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Influence of Polypropylene Derivatives on Soil Mechanical Properties

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Abstract The implementation of natural and artificial fibers as a stabilization technique for construction materials has developed new trends in the last decade and has generated functionality. This research evaluates the implementation of fibers derived from polypropylene as element of soil reinforcement. These fibers have the advantage that they do not have biodegradation or oxidation processes, which makes it a cost-effective and environmentally friendly option. The fibers are used to reinforce samples of silty soil derived from a slope deposit. Specifically, the behavior of the soil under unconfined compressive stresses and penetration stresses in the CBR test is evaluated. Polypropylene fibers derived from industrial processes were used, bringing them to the same size and using the same proportion of these in the soil samples, different percentages of fiber with respect to soil weight were evaluated to identify which was optimal in the experiment. Additionally, the process of formation of the samples was controlled to maintain close values of maximum dry density and optimum moisture content. A comparison and analysis that quantifies the contribution of these fibers is proposed. The results obtained are supported by the laboratory tests performed. These results show that the reinforced material has higher unconfined compressive strength, higher ductility, and higher resistance to penetration. It is proposed to evaluate the effect of the fiber arrangement in future research.

Keywords Soil Reinforcement, Synthetic Fibers, California Bearing Ratio (CBR), Mechanical Properties, Artificial Fibers

1. Introduction

The demand for durable and safe civil projects has challenged engineering to develop new alternatives for construction materials. From geotechnical engineering, methodologies involving the use of replacements of various materials to improve soil behavior have been evaluated. The replacements with recycled concrete aggregates RCA [1,2], crumb rubber CR [3,4], polyethylene terephthalate PET [5,6], geosynthetics [7,8], fibers [9,10], among others, have been highlighted. The use of fibers has been widely evaluated and employed, and among their main advantages is that they do not undergo biodegradation or oxidation processes that in the long term alter the tensional state of the material [9,10]. In general, soil improvement with fibers is a cost-effective and environmentally friendly alternative [11].

The reinforcement with artificial fibers is one of the most widely used methods to improve soil properties and to prolong the chemical and biological degradation times of the stabilizing material. Among the research, in which this type of fibers was used, the use of materials such as polypropylene PP, polyester polyethylene, among others, stands out. In general, it has been concluded that the material withstood unconfined compressive stresses better and the soil improved its ductility; and replacements up to 3% have been evaluated in mainly sandy materials [12,13].

Based on the above, the main objective of this research is to evaluate the influence of PP derivatives on the mechanical properties of a soil. A low strength soil with 0.2% additions of PP derivatives was evaluated. These derivatives were supplied by a local company and represent a waste for the company [14]. Physical and mechanical properties were evaluated in the natural soil such as plasticity, specific gravity, standard compaction, direct shear, unconfined compression and Californian Bearing Ratio CBR. In the PP reinforced soil, mechanical properties such as simple compression, unconfined compression and CBR were evaluated.

It is expected that this research can contribute to the mitigation of environmental problems associated with the poor final disposal of PP industrial waste. It should be noted that, if not properly disposed, these wastes may become potential environmental pollutants since are resistant to water, fire and are not biodegradable [15].

Finally, this study aims to contribute to current soil reinforcement techniques, using waste materials as an alternative to improve the properties of local soils, and to define the potential use of these fibers in the improvement of tensile strength in engineering works.

2. Materials and Methods

For the laboratory tests, soil samples were taken from the northwest of Medellín - Colombia. This area is characterized by the presence of alluvial, alluvial-torrential, colluvial deposits and debris flows and/or mature muds. These deposits are dominated by fine granular materials of silty texture [16].

Samples were obtained from manual excavations at 80cm depth, altered samples were collected in bags and undisturbed samples in shelby tubes. The proposed methodology includes a physical and mechanical characterization of the natural soil, and mechanical properties tests to determine the contribution of the polyproline (PP) derivatives in the soil performance, under different stress distribution events.

2.1. Polypropylene PP Derivatives Fibers

The synthetic material was provided by a flexible packaging company and is the waste from its industrial processes. This waste does not have a defined final disposal; it can be incinerated without being recycled or reused. It should be noted that, given that their main component is PP, they do not biodegrade and can become potential contaminants for the environment [15].

PP is resistant to contact with hot water, withstanding temperatures of approximately 140°C without deforming, does not deteriorate in the presence of external agents such as detergents, microorganisms and some oils at temperatures of 80°C; and its low density (0.90 g/cm^3) allows this material to float on water [17]. The latter does not influence the compaction of the material, since the final density of the soil is not altered by the inclusion of PP fibers [18,19].

Unlike the fibers currently used, this PP fibers is not physically obtained in the dimensions specified by ASTM [20]. On the contrary, the residues of this industrial operation are long pieces of PP in rectangles of a thickness of approximately 0.2 mm. It is important to clarify that the material goes through a printing process where it is printed with dyes that do not interfere with the behavior and possible advantages that PP can provide to the soil.

The standardization of the dimensions was established considering the literature review (Table 1). An important factor to be determined was the width of the fibers since these conditions are their length. They could not be too short in order not to lose the necessary slenderness to allow the soil particles to grip. Based on this, a length of 25 mm and a width of approximately 3 mm were determined for the PP derived fibers used.

Table 1. Literature review for the selection of fiber proportions and dimensions of the PP

Reference	Length [mm]	Diameter width [mm]	Soil type	% Fiber [%]
Miller et al., 2004 [21]	1 - 12	-	CL	0,5
Fernández, 2006 [22]	18	0,02	CH	0,2
Chandra et al., 2008 [23]	25	3,00	S	1,5
Jiang et al., 2010 [24]	15	0,02 – 0,05	CL	0,3
Kalantari et al., 2010 [25]	12	0,02	O	0,2
Ibraim et al. 2012 [26]	20 - 40	0,03 – 0,12	S	0,3
Zhu et al., 2014 [27]	5-150	0,05	CL	-
Donkor et al., 2016 [28]	54	-	SM	0,2 – 1,0
Hossein et al., 2018 [29]	12	-	CL	0,4 – 1,4
Liu et al 2020 [30]	18	0,03	SP	0,4 – 0,8

2.2. Soil Properties

In the natural soil, physical and mechanical properties tests were performed as shown in Figure 1. For the fiber-reinforced soil, the behavior under the application of axial forces in unconfined and confined conditions was analyzed by means of the Simple Compression test and the Californian Bearing Ratio CBR index, respectively. The tests provided the necessary information to make the comparison between the soil in its natural state and the reinforced soil under the established conditions.

