Characterization of the dynamics of a clay soil reinforced with polyethylene terephthalate fiber (PET)

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Abstract

In this study, polyethylene terephthalate (PET) fiber was used to reinforce a fine expansive soil extracted from the former Lake Texcoco in Mexico. The laboratory tests included index tests, compaction tests and unconsolidated undrained (UU) static and dynamic triaxial tests. These tests were performed on soil specimens with fiber contents of 0, 0.1, 0.3, 0.5 and 0.7% as a percentage of the soil dry weight. The results show that the fiber increases the soil compressive strength under a static load. However, no significant changes in the dynamic parameters were observed in the cyclic triaxial tests.

Keywords: PET fiber, reinforcement, dynamic behavior

1. Introduction

The recycling of polyethylene terephthalate (PET) containers into fibers is an environmentally friendly technique, these PET fibers can be integrated into soils for reinforcement and stabilization. An estimated 25 million tons of plastics are disposed of every year and remain unaltered for 100 to 500 years, depending on the type of plastic and the surrounding conditions. The slow degradation of plastic mainly occurs by breakdown into smaller particles that are then dispersed into oceans (where from 3 to 30 kg/km^2 of plastics have been found), rivers, sediments and soils, among others.

Soil reinforcement is not a novel area. However, recycled materials are as yet not widely used or studied, especially in relation to fine soils. Polyethylene terephthalate fiber reinforcement has potential application in structures that need to withstand large deformations without cracking or losing strength, such as the cores of earth-fill and rock-fill dams and in the construction of embankments because fiber inclusion reduces the potential for cracking and increases strength in terms of the level of deformation.

The results of a study on reinforcing a fine soil with PET fiber are presented here. The laboratory tests consist of soil characterization using index tests and a mechanical analysis. The fine soil has poor strength and expansivity and is obtained from the former Lake Texcoco, which lies in a seismic zone.

2. Background

Existing studies on soil reinforcement by artificial fibers were carried out on sandy soils reconstituted with different percentages of polypropylene fibers as a percentage of soil dry weight. The peak and residual shear strengths of the reinforced sandy soil were reported to increase with the fiber content [1, 2 and 3]. The soil shear strength was reported to increase with the fiber content at the expense of increased deformation [4].

Several authors have reported that in triaxial tests performed on loose sandy soil reinforced with synthetic fibers, the deviator stress appeared to increase linearly with the deformation for large deformations, and no maximum deviator stress was observed. In [5] and [6], triaxial tests, California Bearing Ratio (CBR) tests and tensile strength tests were carried out on silty sands and organic clays. The test results showed increased cohesion in both soils, and the internal friction angle decreased with a 3% increase in the fiber content as a percentage of soil dry weight. In [7], the optimal fiber content was reported to depend on the maximum deformation selected to define the failure, such that a decrease in the soil strength was observed for different deformation levels.

In [8], field tests showed the excellent potential of using sandy soil stabilized with polypropylene fiber in airfields and military roads. A 203-mm-thick layer of sand with fibers can support considerable loads of military truck traffic. Field tests also demonstrated that a carpet emulsion must be used to prepare the road surface to prevent the separation of fibers under vehicular traffic.

However, insufficient information is available in the literature to assess the use of artificial fibers for reinforcing fine soils or to determine the influence of these fibers on the soil dynamic parameters.

Studies of clay soil behavior under static loads [9] have shown that polypropylene fibers improve the unconfined compressive strength of soil and reduce the shrinkage and expansion of clays [9, 10 and 11]. A similar increase in the unconfined compressive strength of a clay soil reinforced with polypropylene fibers has been reported [12].

Subsequently, the effect of synthetic polypropylene and polyethylene fibers on the behavior of a clay soil was tested. An increase in the shear strength of the reinforced soil was observed, most notably for polypropylene fiber reinforcements [13].

In [14], polypropylene microfibers were used in a clay with high plasticity that was extracted from the city of Querétaro, Mexico. The fiber size was reported to have a significant effect on the unconfined

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compressive strength of the soil, and small fibers enhanced the overall performance. Reinforcing the soil with an optimal fiber content increased the soil strength by 84%.

There is no consensus on the effect of reinforcing artificial fibers on dynamic soil behavior. The complex dynamic behavior of reinforced soils is affected by many factors, such as the physical and chemical properties of the fibers, the fiber content, the overburden pressure and the relationship between the deviator stress and the cyclic loading [15].

