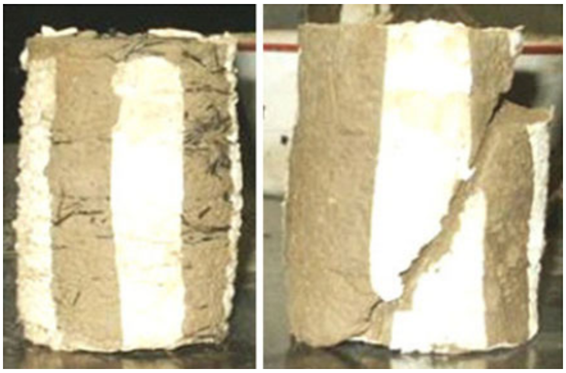


Fig. 1 Specimen deformation pattern for (*right*) unreinforced clay soil specimens and (*left*) clay soil reinforced with 0.25 % PP of 19 mm (Freilich et al. 2010)

To sum up, fiber strands and soil grains interact together due to fiber roughness, the compressive friction forces; and the cohesion properties of soil. Chemical binders could be added to soil to increase soil-fiber adhesion. So, in theory, better properties could be reachable using chemical binders.

This paper attempts to introduce a novel method of soil reinforcement, using PP fibers with polyvinyl Acetate resin (PVAc), as a chemical binder, together. Based on our previous study, it had been found that PVAc has a suitable bond with soil grains but only in the case of dry soil. PVAc resin loses its performance in saturated soil (Abtahi et al. 2009). Due to the fact that water does not considerably change the properties of fiber-composites, fibers can perform at a superior level in a fully wet condition in the soil. Thus, the combination of PP fiber and PVAc resin is presented in this study.

2 Experimental

2.1 Materials

A clayey soil, a very loose problematic soil with high amounts of sulfate, used in the present experimental tests was obtained from an arid zone in the vicinity of

Table 1 Properties of selected soil

Property	Value
Specific gravity	2.67
Liquid limit (%)	31
Plastic limit (%)	13.8
Plasticity index	17.2
USCS classification	SC
Optimum moisture context (%)	13.7
Dry CBR (%)	1.63

Isfahan, Iran. Soil was sieved in accordance with ASTM10 standard and was washed in accordance with ASTM200 standard. It was classified as SC, based on the Unified Soil Classification System. Its properties are listed in Table 1. The optimum moisture was gained at 13.7 %, based on the standard proctor compaction test.

Polypropylene (PP) and polyvinyl acetate (PVAc) are used as fiber and resin, respectively. Polyvinyl acetate is a polymeric material which is obtained from polymerization of free vinyl radicals based on Vinyl monomers. This material was made and discovered in 1912 by Fritz Kalath in German, known as PVAc in the market (Tolleson et al. 2003). The chemical formulation of PVAc is shown in Fig. 2. Polypropylene (PP), also known as polypropene, is a thermoplastic polymer. Polymer made from the monomer propylene, it is rugged and unusually resistant to many chemical solvents, bases and acids. In addition, polypropylene is reasonably economical. One important reason for using polypropylene fiber in this study is its workability in saturated soil. Polypropylene fibers are shown in Fig. 3. Some physical and mechanical properties of PP fibers are listed in Table 2.

2.2 Preparation of Soil Specimens

In this study, two groups of samples including dry and saturated samples were prepared, based on ASTM D 1883.

2.2.1 Dry Samples

The optimum water content, gained from standard proctor test was added to the soil. Three layers of soil compacted with a 2.5 kg hammer at 56 blows into the mold based on standard compaction test of ASTM D698. Before each layer was compacted, some percentage of fiber was poured into the mold. All soil samples had been kept 48 h in an isolated chamber at the temperature of the laboratory (25°–30°) to let the PVAc cure before the test. Nine groups of dry samples, groups of three, were prepared with different fiber and resin percentages based on Table 3.

2.2.2 Saturated Samples

Samples were compacted in the same way as dry samples. After compacting a piece of filter paper was placed over the trimmed or struck-off top of the sample and the base plate was placed over this top. A surcharged of 4.5 kg was placed on the sample. The mold was immersed in water for 96 h. Similar to dry samples, 9 groups of saturated samples, groups of three, were prepared with different fiber and resin percentages based on Table 3.