All laboratory tests were performed according to the corresponding American Society for Testing and Materials ASTM standards [31–36]. In addition, at least three samples were taken for each test to establish a trend in the results.

3. Results and Discussion

The section is divided into three parts: the first part corresponds to the characterization of the natural soil; the second part corresponds to the characterization of the soil reinforced with polypropylene PP fibers and finally the comparison and discussion of the results obtained is presented.

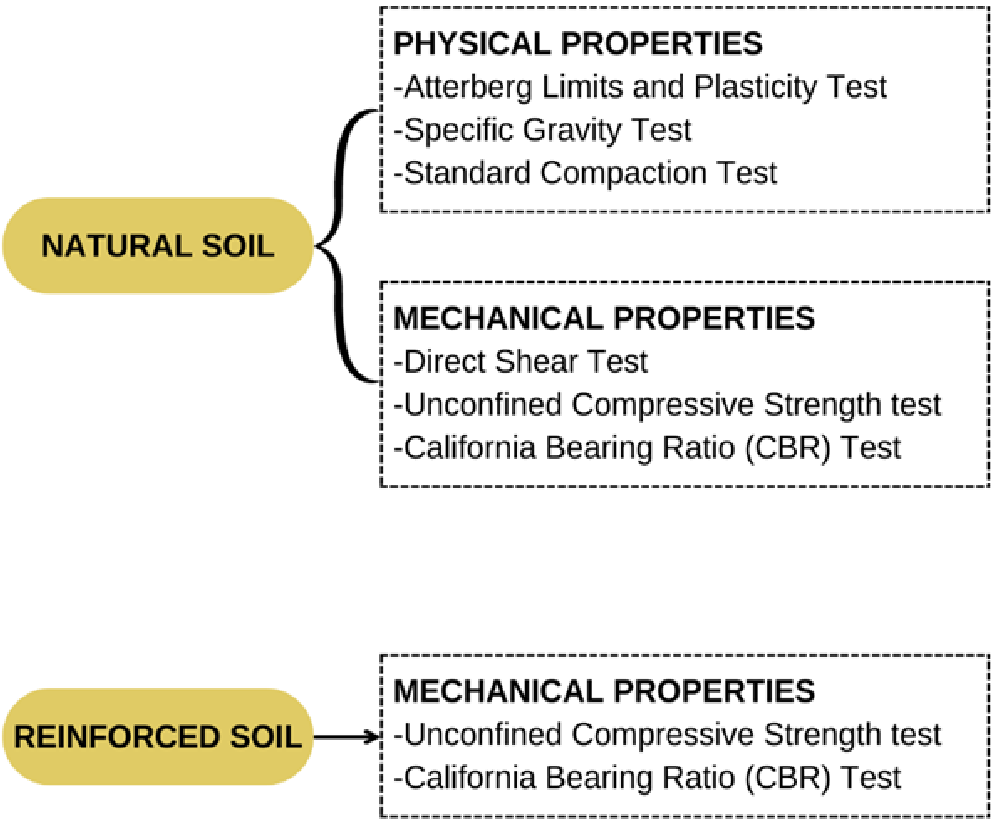

Figure 1. Properties evaluated on natural soil and soil reinforced with PP fibers

3.1. Characterization Tests on Natural Soil

3.1.1. Atterberg Limits and Plasticity Test

Atterberg limits and plasticity index tests were performed on three samples of the natural soil, following ASTM D4318 [31]. Considering that the material is predominantly fine, consistency limits were performed, obtaining the average results shown in Table 2. According to the Unified Soil Classification System USCS plasticity chart, the material is classified as a highly compressible silt MH.

Table 2. Liquid limit LL, Plastic limit PL, Plasticity index PI and Classification of the material according to the USCS plasticity chart

LL	74,86%	**USCS plasticity chart classification.**
PL	40,59%	**MH**
PI	34,27%	

3.1.2. Specific Gravity Test

The specific gravity was tested following ASTM D854 [32], and the result obtained was 2.70. According to the literature, the value obtained is among the typical values reported for silty soils [37].

3.1.3. Standard Compaction Test

The compaction test was performed using the standard Proctor methodology, standardized by ASTM D698 [33]. Figure 2 shows the moisture vs. dry density curve and Table 3 shows the results of optimum moisture and maximum unit dry weight (Υd_{max}).

Table 3. Proctor results.

Optimum Moisture [%]	31
Υd_{max} [g/cm^3]	1,35

3.1.4. Direct Shear

The direct shear DC test was performed to determine the strength parameters of the soil without fibers, following ASTM D3080. The test was performed for normal stresses of 29.9, 61.9 and 124.5 kPa. Figure 3 shows the results obtained.

The values of cohesion and friction angle obtained correspond to the parameters of a low strength material according to the literature [38]. Considering these parameters, the material requires reinforcement in order to increase its strength.

