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Research Article

Effect of Polypropylene Fiber Dimensions on Undrained Compressive Strength of Silt Soil

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Keywords

Polypropylene fiber,
Unconfined compression test,
Silt soil,
Signal-to-noise,
Optimum fiber ratio.

Abstract

In the study where the effect of polypropylene (PP) fibers on the mechanical properties of low plasticity silt soils was investigated, unconfined compressive strength (UCS) tests were carried out by adding PP fiber additives to the soil at different rates (0%, 0.4%, 0.8%, 1.25%) and lengths (6 mm and 12 mm). The Taguchi method analyzed the experimental results using signal-to-noise (SN) ratios. The findings show that PP fiber additive significantly increases the strength and ductility behavior of the soil. It was determined that the unconfined compressive strength also increased with the increase in the fiber ratio. It was also determined that the fiber size was adequate on the strength. While 6 mm long fibers provided a more regular and stable strength increase, it was determined that the effect of 12 mm long fibers varied depending on the fiber ratio in the mixture. A significant 1.25% fiber ratio and 6 mm long fibers were determined to give optimum results. SN analysis results were evaluated according to the "bigger is better" principle, and the highest SN ratios were obtained at 1.25% fiber ratio. The study results show that PP fibers are an effective additive in improving low-plasticity silty soils and provide an economical solution. These results show the usability of PP fibers in soil engineering projects.

1. Introduction

Soils are multiphase compact particle systems containing soil particles, water, and air in different sizes and volumes. Fine-grained (cohesive) soils generally have low bearing capacity, high compressibility, and high swelling potential [1-2] Therefore, improving cohesive soil in project areas reduces project costs by increasing its strength and extending the structure's service life. Soil improvement is an application that aims to improve the properties of the soil with different engineering methods [3-6].

Nowadays, ground improvement methods have an essential place in civil engineering applications. Different techniques are distinguished in terms of cost, ease of application, and the effects they provide. This study aims to improve the strength parameters of cohesive soil by using polypropylene fibers [7-9]. Unlike the studies in the literature, the impact of fiber length on ground improvement is also examined, and the relationship between the performance parameters of soils reinforced with different fiber lengths is revealed. In this context, an alternative solution to the existing ground improvement methods will be presented by determining the optimum fiber length for improving cohesive soils.

In ground system applications, protective materials such as cement and lime are often used, and although these materials are effective in increasing ground strength, they have sustainability limitations [10-17]. In this context, in recent years, attention has been paid to the use of different additives in the ground, especially life additives. It is known that fiber additives increase ground strength by being distributed homogeneously in the ground, limit crack propagation, and improve deformation formation [18-22]. Civil engineers frequently prefer polypropylene fibers due to their low cost and easy availability. In geotechnical problems, polypropylene fibers are mixed with cohesive soils in specific proportions to reduce the soil's settlement under load, deformation under tension, and swelling shrinkage potential, thus achieving maximum efficiency at minimum cost [23-25].

Polypropylene (PP) fibers increase the resistance against shear stresses within the soil and improve the strength properties of the soil [23-25]. In this context, complete factorial experiments were designed to determine the strength parameters of soils reinforced with polypropylene fibers. Within the scope of the study, the soil class used in the experiments was determined by performing classification experiments. Then 0%, 0.4%, 0.8%, and 1.25% PP fibers were added to this soil whose class was chosen, and optimum water contents were determined at standard projector energy. Samples prepared at maximum dry unit volume weight and optimum water content by dynamically compressing in four layers in a laboratory environment were subjected to uniaxial compression t, est, and PP fiber's effect on silty soil's unconfined compressive strength was investigated.

2. Materials and methods

The aim aimed to determine PP fibers' effect on free compressive strength by mixing them with silt soil in different proportions. The laboratory test program consists of three stages. In the first stage, the physical properties of the soil were determined, and the soil samples to be used in the test were prepared. In the second stage, the maximum dry unit volume weight and optimum water contents of the PP fiber and soil mixtures were determined in the proportions. In the third stage, free compression tests were performed on the samples of PP fiber layered soils in different proportions, at maximum dry unit volume weight and optimum water contents, and deformation values for free compressive strengths and peak stresses were obtained.

2.1. Materials

More than 200 kg of soil samples taken from the Kastamonu Province from a depth of approximately 3-4 meters were laid on a suitable surface to be air-dried after cleaning the organic materials inside. The samples that reached air dryness were mixed thoroughly to obtain a homogeneous mixture, and the existing agglomerations were crushed. Then, the sample was passed through a NO.40 sieve that allowed the largest grain diameter to pass.

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The permanent water content of the sieved and air-dried soil samples was between 1.0% and 1.05%. This sample was stored in the laboratory environment before the experiments were carried out.