In a related study [16], resonant column and torsional shear testing was performed on a sandy soil reinforced with different types of natural and synthetic fibers. The shear modulus (G) and the damping ratio (ƛ) increased linearly by approximately 4% with increasing fiber content. An increase the deformation amplitude increased the effect of the fiber on the shear modulus but reduced the effect on the damping ratio. Increasing the confinement pressure did not improve the effect of the fiber on the shear modulus.

In [17], the inclusion of fibers did not change the initial stiffness of a sandy soil at low deformation levels (10-5 mm/mm). In [18], incorporating polypropylene fibers into a soil did not change the shear modulus at medium deformations (10-3 mm/mm). In [19], the shear modulus of a loose and dense sand reinforced with polypropylene fibers was determined for overburden pressures from 28 to 440 kPa. The inclusion of fibers tended to reduce the initial stiffness of the soil at small deformations.

In [20], unconsolidated undrained (UU) cyclic triaxial tests were carried out for on clayey sand at confinement pressures of 50 and 100 KPa for 150 loading cycles and two deviator stress ratios of 0.3 and 0.6. The shear modulus increased with the fiber content. The shear modulus also increased with the number of loading repetitions of the deviator stress. Using fiber contents above the optimal value resulted in negative effects. The optimal fiber content was not constant and increased with the deviator stress ratio.

In [21], cyclic triaxial tests were used to determine the shear modulus of a sandy soil containing different lengths (6, 12 and 18 mm) of polypropylene fibers. The stiffness increased with the fiber content, and this increase was more distinct in samples with longer fibers.

In [22], resonant column and wave transmission tests were performed on a sandy soil reinforced with polypropylene fibers. Increasing the fiber content increased the maximum shear modulus (Gmax) and slightly decreased the damping.

3. Materials used

3.1. Reinforcing material

The PET fibers that are available on the market have different lengths and diameters and are obtained from plastic waste. In this study, PET fibers were used as reinforcing elements. The fibers were 50-mm long with a diameter of 15 µm.

3.2. Soil

The following tests were performed on the soil sample without reinforcement.

Determination of solids density: the wet bulk density of solids of the reconstituted sample was determined using the standard in [23] as a reference.

Determination of the liquid limit of soil: A penetration cone was used because the soil particles would not adhere to the traditional Casagrande cup. The test procedure is described in [24].

Determination of the plastic limit of soil: this test was performed according to the standard [25].

The results of these tests are shown in the following table.

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Table 1- Index test results

Depth (m)	ω_L (%)	ω_P (%)	IP (%)	Gs	SUCS
0.5	**123.7**	**53.4**	**70.3**	**2.74**	**MH**

The liquid limit of the soil samples with PET fiber inclusions was similarly determined using a penetration cone. According to the tests the soil was classified as a high plasticity silt (MH).

The variation in the soil plasticity with fiber inclusions is shown in Table 2. The amount of water required to transform the soil from a plastic to a liquid state increases with the fiber content.

Table 2. Variation in liquid limit with fiber content

% Fiber	ω_L (%)
0	123.69
0.1	126.51
0.3	127.66
0.5	132.06
0.7	135.83

4. Experimental tests

4.1. Compaction tests

Compaction tests were carried out on the soil without and with fiber inclusions to determine the conditions for performing the different tests within the scope of the study.

A reduced compaction mold was used that consisted of a split tube 9 cm long and 3.6 cm in diameter. Compaction tests were performed for each fiber-reinforced soil mixture by kneading with a 2500 g compaction rammer. Compared to the soil without fiber, the maximum dry volumetric weight (γ_{dmax}) increased by 0.7% for soils with 0.5 fiber content and decreased by 0.3% for soils with 0.1 fiber content. The minimum γ_d of 1.2 g/cm^3 was obtained for a soil sample with 0.1% fiber, and the maximum γ_d of 1.33 g/cm^3 was obtained for a soil sample with 0.5% fiber. The optimal water content obtained from these tests was used to determine the specimen composition in subsequent tests.

4.2. UU static triaxial tests

The compressive strength was measured according to the standard [26] in a triaxial test chamber. Five series of tests were performed on soil samples with different fiber contents as a percentage of the soil dry weight: 0, 0.1, 0.3, 0.5 and 0.7%. For each series, tests were carried out at confinement pressures (σ_3) of 50, 100 and 150 KPa). The shear strength parameters at these confinement pressures were then calculated. The UU tests were performed under static and dynamic loads and controlled deformation. The static tests were performed at a deformation rate of 0.16666667 mm/min (10 mm per hour).