0.6 % of resin content was assumed as the optimum content based on our previous work (Abtahi et al. 2009).

2.3 Tests

The proctor standard test was done on the soil for determining the optimal moisture content in soil, and the test was conducted as the normal proctor test based on ASTM D698.

CBR test is used to assess the bearing stress of soil in roads and airports bed pavements and also to assess the bearing stress of stone materials. Test procedure is based on (ASTM.D698-B) standard. Specimens are cylindrical metals with the internal diameter of 15.2 ± 0.1 cm (6 ± 0.026 inches) and height of 17.8 ± 0.4 (7 ± 0.16 inches), compacted in three layers and 56 taps under the condition of optimum moisture.

3 Results and Discussion

3.1 Effect of Fiber on CBR

The CBR-Fiber percent curves in both dry and saturated states obtained from CBR tests are given in Fig. 4. It can be seen from Fig. 4 that fiber inclusion increased the peak stress of soil. According to Fig. 4,

Fig. 2 Chemical formulation of PVAc

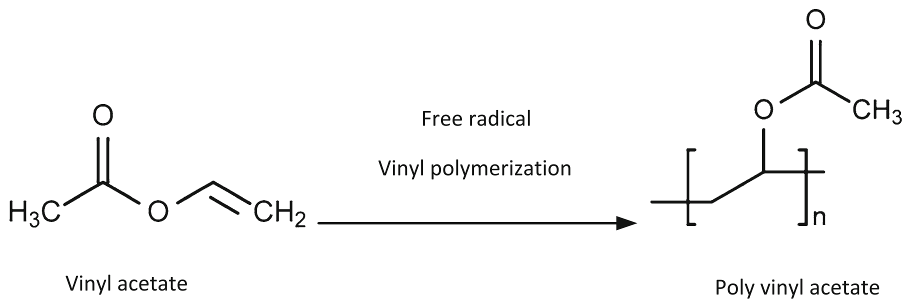


Fig. 3 12 mm polypropylene fibers

Table 2 Physical and mechanical properties of PP fiber used in this study

Property	Value
Density (gr/cm3)	0.91
Length (mm)	12
Shape	Beam-like net
Acid and alkali resistance	Strong
Tensile strength (MPa)	350–550
Elastic modules (MPa)	>3,500
Elongation at rupture	118.5 %
Water absorbency	NO
Melting point (C°)	160
Fire point (C°)	590
Color	Transparent
Homogeneity	100

the fiber content in the soil has an optimum value, 0.1 % of 12 mm fiber, in which the CBR value enhanced from 1.64 to 13.34 in a dry state, about 700 % increase, and from 0.18 to 1.64 in a saturated state, about 800 % increase. More fiber content in soil decreases the CBR value; It seems that "lubricating concept of fibers", i.e. interaction of fiber-to-fiber instead of fiber-to-soil, dominates the reinforcing performance of fibers decreasing the CBR value as the fiber content increases (Marsh 1942). There are two reasons explaining the fact that 12 mm fibers have better CBR values. First of which, longer strands bend over themselves, for example, 19 mm fibers bend more than 12 mm fibers. Second of which, in 0.1 % fiber content there are more strands of 12 mm than 19 mm in specimens.

3.2 Effect of Resin on CBR

Figure 5 obtained from our previous work, based on which the optimum resin content in soil is 0.6 % (Abtahi et al. 2009).Resin is used in soil to increase interfacial fraction between soil grains not to fill voids; so, more resin contents would not be effective. On the other hand, resin has lower strength than soil grains and if the voids are filled with resin, lower CBR value would be attained. As a result, 0.6 % resin content would be appropriate to increase the bond strength.

3.3 Effect of Fiber-Resin on CBR

In other groups of samples, the optimum content of resin, 0.6 %, added to fiber-soil samples. The penetration-stress curves obtained from CBR are given in Fig. 6, based on which it can be seen that the peak stress is increased in fiber-resin samples. The optimum content of fiber in presence of resin was determined 0.1 % of 12 mm fibers in the CBR test. At the optimum contents of fiber and resin (0.6 % PVAc with 0.1 % PP of 12 mm), the CBR value enhanced from 1.64 to 16.31, about 900 % increase in dry states; and from 0.18 to 2.4, about 1,233 % in saturated states.