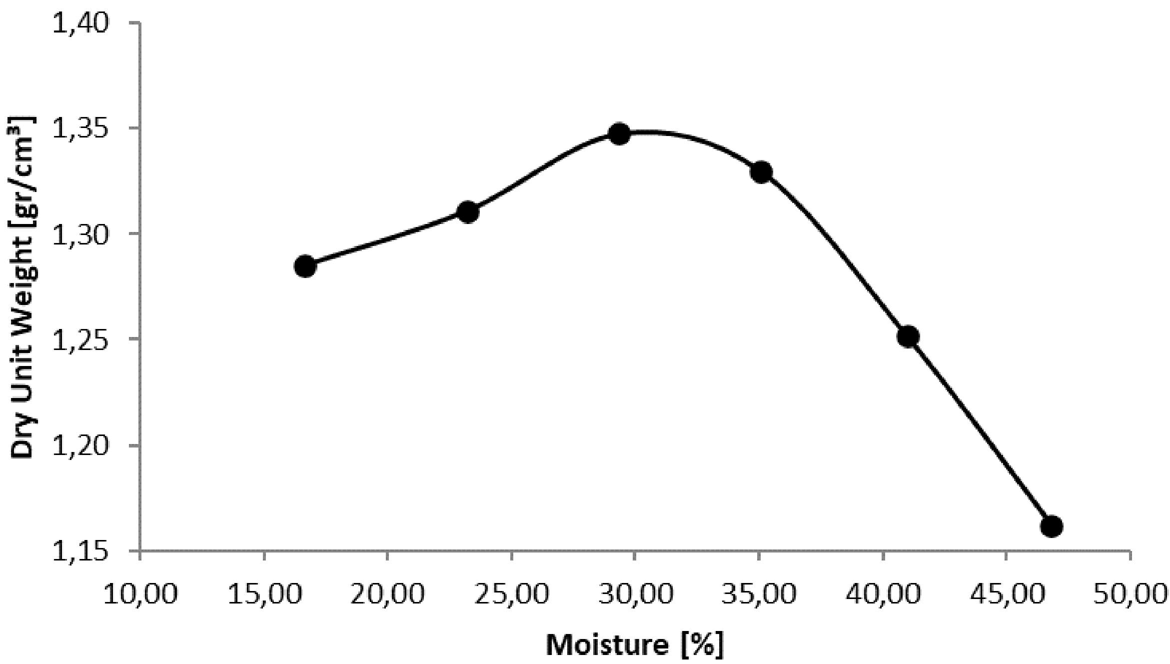

Figure 2. Moisture content vs. unit dry weight

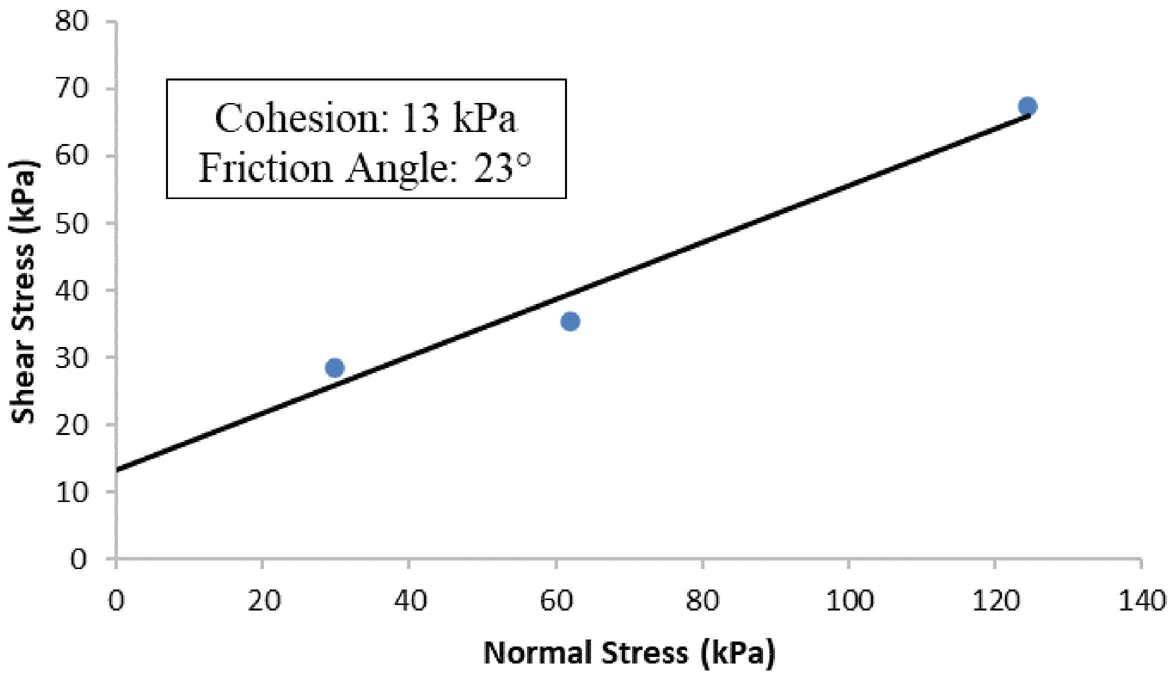

Figure 3. Shear stress VS axial deformation

3.1.5. Unconfined Compressive Strength Test

Simple compression tests were performed on the specimens to determine the ultimate unconfined strength, following ASTM D2166 [35]. Figure 4 shows the results obtained for 5 specimens of 100 mm in height and 50 mm in diameter, prepared manually considering the parameters obtained previously (dry unit weight and optimum moisture content), which were controlled during the preparation of the cylinders. Table 4 shows the statistical results obtained for the parameters of the unconfined strength in the unreinforced soil.

Table 4. Statistical results of natural soil parameters unconfined compression

Item	Geometric Mean
Unconfined Strength [kPa]	269,08
Moisture [%]	25,40
Dry Unit Weight [gr/cm^3]	1,34
Deformation [mm]	2,05

3.1.6. California Bearing Ratio (CBR) Test

Four samples were taken for CBR calculation, following ASTM D1883 [36]. CBR tests were performed using the same compaction energy of the Standard Compaction Test and the CBR was calculated for a dry unit weight corresponding to 95% of the maximum dry unit weight obtained. Figure 5 shows the results obtained for the natural soil samples and the CBR representing them is 9%.

3.2. Characterization Tests on Reinforced Soil

3.2.1. Atterberg Limits and Plasticity Test

To determine the appropriate proportions of polypropylene PP fibers with respect to the weight of the soil, simple compression tests were performed for three percentages 1) 0.1; 2) 0.2 and 3) 0.5% of the dry weight of the soil. The tests were performed following ASTM D2166 [35] and the results are shown in Figure 6.

The results show that the simple compressive strength of the soil is affected by the fiber content. Improvements in strength are observed for the proportions of 0.2 and 0.5%, reaching a higher strength when it contains 0.2% fiber.