4.3. UU dynamic triaxial tests

The cyclic triaxial tests were performed according to the standard [27] using the same equipment as in the static tests and switching the failure stage. These tests were carried out by varying the wave amplitude, while maintaining a constant frequency of one hertz at 20 cycles for all amplitudes.

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The same number of tests and conditions were used in the dynamic tests as in the static tests. Five series of tests were performed for each dynamic test on soil samples with different fiber contents as a percentage of the soil dry weight: 0, 0.1, 0.3, 0.5 and 0.7%. Each test series was performed at confinement pressures of 50, 100 and 150 KPa (σ_c). A total 30 trials were performed.

5. Results

The stress-strain curves obtained from the UU static triaxial tests at a confinement pressure of 50 KPa show that the compressive strength increases with the fiber content (Figure 1).

This increase is more noticeable as the engineering strain increases; thus, the optimal fiber content depends on the maximum deformation considered. Compared to the soil without fiber, the compressive strength of the soil with 0.1% fiber increases by 90% at 10% engineering strain. The corresponding increase is 119% for soil samples with 0.3 and 0.5% fiber and 163% for soil with 0.7% fiber.

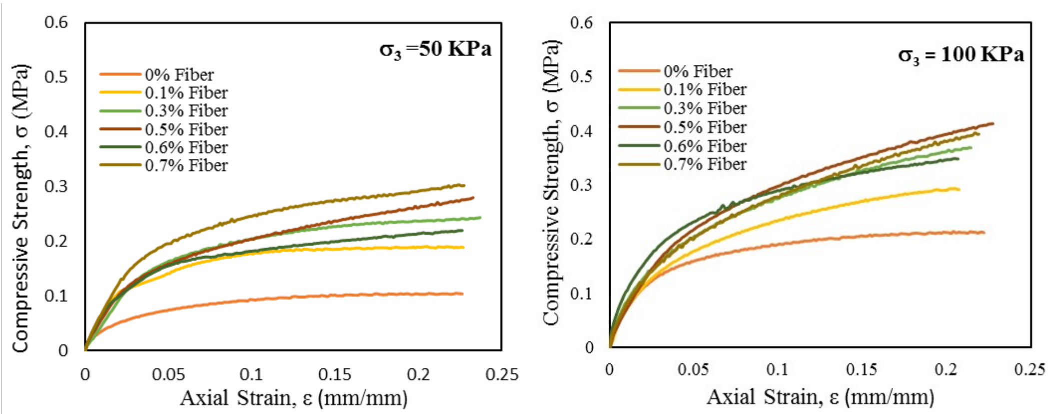

Fig. 1 Stress vs. strain for confinement pressures of 50 KPa (left) and 100 KPa (right)

For a confinement pressure of 100 KPa, the maximum strength is obtained for a soil with 0.5% fiber at 10% deformation (Figure 1).

As the confinement pressure increases from 100 to 150 KPa, the soil with 0.7% fiber decreases in strength compared to the other samples. The maximum strength is obtained at a confinement pressure of 150 KPa (Figure 2) for a soil with 0.5% fiber at 10% deformation.

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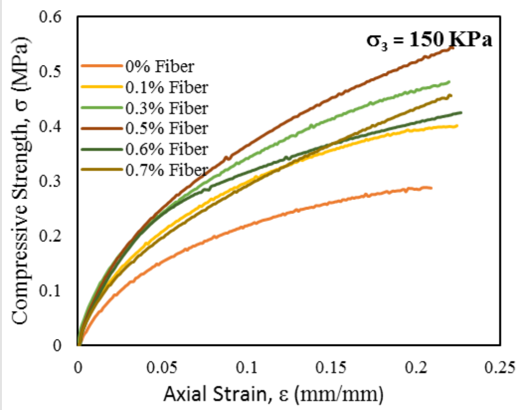

Fig. 2 Stress vs. strain for a confinement pressure of 150 KPa

Plastic failure is observed in the fiber-reinforced soil specimens (Figure 3). Slight cracking is observed in the tests on these samples, because discontinuity planes can be induced at significant fiber contents. There is no uniform direction or continuous pattern for the cracks.


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Fig. 3 Soil specimens with different fiber contents after testing: (left to right) 0.1% fiber, 0.5% fiber and 0.7% fiber

Well-defined failure did not occur in the fiber-reinforced soils. Therefore, a maximum linear deformation of 20% with respect to the total specimen height was used to determine the shear strength parameters. The strength parameters obtained from the UU triaxial tests are presented in Figures 7 and 8.

