Black Sea Journal of Engineering and Science

doi: 10.34248/bsengineering.1600157

Open Access Journal
e-ISSN: 2619 - 8991

Research Article
Volume 8 - Issue 3: 784-792 / May 2025

MECHANICAL STABILIZATION OF GRANULAR SOILS WITH CHICKEN FEATHER FIBER WASTE

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Abstract: Taking into account that 26 billion chickens were produced worldwide in 2021, a total of 2.6 million tons of chicken feather waste is generated for consumed chickens. Methods such as burning and burying are commonly utilized for the disposal of chicken feather waste, especially burning pollutes the environment. Recently, it has been shown that organic fibers can be used as an alternative to synthetic fibers for soil improvement by reinforcing them. This study examined the usability of chicken feathers as an alternative to organic fibers. In this context, chicken feathers obtained from chicken production facilities were processed and chicken feather fibers were obtained. The sand soil reinforced with 0.2% and 0.4% fibers were tested in a direct shear test apparatus. The data obtained indicated an increase in peak shear strength values in the range of 16-25% and residual shear strength values in the range of 23.5-34.6%. The highest strength values were obtained with 0.2% reinforcement. According to findings, it was found that the soil has a saturation point in chicken feather fiber reinforcement and the amounts of fiber on it are of no benefit. In summary, chicken feathers that need to be discarded can be used as a promising soil stabilization method. Considering all these advantages, chicken feather fibers can be considered a favorable alternative for soil stabilization in terms of their contribution to both the economy and nature.

Keywords: Peak shear strength, Chicken feather fiber; Direct shear test, Friction angle

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Received: December 11, 2024
Accepted: March 27, 2025
Published: May 15, 2025

Cite as: Öztürk M, Yurtcan UE. 2025. Mechanical stabilization of granular soils with chicken feather fiber waste. BSJ Eng Sci, 8(3): 784-792.

1. Introduction

Considering that the world population has increased from 1 billion to 8 billion in the last 75 years, it is not difficult to predict that the human population and its needs will continue to rise. According to the projection for 2030, this number is expected to increase by 10% to 9 billion (Brakman et al., 2025; Ghosh et al., 2024; United Nations (UN), 2024). As of 2022, 28 billion chickens were produced in the world. In Türkiye, as of 2023, annual chicken production will increase by 1.1% and reach 254 million units. 1.27 billion chickens were slaughtered and 2.3 million tons of chicken meat was produced in 2023 (Kadakoğlu et al., 2024; Republic of Türkiye Ministry of Agriculture and Forestry, 2024). Assuming that the average weight of a chicken is 2 kg and about 5% of its weight is feathers, a rough estimate would amount to 2.6 million tons of chicken feather waste in the world and about 36,000 tons in Türkiye. Burning, burying, and composting methods are used to dispose of these wastes. Any of these methods can lead to problems such as increased air pollution, increased soil pollution, reduced soil fertility, and groundwater contamination by causing excess nitrogen in the soil (Hancock et al., 1995; Depison et al., 2020; Latshaw and Bishop, 2001; Uzun, 2010). For this reason, the correct handling of chicken feathers, one of the wastes from chicken production, is becoming increasingly important and necessary. Problems related to the mechanical behavior of soils are known to be studied under two main headings: deformation and stability problems. In all categories of stability problems (bearing capacity problems, slope stability problems, etc.), which cover the majority of soil mechanical problems, the shear strength of the soil is crucial. If the problem caused by the soil-structure interaction in the system cannot be solved by changing the structural properties, an improvement in the soil parameters is sought. To increase the shear strength properties of the soil, solution methods such as soil improvement with cohesive material (chemical improvement), compaction, additive inclusion, thermoelectric methods (physical improvement) or improvement with various reinforcing elements such as geosynthetics and geocomposites (mechanical improvement) can be used (Bowles, 1996; Das and Sivakugan, 2017; Hausmann, 1989; Holtz et al., 2010; Ingles and Metcalf, 1973; Öztürk, 2024a; Öztürk, 2024b). There are many studies on the use of waste materials, especially in the chemical and mechanical stabilization categories. For example, many studies have been conducted on cohesion improvement of soils using waste materials such as fly ash, furnace slag, rice husk ash (RHA), sewage sludge ash, bottom ash, sugarcane straw ash, copper slag, sawdust ash, and cement kiln dust as a cohesive waste alternative to materials such as lime and cement (Rahman et al., 2011; Syed Zuber et al., 2013; James and Pandian, 2015; Ahmed and Adkel, 2017; Singh et al., 2017; ; Zorluer and Gücek, 2017; Sudhakaran et al., 2018; Aamir et al., 2019; Jafer et al., 2020; Keleş et al., 2024). Reinforcement with fibers is one of the common methods of soil improvement by reinforcement. Soil improvements with steel reinforcements (e.g. approach embankments, reinforced earth walls) or geosynthetic products (Holtz et al., 1998; Koerner, 2005; Jones and Bell, 2013; Saran, 2017; Öztürk et al., 2024) (e.g. road embankments with geowalls or geosynthetics) are commonly used today (Hausmann, 1989; Koerner, 2012). In these processes, the reinforcement must be placed and compacted using special manufacturing techniques. Another and more practical approach to improving soil through reinforcement is to reinforce the soil with randomly distributed fibers. Recently, the subject of reinforcement with waste fibers has attracted attention and has been studied. For this purpose, synthetic waste fibers such as polypropylene, polyester, nylon, palm fibers, jute, coconut fibers, bamboo fibers and many natural fibers such as wool, hair and silk were examined. The investigations generally relate to the construction of cohesive fine-grained soils or mixed soils with a high proportion of fine-grained soils as embankments and the problems that arise. For this reason, general emphasis is placed on the mechanical behavior of reinforced soil samples as qualified filling (with Proctor test and unconfined compression test) or improving compression properties (with consolidation test) (Hejazi et al., 2012; Bordoloi et al., 2017; Yazıcı and Keskin, 2021; Zafar et al., 2023). Sandy soils have low water retention capacity (cohesive character), high permeability and are sensitive to compression. Reinforcement with fibers can be considered as a good option to eliminate the weak points in the mechanical behavior of sandy soils. The effect on the mechanical behavior of coarse-grained soils reinforced with fibers has been investigated to a lesser extent (Adlin Rose et al., 2022; Anagnostopoulos et al., 2013; Choobbasti et al., 2019; Darvishi and Erken, 2018; Islam et al., 2021; Liu et al., 2017; Noorzad and Zarinkolaei, 2015; Yetimoglu and Salbas, 2003). Adlin Rose et al. (2022) investigated improving the shear strength of sandy soils using chicken feathers. In their study, washed, air-dried and 5 mm long chicken feather fibers (CFF) were used to improve the mechanical behavior of poorly graded clean (SP) natural sand. To this end, the author investigated the improvement of soil shear strength by conducting a series of direct shear tests on samples obtained by mixing sandy soil with chicken feather fibers at different ratios between 0.25% and 3.0%. The maximum shear strength values of chicken feather enhanced samples ranging from 1.5% to 2.5% were found to be 61kPa, 103kPa and 159 kPa at normal stress values of 50 kPa, 100 kPa and 150 kPa, respectively. and the internal friction angle was 45°. Thus, the addition of CFF provided an improvement in shear strength by 50%, 32%, and 30% at normal stress values of 50 kPa, 100 kPa, and 150 kPa, respectively, and an increase in the internal friction angle by 13%. In this context, the principle of reinforcement with randomly distributed fibers was used to study how chicken feathers would affect the shear strength properties of the sandy soil, taking the studies carried out as a reference. Experiments were carried out by adding 60 mm long chicken feather fibers to the sand substrate in amounts of 0.2% and 0.4% by weight. The experimental results were examined in terms of load-deformation behavior, peak shear stress, friction angle and dilatation behavior for samples with and without additives. By conducting this comparative analysis, the study aimed to understand the effects of chicken feather additive on soil behavior and highlight the key differences in their behavior. Chicken feathers can be a favorable alternative as a fiber supplement as they provide increased strength, and the use of chicken feather fibers in waste management and recycling can help protect nature.