Table 3 Different sample contents

Sample no.	PP fiber content (%)	PVAc resin content (%)	Soil state
1–2	_	_	Dry-saturated
3–4	0.05	0	Dry-saturated
5–6	0.1	0	Dry-saturated
7–8	0.15	0	Dry-saturated
9–10	0.25	0	Dry-saturated
11–12	0.05	0.6	Dry-saturated
13–14	0.1	0.6	Dry-saturated
15–16	0.15	0.6	Dry-saturated
17–18	0.25	0.6	Dry-saturated

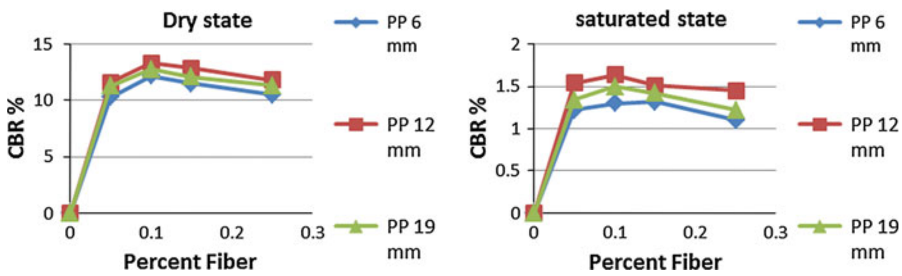


Fig. 4 Effect of PP fiber content in dry and saturated states

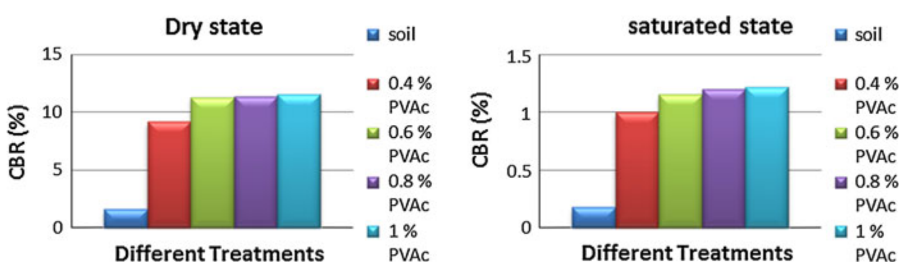


Fig. 5 Effect of PVAc resin content in dry and saturated states

As it is clear from the results, fiber-resin-soil composite has a very good workability in both saturated and dry states, especially in saturated states.

3.4 Comparison Between Different Samples in Dry and Saturated Conditions

Table 4 and Fig. 7 show the optimum CBR values.

Based on Table 4, the best results are gained in fiber-resin-soil samples. Figure 7 shows the optimum CBR in various samples, based on which, the CBR was enhanced in a more dramatic way in saturated states in fiber-resin-soil composite in comparison with resin-soil samples. This phenomenon is referred to the fact that water cannot alter any unfavorable effect on synthetic fibers including polypropylene fiber. Generally, synthetic fibers have a smooth morphological surface, there is no pores on the fiber structure (Marsh 1942). Figure 8 shows SEM image of electro-spun polypropylene fibers, in which the smooth morphological surface of polypropylene fiber can be seen (Rangkupan and Reneker 2003). Thus, synthetic fibers absorb physically little water and humidity; It is because PP fiber keeps the integrity of the soil-composite at fully wet conditions in a saturated state.

To have a comparison between dry and wet conditions, the increase in strength of the soil in wet to dry condition is obvious. Dry soil's CBR increased about 9 times (from 0.18 to 1.64 kpa) and saturated soil's CBR increased about 6.8 times (from 2.4 to 16.3 kpa) when reinforced. It appears that the increase of effective stress in dry conditions due to negative pore water pressure is the cause of the increase in strength from wet to dry conditions. This