No difference in the cohesion of soil without fiber and with 0.1% fiber was observed. Soils with fiber percentages above 0.1% exhibited higher cohesion than the soil without fiber: for soil with 0.7% fiber, this increase in cohesion was 47.5%.

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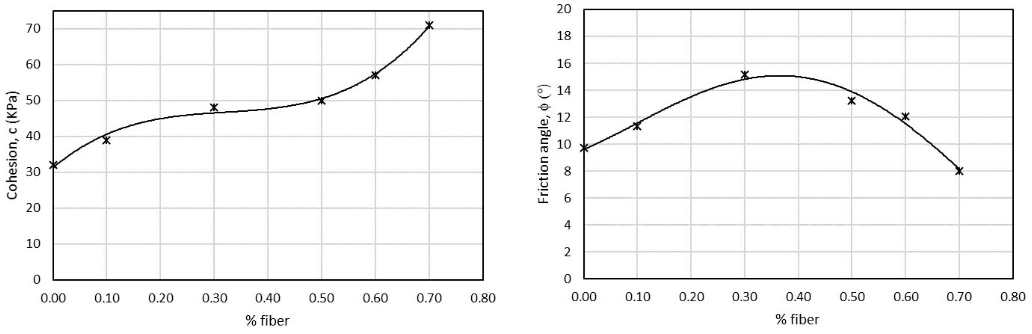

Fig. 4 Left: change in soil cohesion with fiber content; right: change in the soil internal friction angle with fiber content

The internal friction angle increased with the fiber content up to 0.5% fiber and then decreased. The maximum friction angle was 50% greater than the calculated friction angle for a soil without fiber.

Figure 5 shows the Young's modulus for different fiber percentages and overburden pressures. All of the fiber-reinforced specimens exhibit higher Young's moduli than the soil without fiber, because fiber inclusions increase the soil deformation capacity.

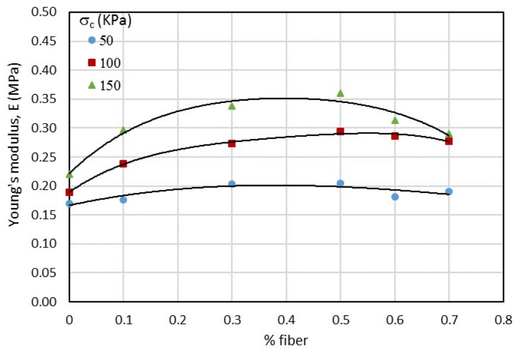

Fig. 5 Young's modulus for soil samples with different fiber percentages and confinement pressures

Lastly, the dynamic test results are shown. Figures 6 and 7 are the decay curves for the shear modulus, G. At all of the investigated confinement pressures, different dynamic behavior is observed for the soil with and without fiber. Different dynamic behavior is observed at each overburden pressure.

At the confinement pressure of 50 KPa, G increases with the fiber content. The maximum G is obtained for the sample with 0.7% fiber, and the minimum G is obtained for the sample with 0.3% fiber, followed by the sample without fiber. The same behavior is not observed at the other confinement pressures. At the confinement pressure of 100 KPa, the highest G are found for the specimens with 0 and 0.3% fiber contents, and the G values of both samples are practically identical. At this confinement pressure, the samples at higher fiber contents have approximately 30% lower G. Lastly, less variation in G is observed in the tests performed at the confinement pressure of 150 KPa than in the tests performed at other confinement pressures. The highest G at 150 KPa confinement pressure is found for the sample with 0.7% fiber, and the lowest G is found for the sample with for 0% fiber. The absence of a well-defined trend in G with the fiber content is attributed to the random fiber distribution in the samples.

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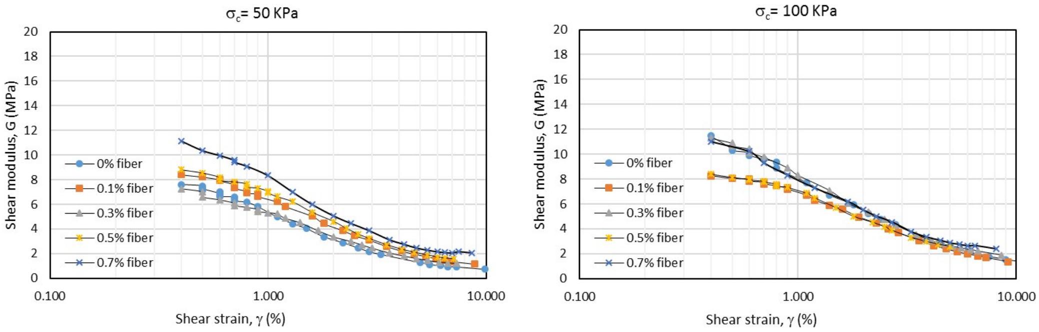