The sample subjected to simple compression with 0.5% PP fibers presents a more ductile behavior. In addition, it was identified that for the size of the experiment carried out, with the percentage of 0.5% it was difficult to make the test specimens.

As mentioned, the size of PP fibers was standardized considering the literature review (Table 1). Specifically, waste from industrial processes was received in sheets of irregular size. Their size was standardized in rectangles of approximately 25 mm long and 3 mm wide.

3.2.2. Unconfined Compressive Strength Test

Samples of fiber-reinforced soil were tested to evaluate their unconfined compressive strength by controlling moisture and unit weight with the same process done for unreinforced soil. Figure 7 shows the results obtained for 5 specimens of 100 mm in height and 50 mm in diameter. Table 5 shows the statistical results obtained for the parameters of the unconfined strength in the reinforced soil. Figure 8 shows one of the fiber-reinforced cylinders failed in unconfined compression.

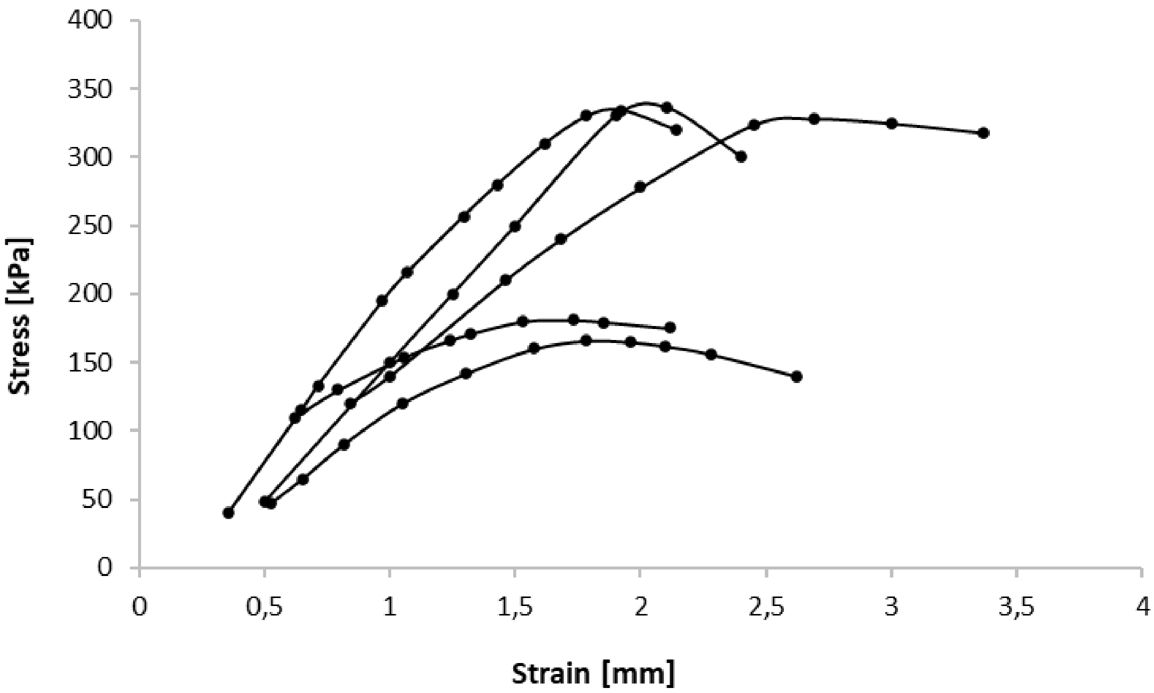

Figure 4. Stress-strain curves for samples of unreinforced soil

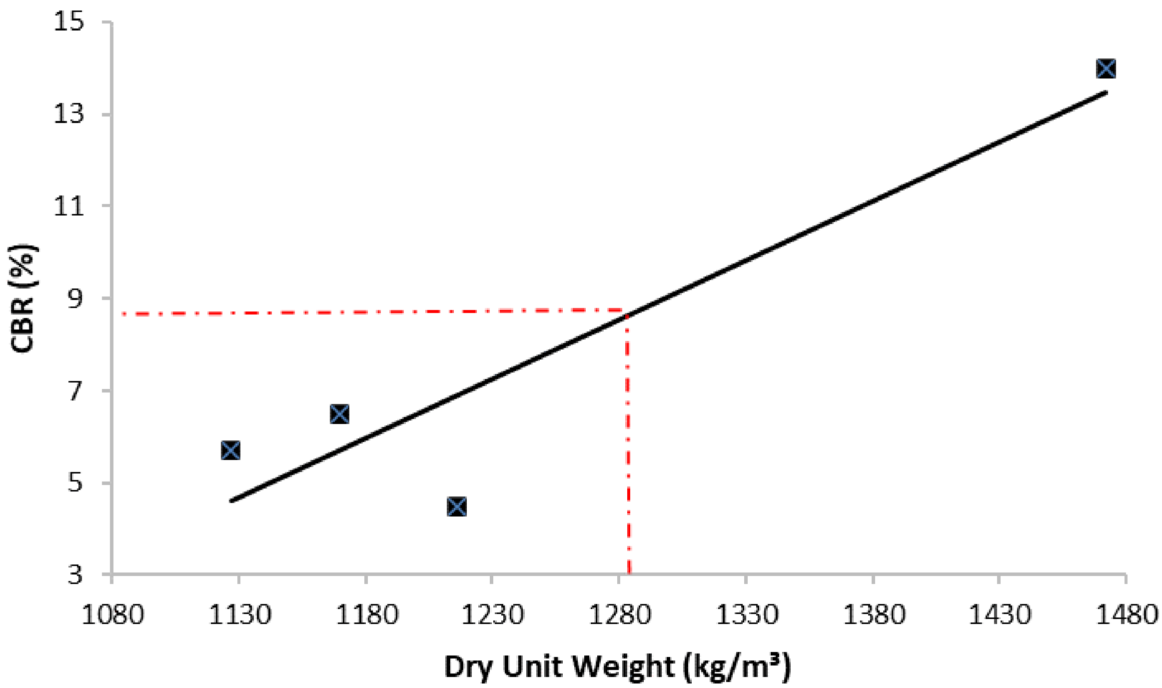