The soil used in the experimental studies is silty with a low clay content. The analysis results made according to the ASTM D4318 [26] standard are presented in Table 1. The silty soil sample was classified as low plasticity silt (ML) according to the USCS (Unified Soil Classification System).

Table 1. Physical properties of the soil used in experimental study

Property	Value	Symbol and Unit
No 200#	66.5	FC (%)
Liquid limit	32	LL (%)
Plastic limit	24.8	PL (%)
Plasticity index	7.2	IP (%)
Specific gravity	2.54	Gs
Clay ratio	19.9	C (%)
Silt ratio	46.6	M (%)
Sand ratio	33.5	S (%)
Soil class: Low Plasticity Silt (ML)		

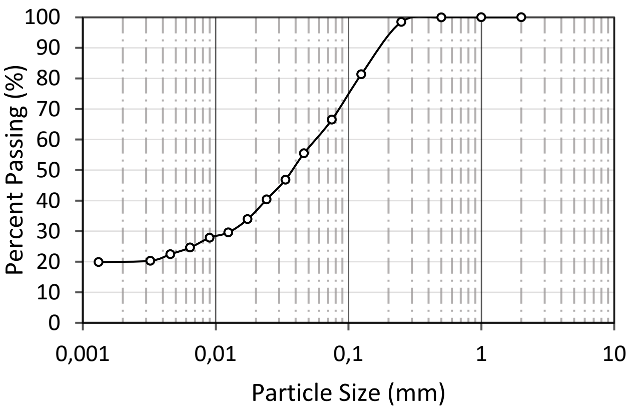


Figure 1. Grain size distribution curve

2.2. Sample Preparation

The silty soil sample taken to the laboratory environment was first air-dried. The sample that reached air dryness was pulverized by hand. To ensure homogeneous preparation of the samples and to prevent clumping, it was passed through a No. 40 sieve with an opening suitable for the maximum grain diameter. Organic materials were also removed during this process (Figure 2c). The sieved soil material was separated into 2 kg groups and moistened by spraying distilled (deionized and deaired) water to reach the previously determined optimum water content. Then, polypropylene (PP) fibers were added to the mixture and mixed thoroughly with the help of a sample preparation mixer. The 2 kg soil groups prepared this way were placed in airtight containers and kept at room temperature for 4 hours for curing.

(a) (b)

(c) (d)

Figure 2. a) 12 mm PP fiber, b) 24 mm PP fiber, c) silt soil sample, d) sample preparation equipment

The process was repeated on each sample for each PP fiber ratio and water content. This procedure prepared all samples as a homogeneous soil-water mixture without any measurable difference. After the curing period, water content was checked by taking samples from different points of each airtight container. It was confirmed that the water content of all mixtures was within ±0.62% of the evaporation or moisture change error.

The prepared soil samples were dynamically compressed in a specially designed mold at standard compaction energy to obtain a sample of 50 mm in diameter and 100 mm in height. While preparing the samples for the experiments, they were compressed into four layers to obtain homogeneous compression. Possible separations were prevented by creating scratches between the layers; for each PP fiber ratio and optimum water content values, previously prepared and cured soil samples were compressed into the tank according to the sample weights calculated using the soil volume-weight relations. After the experiment, samples were taken from different parts of the sample, and their water content was checked. The prepared samples were removed from the molds and pushed statically using the jack system. (Figure 2.d).

2.3. Test Methods

Concrete is the main factor that determines the strength of buildings. Therefore, many studies are carried out on concrete properties [27-35]. This study investigated the effect of PP fibers on the undrained shear strength of silty soil. First, the basic geotechnical properties of the silt sample obtained from Kastamonu province were determined, and the fiber additive ratios used in the tests were selected using the literature [7-13]. Details regarding the mixing ratios are presented in Table 2. Standard compaction tests were carried out on the prepared mixtures by the ASTM D698 [36] standard (Figure 3). The optimum water content and maximum dry unit weight values obtained as a result of the standard compaction tests are given in Table 3.

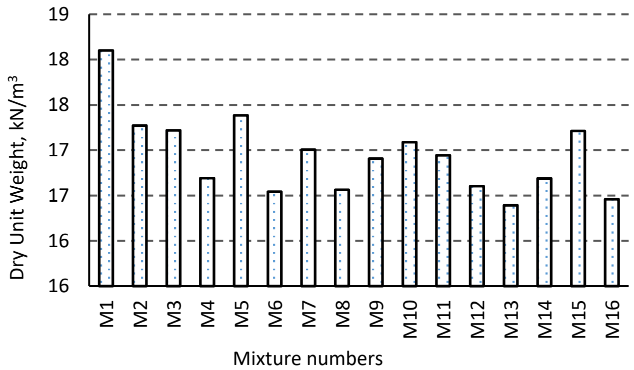
Table 2. Mixture properties and experimental design