Fig. 6 Effect of PP fiber + PVAc resin content in dry and saturated states

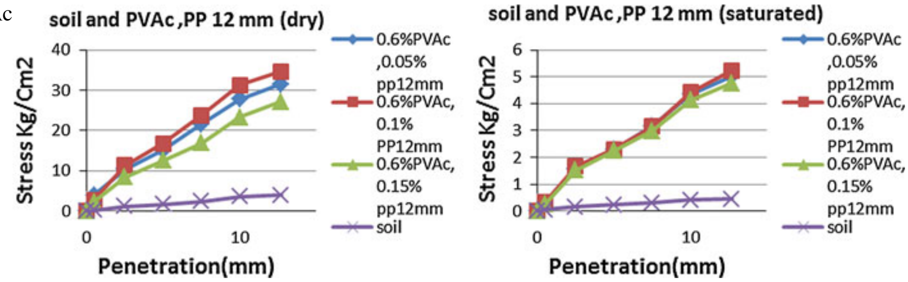
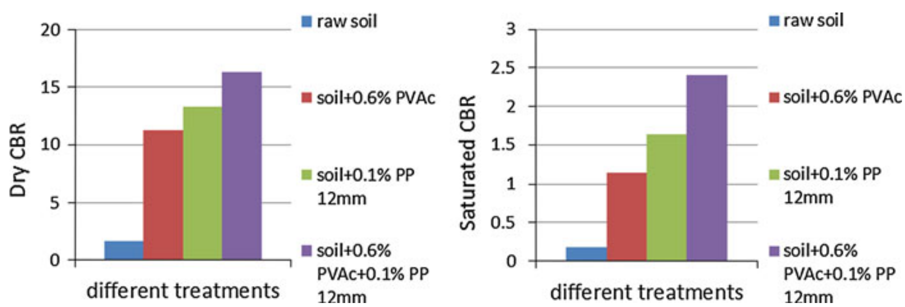


Table 4 Optimum CBR value in different groups of samples

Specimen type	Fiber	Fiber weight percentage	Resin	Resin weight percentage	Dry CBR value	Saturated CBR value
1	–	–	–	–	1.64	0.18
2	PP	0.1 %	–	–	13.34	1.64
3	–	–	PVAc	0.6 %	11.3	1.15
4	PP	0.1 %	PVAc	0.6 %	16.3	2.4

Fig. 7 Comparison of optimized samples



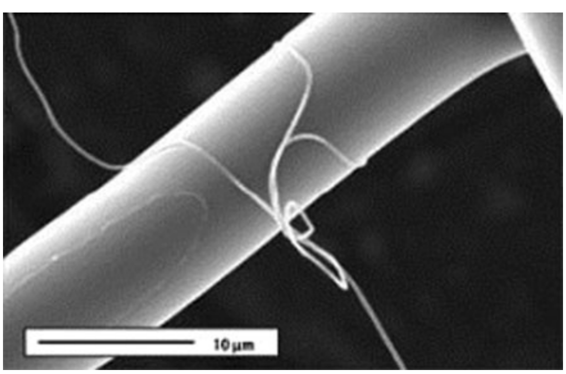


Fig. 8 SEM image of electro-spun polypropylene fibers (Rangkupan and Reneker 2003)

negative pore pressure is lower in reinforced soils samples which cause lower increase in strength in reinforced samples.

4 Conclusions

Due to some characteristics of chemical resins, e.g. PVAc, easy-to-use and rapid-to-perform, they are used to improve soft soil properties. Some drawbacks of chemical resins, such as being low water-resistance, however, have lead us to find a new solution to solve their problems in the saturated soil. Thus, usage of a synthetic fiber which can perform well in wet conditions in soil was regarded and consequently convinced us to use the combination of PP (polypropylene) fiber with PVAc (polyvinyl acetate) resin in the present study. CBR tests at both dry and saturated states were conducted to evaluate the compressive behavior of the soil composite of PP fiber-PVAc resin-soil. The results revealed that the combination of 0.1 % PP fibers with 0.6 % PVAc resin contents is more effective on CBR values at both dry and saturated states in comparison to resin modified and/or fiber reinforced soil samples separately. At the optimum contents of fiber and resin (0.6 % PVAc + 0.1 % PP of 12 mm), the CBR value enhanced from 1.64 to 16.31, about 900 % increase in dry states; and from 0.18 to 2.4, about 1,233 % in saturated states. Consequently, using both PP fiber and PVAc resin in soil composite can significantly improve properties of soil. Finally, about the costs of this method, it should be mentioned that regarding the CBR increases in the soil and low prices of PP fiber and PVAc resin in the world, (each PP fiber and PVAc resin costs about 2,000$ per metric ton), obtained resistances in soil could be clearly more valuable in most civil projects, for example for using in road beds.

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