Figure 5. CBR - Natural Soil

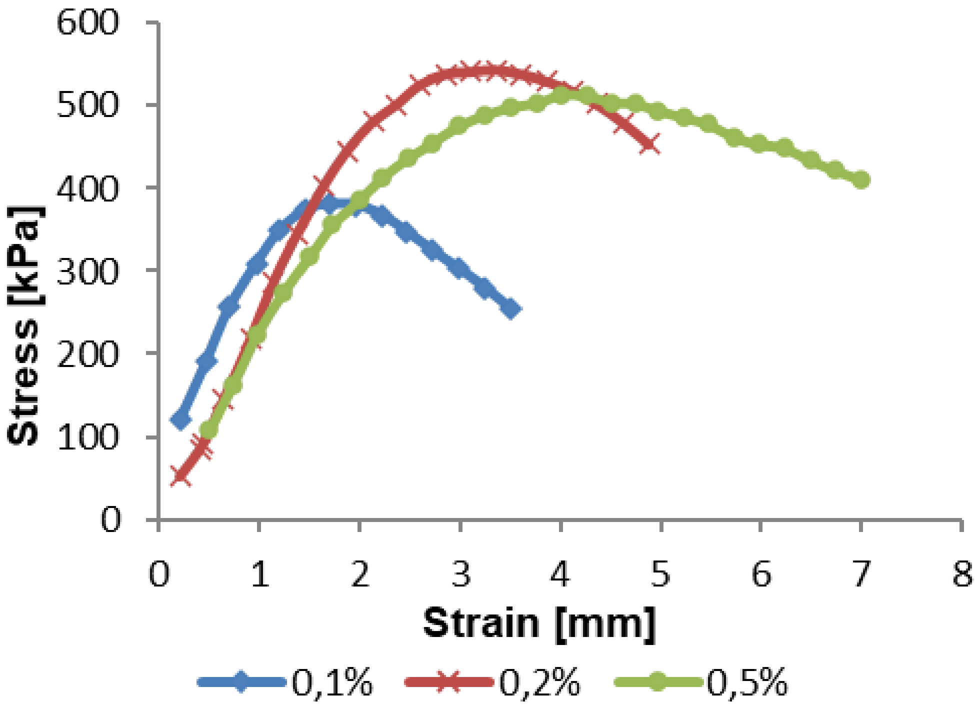

Figure 6. Stress-strain curves for three soils reinforced with 0.1, 0.2 and 0.5% PP fibers

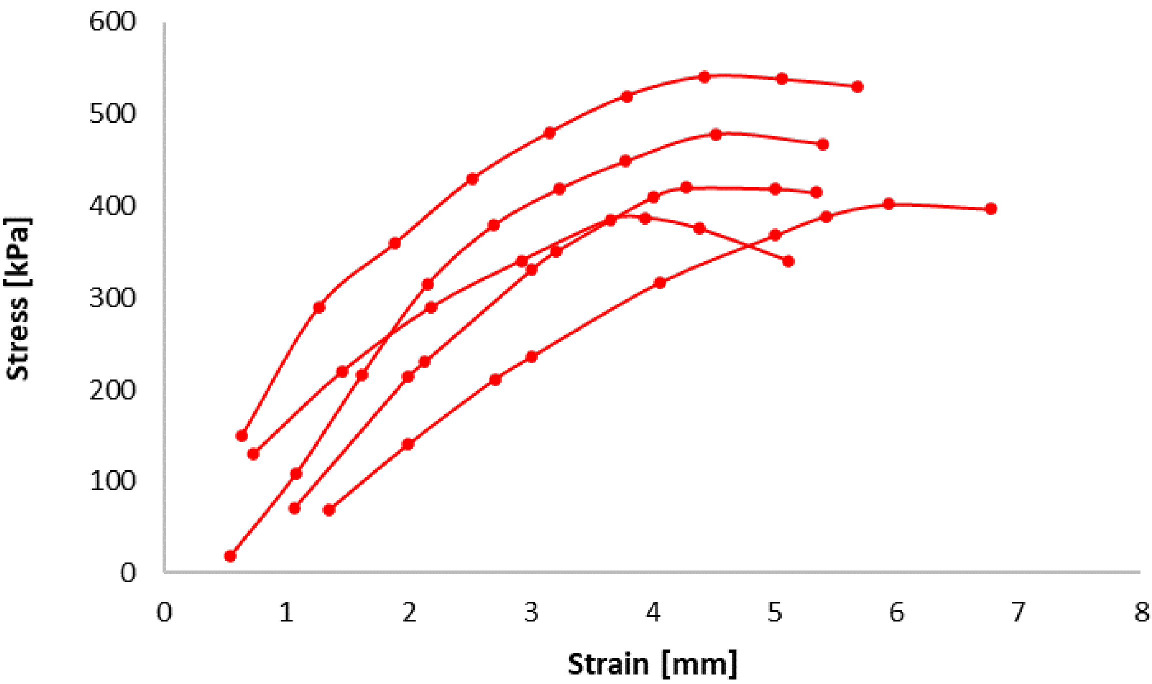

Figure 7. Stress-strain curves for samples of reinforced soil

Table 5. Statistical results of reinforced soil parameters Simple compression

Item	Geometric Mean
Unconfined Strength [kPa]	445,57
Moisture [%]	31,40
Dry Unit Weight [gr/cm^3]	1,37
Deformation [mm]	4,62

Figure 9 shows the unconfined strength comparison between reinforced and unreinforced samples. The reinforced soil has a higher unconfined strength than the unreinforced soil.

3.2.3. Unconfined Compressive Strength Test

The CBR test was performed for the fiber-reinforced soil as a measure to control its penetration resistance by comparing it with that obtained for the unreinforced soil. The test was made for 95% of the maximum dry unit weight of the compaction test. Figure 10 shows the results obtained for the reinforced soil samples and the CBR representing them is 12%. Figure 11 shows one of the fiber-reinforced specimens tested in the CBR test. There is an approximate 12% increase in CBR over the non-reinforced sample.