Mix ID	PP fiber %		Mix ID	PP fiber %	
	12 mm	24 mm		12 mm	24 mm
M1	0	0	M9	0,8	0
M2	0	0,4	M10	0,8	0,4
M3	0	0,8	M11	0,8	0,8
M4	0	1,25	M12	0,8	1,25
M5	0,4	0	M13	1,25	0
M6	0,4	0,4	M14	1,25	0,4
M7	0,4	0,8	M15	1,25	0,8
M8	0,4	1,25	M16	1,25	1,25

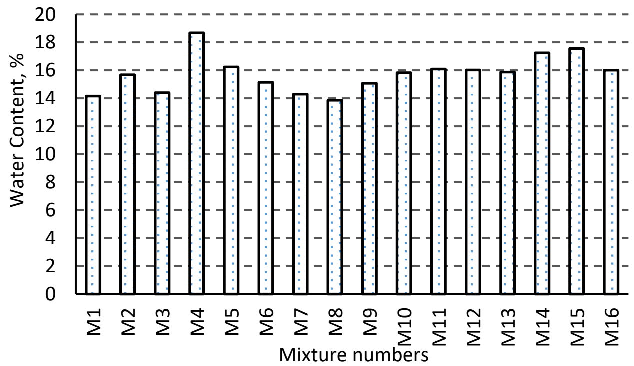
Table 3. Compaction test results

Mix ID	Dry Unit Weight kN/m^3	Water Content %	Mix ID	Dry Unit Weight kN/m^3	Water Content %

M1	18.10	14.15	M9	16.91	15.08
M2	17.27	15.68	M10	17.09	15.83
M3	17.22	14.40	M11	16.94	16.10
M4	16.69	18.68	M12	16.60	16.03
M5	17.38	16.24	M13	16.39	15.88
M6	16.54	15.14	M14	16.69	17.25
M7	17.01	14.30	M15	17.21	17.56
M8	16.56	13.86	M16	16.46	16.01



(a)



(b)

Figure 3. Standard compaction test results, a) dry unit weight, b) optimum water content

3. Results

In the study examining PP fiber's effects on silt soil's mechanical behavior, 64 unconfined compressive (UC) tests were performed on the samples. When classified according to the mixture properties and experimental design, the average values of the samples with two similar properties of 16 different scenarios are shown in Table 4.

Table 4. Unconfined compressive test results

Mix ID	q_u (kPa)	Peak Strain %	Mix ID	q_u (kPa)	Peak Strain %
M1	87.08	2.724	M9	83.02	1.968
M2	95.85	2.729	M10	133.03	3.171
M3	85.47	2.740	M11	143.16	3.994
M4	73.99	3.244	M12	203.32	4.480
M5	78.30	2.967	M13	234.41	4.151
M6	89.38	3.222	M14	111.33	2.482
M7	101.10	3.705	M15	152.28	4.494
M8	87.21	3.205	M16	145.47	4.947

Figure 4 presents the unconfined compressive strengths of silty soil with weight percent PP fiber addition. According to the results, the average UCS of the natural silty soil (reference sample) was 87.08 kPa. The average UC values of the PP fiber added samples were the highest and lowest values of 234.41 and 73.99 kPa, respectively.

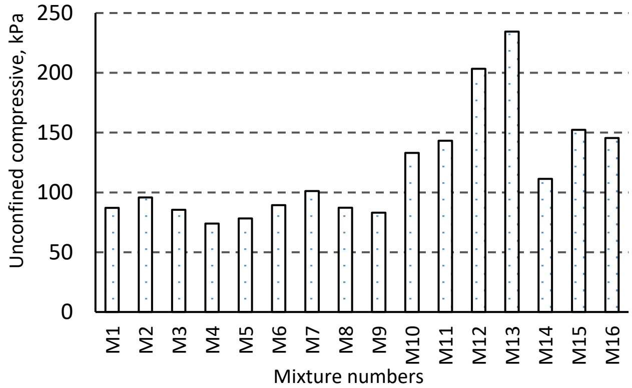


Figure 4. Unconfined compression stress test results of samples

Percentage changes in unconfined compressive strength (UCS) values of the mixtures compared to the reference sample depending on the WAFF additive ratio are shown in Figure 4.