Fig. 6 Shear modulus vs. shear strain curves at confinement pressures of 50 KPa (left) and 100 KPa (right)

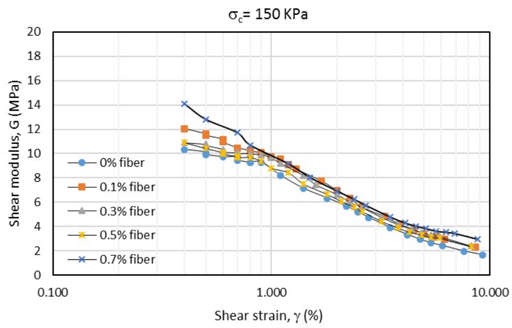

Fig. 7 Shear modulus vs shear strain for a confinement pressure of 150 KPa

The variation in the damping ratio for the reconstituted specimens was also calculated and is shown in Figures 8 and 9. The effect of the fiber content on the damping ratio is most distinct at the confinement pressure of 50 KPa. However, the damping ratio only varied by 5% between the lowest (0%) and highest (0.3%) fiber contents.

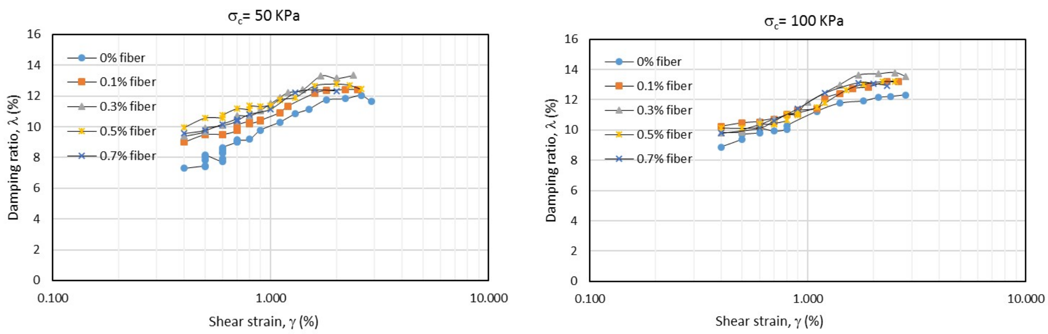

Fig. 8 Damping ratio vs shear strain for confinement pressures of 50 KPa (left) and 100 KPa (right)

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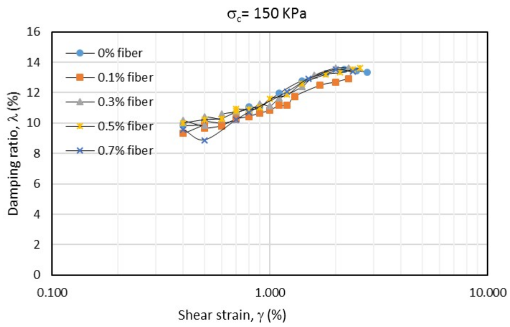

Fig. 9 Damping ratio vs shear strain for a confinement pressure of 150 KPa

6. Conclusions

The results of UU static triaxial tests showed that the compressive strength of reinforced soil samples increases with the fiber content. This fiber strengthening effect becomes more distinct with increasing engineering strain.

The fiber-reinforced soil specimens fail by plastic deformation. Slight cracking is observed in the tested samples with fiber, because discontinuous planes are induced in the sample at significant fiber contents.

The same cohesion is observed for soil without fiber and with 0.1% fiber. Fiber reinforcement increases the soil cohesion for fiber contents above 0.1%: there is a 47.5% increase in the cohesion for a soil with 0.7% fiber compared to the soil without fiber.

The internal friction angle increases with the fiber content up to 0.5% fiber and then decreases. The maximum friction angle is 50% greater than the calculated friction angle for a soil without fiber.

In the cyclic triaxial tests at low deformations (true shear strains from 0.4 to 10%), the absence of a clear trend in G with the fiber content is attributed to the random fiber distribution in the specimens. The damping ratio behavior varies similarly with the shear strain for all of the tests on samples with varying fiber content. The minimum damping ratio value decreases as the confinement pressure increases, and the lowest damping ratio is found for samples with between 0.1 and 0.3% fiber content.

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