Figure 8. Reinforced soil cylinder failures

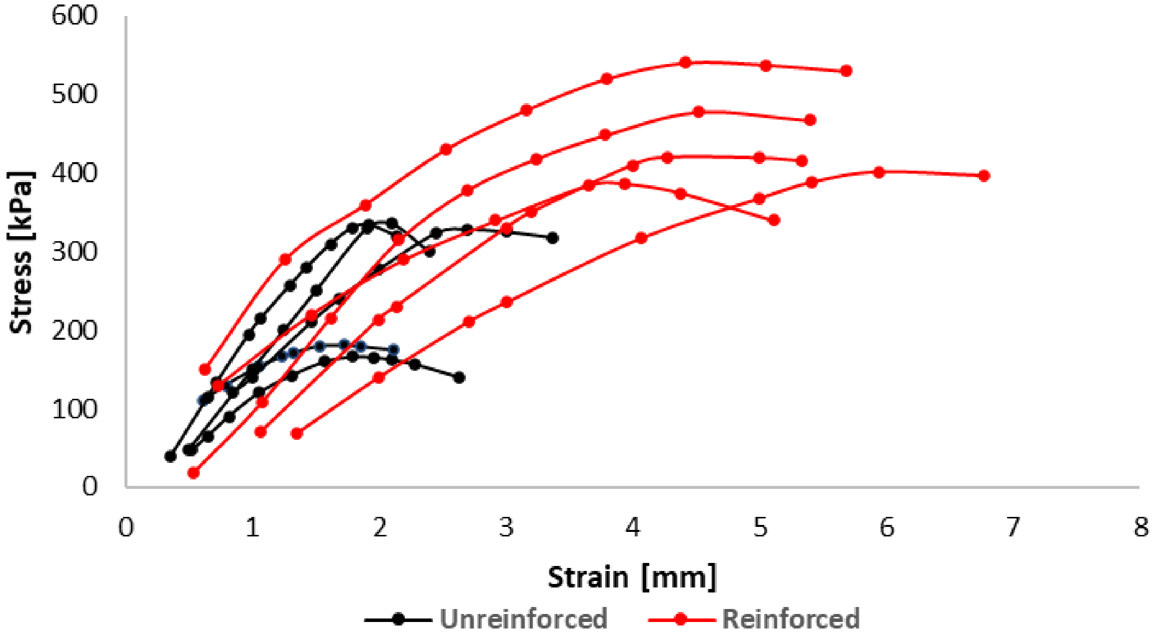

Figure 9. Reinforced and unreinforced test comparison

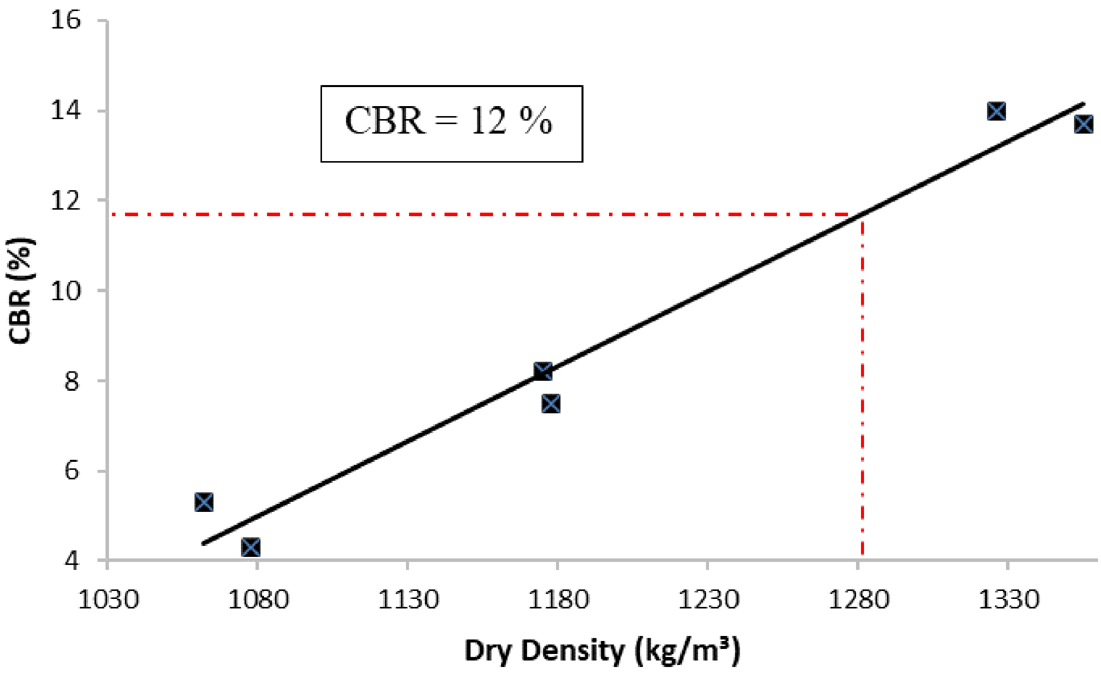

Figure 10. CBR – Fiber-reinforced soil

Figure 11. CBR test - reinforced soil

4. Conclusions

After the methodology developed, the following conclusions can be drawn. The soil material shows a greater deformation capacity when containing the synthetic fibers, the material is more ductile due to the application of reinforcement as indicated in the literature [12,13]. Under these conditions the soil reached an increase of strain with respect to the unreinforced soil, this was determined after comparing their average values.

Specific gravity and direct shear values correspond to typical values reported in the literature [37,38].

Regarding the unconfined compression, the unconfined strength in higher in reinforced soil that the obtained strengths in unreinforced samples.

In addition, it is observed that the average moisture content in the reinforced soil is higher, so for this group of tests the material was closer to the plastic state and more likely to have less resistance; even so the soil achieved an increase in its resistance when it was reinforced. This is probably attributed to the development of a more ductile failure due to the development of shear planes generated by the fibers [39].