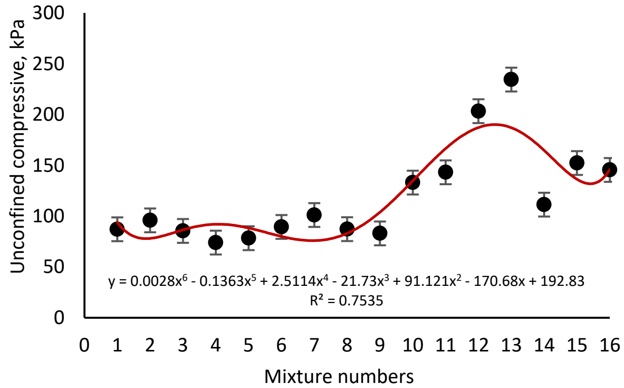


Figure 5. UCS value increase of PP fiber additive samples compared to a reference sample

The changes in the deformation values at the moment of peak stress depending on the silt soil PP fiber contribution rate and size of the mixtures are shown in Figure 6. When looking at the graph, the ductility value of the sample increases as the PP fiber contribution increases, independent of the size effect.

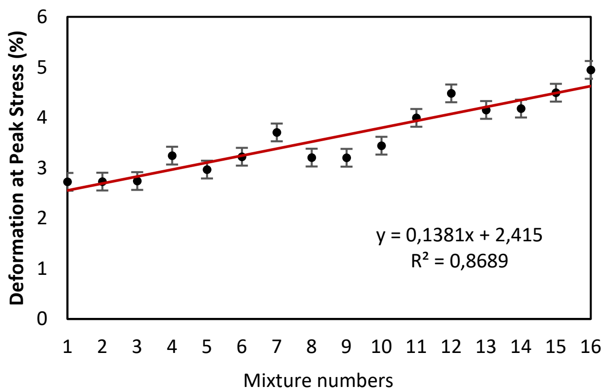


Figure 6. Deformation changes of the samples at peak stress

Signal-to-noise (SN) ratio analysis using the Taguchi method in the Minitab program was used to evaluate the sensitivity and stability of the experimental results. This method was analyzed to investigate the effect of controllable parameters (e.g., fiber length and ratios) on the unconfined compressive strength of the samples and to determine the optimum parameter combinations (Figure 7).

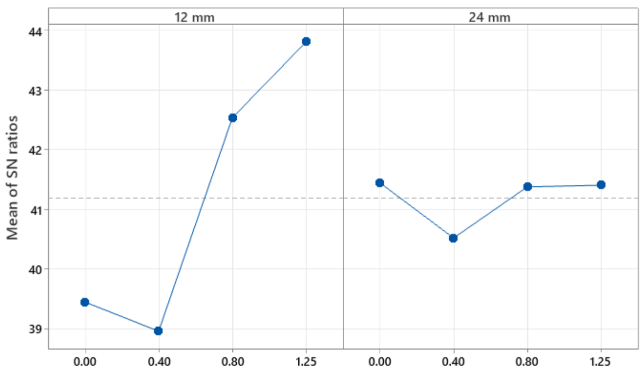


Figure 7. Signal-to-noise (SN) ratio analysis of experimental results (SN: Lager is better)

4. Conclusions

The effect of polypropylene (PP) fibers on the mechanical behavior of low plasticity silt (ML) soil was investigated. Within the scope of the study, unconfined pressure (UC) tests were carried out using PP fiber additives at different ratios (0%, 0.4%, 0.8%, 1.25%) and lengths (12 mm and 24 mm). The findings can be summarized as follows:

- In PP fiber-added mixtures, UCS values ranged from 73.99 kPa (1.25% 12 mm PP fiber) to 234.41 kPa (1.25% 24 mm PP fiber). Increasing the fiber ratio and fiber length significantly increased UCS values.
- It was observed that the fiber addition improved the ductility behavior of the soil. Significantly, higher PP fiber ratios (1.25%) and extended fiber usage (24 mm) increased the deformation capacity of the soil at the peak stress. This shows that the ability to limit crack propagation and improve deformation formation was enhanced.
- The SN ratio increased regularly as the 6 mm PP fiber ratio increased. In particular, the SN ratio reached its maximum value at 1.25% fiber ratio. This shows that short fibers do not significantly increase strength on the ground at low rates but are effective at high rates.
- The SN ratio decreased at 24 mm size and 0.4% fiber ratio. However, an increase was observed at 0.8% and 1.25% ratios. This situation reveals that long fibers cannot be effectively integrated into the soil at low ratios and do not provide the expected strength increase but are effective at higher ratios.
- Figure 6 was evaluated according to the "Larger is better" principle. 1.25% fiber ratio showed the best performance for both fiber lengths. The effect of fiber length on SN ratio shows that short (12 mm) fibers are more effective at high ratios. The effect of prolonged (24 mm) fibers varies depending on the mixing ratio.

In summary, the increase in the fiber ratio and, especially, the contribution at the level of 1.25% was decisive in increasing the unconfined compressive strength of the soil.
The effect of the fiber length showed a more linear trend for 12 mm, while a more variable effect was observed for the 24 mm fiber length. Generally, it was understood that the fiber ratio should be increased to achieve optimum results, but the selection of the fiber length should be made carefully according to the mixture.

Declaration of Conflict of Interests

The author declares that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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