Regarding the penetration stress, the material reached an increase in the CBR up to 12%, thus the material could be used as a more competent compacted subgrade [40].

According to the above, the polypropylene fibers used serve to reinforce the tested highly compressible silty soil material, improving the strength and ductility. This may indicate that the soil is axially reinforced, and the fibers provide strength and prevent seepage-induced volume increase [41].

In the experiments carried out, the fibers were distributed without any specific pattern; the effect of arranging the fibers and thus evaluating the strength of the material could be evaluated at a later time. The effect of increasing the percentage of fibers could also be evaluated with a number of tests similar to the one carried out in this research.

REFERENCES

[1] D. L. Vega A., J. E. Salcedo Fontalvo, R. Jimenez Triana, D. M. Palacios Del Barre, And C. Fresneda Saldarriaga, “Granular Subbase Improvement With Recycled Concrete Aggregates In Tropical Areas,” *Iium Engineering Journal*, Vol. 23, No. 2, Pp. 59–71, Jul. 2022, Doi: 10.31436/Iiumej.V23i2.2367.

[2] E. B. Toka And M. Olgun, “Performance Of Granular Road Base And Sub-Base Layers Containing Recycled Concrete Cggregate In Different Ratios,” *International Journal Of Pavement Engineering*, 2021, Doi:10.1080/10298436.2021.1916819.

[3] Z. Yang, Q. Zhang, W. Shi, J. Lv, Z. Lu, And X. Ling, “Advances In Properties Of Rubber Reinforced Soil,” *Advances In Civil Engineering*, Vol. 2020. Hindawi Limited, 2020. Doi: 10.1155/2020/6629757.

[4] D. Akbarimehr, A. Eslami, and E. Aflaki, “Geotechnical Behaviour of Clay Soil Mixed With Rubber Waste,” *J Clean Prod*, Vol. 271, Oct. 2020, Doi: 10.1016/J.Jclepro.2020.122632.

[5] M. Koohmishi And M. Palassi, “Mechanical Properties Of Clayey Soil Reinforced With Pet Considering The Influence Of Lime-Stabilization,” *Transportation Geotechnics*, Vol. 33, Mar. 2022, Doi: 10.1016/J.Trgeo.2022.100726.

[6] I. Milena Reyes Martínez, N. Dos Santos Lopes Louzada, L. Mendes Repsold, M. Dal Toé Casagrande, And D. Folle, “Study Of Clayey Soil Reinforced With Fine Crushed Polyethylene Terephthalate (Pet),” *Revista De Engenharia Civil Imed*, Vol. 1, No. 2, Pp. 10–14, 2014.

[7] S. Prasanna, “Application of Geosynthetic Inclusions in Cohesion Less Soil Reinforcement,” *Mater Today Proc*, Vol. 54, Pp. 448–450, Jan. 2022, Doi: 10.1016/J.Matpr.2021.10.178.

[8] T. S. Da Silva Burke And M. Z. E. B. Elshafie, “Geosynthetic-Reinforced Soils Above Voids: Observation And Prediction Of Soil Arching,” *Geotextiles And Geomembranes*, Vol. 49, No. 3, Pp. 579–592, Jun. 2021, Doi: 10.1016/J.Geotexmem.2020.11.005.

[9] S. M. Hejazi, M. Sheikhzadeh, S. M. Abtahi, And A. Zadhoush, “A Simple Review Of Soil Reinforcement By Using Natural And Synthetic Fibers,” *Construction And Building Materials*, Vol. 30. Pp. 100–116, May 2012. Doi: 10.1016/J.Conbuildmat.2011.11.045.

[10] H. Jiang, Y. Cai, And J. Liu, “Engineering Properties Of Soils Reinforced By Short Discrete Polypropylene Fiber”, Doi: 10.1061/Ascemt.1943-5533.0000129.

[11] A. Aldaood, A. Khalil, And I. Alkiki, “Soil Reinforcement Using Natural And Synthetic Fibers (A Review),” *Al-Rafidain Engineering Journal (Arej)*, Vol. 25, No. 1, Pp. 118–125, Jun. 2020, Doi: 10.33899/Rengj.2020.126506.1006.

[12] [12] S. M. Hejazi, M. Sheikhzadeh, S. M. Abtahi, And A. Zadhoush, “A Simple Review Of Soil Reinforcement By Using Natural And Synthetic Fibers,” *Construction And Building Materials*, Vol. 30. Pp. 100–116, May 2012. Doi: 10.1016/J.Conbuildmat.2011.11.045.

[13] S. Prasanna, “Application Of Geosynthetic Inclusions In Cohesion Less Soil Reinforcement,” *Mater Today Proc*, Vol. 54, Pp. 448–450, Jan. 2022, Doi: 10.1016/J.Matpr.2021.10.178.

[14] J. Rashmi Nayak, J. Bochen, and M. Gołaszewska, “Experimental Studies on the Effect of Natural and Synthetic Fibers on Properties of Fresh and Hardened Mortar,” *Constr Build Mater*, Vol. 347, P. 128550, Sep. 2022, Doi: 10.1016/J.Conbuildmat.2022.128550.

[15] R. Beiras, “Plastics and Other Solid Wastes,” In *Marine Pollution*, Elsevier, 2018, Pp. 69–88. Doi: 10.1016/B978-0-12-813736-9.00006-4.

[16] Alcaldía De Medellín, “ Descripción De Zonas Homogéneas, Microzonificación Sismica Del Área Urbana De Medellín.,” 2011.

[17] Propilco, “Información Sobre Polipropileno Y Generalidades,” 2013. Accessed: Aug. 11, 2022. [Online]. Available: Http://Www.Propilco.Com.Co/?Lang=Es&Opc=2&Sel=1

[18] Y. Qin, Y. Li, X. Zhang, And H. Zhou, “Constitutive Model Of Polypropylene-Fiber-Fabric-Reinforced Concrete Under Uniaxial Compression And Index Conversion Of Mechanical Properties,” *Constr Build Mater*, Vol. 347, P. 128508, Sep. 2022, Doi: 10.1016/J.Conbuildmat.2022.128508.

[19] Y. Qin, X. Zhang, J. Chai, Z. Xu, And S. Li, “Experimental Study of Compressive Behavior of Polypropylene-Fiber-Reinforced and Polypropylene-Fiber-Fabric-Reinforced Concrete,” *Constr Build Mater*, Vol. 194, Pp. 216–225, Jan. 2019, Doi: 10.1016/J.Conbuildmat.2018.11.042.

[20] Astm Standars, “Standard Specification for Fiber-Reinforced Concrete,” 2015.

[21] C. J. Miller, M. Asce, And S. Rifai, “Fiber Reinforcement For Waste Containment Soil Liners,” *Journal Of Environmental Engineering © Asce*, Vol. 130, Pp. 891–895, 2004, Doi: 10.1061/Asce0733-93722004130:8891.

[22] C. Fernández Calvo, “Experimental Study of Soil Reinforcement with Synthetic Fibers,” *Geogaceta*, Vol. 40, Pp. 303–306, 2006.

[23] S. Chandra,; M N Viladkar, And P. P. Nagrale, “Mechanistic Approach For Fiber-Reinforced Flexible Pavements,” *J Transp Eng*, Vol. 134, Pp. 15–23, 2008, Doi: 10.1061/Asce0733-947x2008134:115.

[24] H. Jiang, Y. Cai, And J. Liu, “Engineering Properties Of Soils Reinforced By Short Discrete Polypropylene Fiber,” *Journal Of Materials In Civil Engineering © Asce*, Vol. 22, Pp. 1315–1322, 2010, Doi: 10.1061/Ascemt.1943-5533.0000129.

[25] B. Kalantari, B. B. K. Huat, And A. Prasad, “Effect Of Polypropylene Fibers On The California Bearing Ratio Of Air Cured Stabilized Tropical Peat Soil,” *American J. Of Engineering and Applied Sciences*, Vol. 3, No. 1, Pp. 1–6, 2010.

[26] E. Ibraim, A. Diambra, A. R. Russell, and D. Muir Wood, “Assessment of Laboratory Sample Preparation for Fibre Reinforced Sands,” *Geotextiles and Geomembranes*, Vol.

34, Pp. 69–79, Oct. 2012, Doi:10.1016/J.Geotexmem.2012.03.002.

[27] H.-H. Zhu, C.-C. Zhang, C.-S. Tang, B. Shi, and B.-J. Wang, "Modeling the Pullout Behavior of Short Fiber in Reinforced Soil," *Geotextiles And Geomembranes*, Vol. 42, No. 4, Pp. 329–338, Aug. 2014, Doi:10.1016/J.Geotexmem.2014.05.005.

[28] P. Donkor and E. Obonyo, "Compressed Soil Blocks: Influence of Fibers on Flexural Properties and Failure Mechanism," *Constr Build Mater*, Vol. 121, Pp. 25–33, Sep. 2016, Doi: 10.1016/J.Conbuildmat.2016.05.151.

[29] A. H. Vakili, J. Ghasemi, M. R. Bin Selamat, M. Salimi, and M. S. Farhadi, "Internal Erosional Behaviour of Dispersive Clay Stabilized with Lignosulfonate and Reinforced With Polypropylene Fiber," *Constr Build Mater*, Vol. 193, Pp. 405–415, Dec. 2018, Doi: 10.1016/J.Conbuildmat.2018.10.213.

[30] J. Liu *Et Al.*, "Stabilization of Sand Using Different Types of Short Fibers and Organic Polymer," *Constr Build Mater*, Vol. 253, Aug. 2020, Doi:10.1016/J.Conbuildmat.2020.119164.

[31] American Society for Tersting and Materials Astm International, "Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils," 2017. Doi: 10.1520/D4318-17.

[32] American Society for Tersting and Materials Astm International, "Specific Gravity Of Soil Solids By Water Pycnometer," 2002.

[33] "Standard Test Methods For Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 Ft-Lbf/Ft 3 (600 Kn-M/M 3)) 1", Doi: 10.1520/D0698-12r21.

[34] "Standard Test Method for Direct Shear Test of Soils under Consolidated Drained Conditions 1", Doi: 10.1520/D3080_D3080m-11.

[35] "Standard Test Method for Unconfined Compressive Strength of Cohesive Soil 1", Doi: 10.1520/D2166_D2166m-16.

[36] "Standard Test Method for California Bearing Ratio (Cbr) Of Laboratory-Compacted Soils 1", Doi: 10.1520/D1883-21.

[37] K. Prakash, A. Sridharan, H. K. Thejas, And H. M. Swaroop, "A Simplified Approach of Determining The Specific Gravity of Soil Solids," *Geotechnical And Geological Engineering*, Vol. 30, No. 4, Pp. 1063–1067, Aug. 2012, Doi: 10.1007/S10706-012-9521-6.

[38] D. Stefanow and P. A. Dudziński, "Soil Shear Strength Determination Methods – State Of The Art," *Soil and Tillage Research*, Vol. 208. Elsevier B. V., Apr. 01, 2021. Doi: 10.1016/J.Still.2020.104881.

[39] A. Abou Diab, S. S. Najjar, S. Sadek, H. Taha, H. Jaffal, And M. Alahmad, "Effect of Compaction Method on the Undrained Strength of Fiber-Reinforced Clay," *Soils And Foundations*, Vol. 58, No. 2, Pp. 462–480, Apr. 2018, Doi: 10.1016/J.Sandf.2018.02.013.

[40] A. Abou Diab, S. S. Najjar, S. Sadek, H. Taha, H. Jaffal, And M. Alahmad, "Effect of Compaction Method on the Undrained Strength of Fiber-Reinforced Clay," *Soils And Foundations*, Vol. 58, No. 2, Pp. 462–480, Apr. 2018, Doi: 10.1016/J.Sandf.2018.02.013.

[41] K. H. Yang, S. B. Wei, W. M. Adilehou, And H. C. Ho, "Fiber-Reinforced Internally Unstable Soil Against Suffusion Failure," *Constr Build Mater*, Vol. 222, Pp. 458–473, Oct. 2019, Doi: 10.1016/J.Conbuildmat.2019.06.142.