2. Materials and Methods

2.1. Soil Sample

In this study, as in many studies, poorly graded clean sand (SP) was used as a proxy for problematic sandy soils (Anagnostopoulos et al., 2013; Liu et al., 2017; Benziane et al., 2019). Specific gravity, grain size distribution and relative density tests were carried out to determine the index properties of the sand used (ASTM D4253-16e1, 2016; TS EN ISO 17892-3, 2016; TS EN ISO 17892-4, 2016). Information on the index properties of the soil is given in Figure 1 and Table 1.

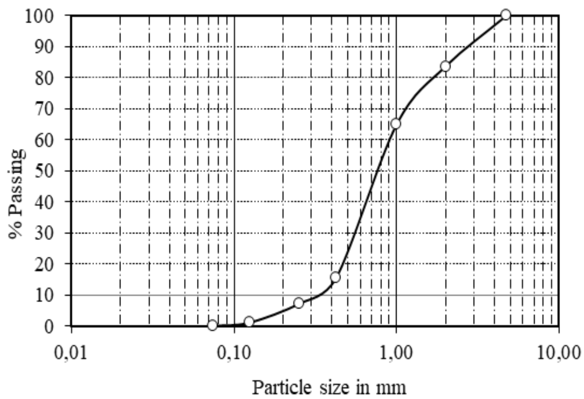

Figure 1. Particle sizes distribution.

Table 1. Characteristics of the soil

Properties	Value
Specific gravity, Gs	2.73
D_{10} (mm)	0.35
D_{30} (mm)	0.55
D_{60} (mm)	0.90
Coefficient of uniformity, Cu	2.57
Coefficient of curvature, Cc	0.96
Minimum dry density (kN/m^3)	15.15
Maximum dry density (kN/m^3)	17.20
Maximum void ratio, e_{max}	0.81
Minimum void ratio, e_{min}	0.59
Relative density (%)	80
Soil classification (USCS)	SP

Figure 2. Prepared chicken feather fibers.

2.2. Chicken Feather Fiber (CFF)

When soil stabilization studies with fibres are examined, although an increase in shear strength is observed as the fibre length increases, however, after a certain length of fibre, a decrease in shear strength is observed. This situation is justified by many authors because the locking mechanism between the strands of fibres above a certain length is adversely affected. However, the preferred length of fibre varies depending on the fibre type (Yazıcı and Keskin, 2021). Therefore, the fibre length chosen in our study was chosen according to an ideal average size which requires less processing and can be applied without the need to separate the hair from the fibre. Chicken feather fiber (CFF) was used for reinforcement. Chicken feathers were washed and air dried before experiments. Afterwards, they were cut to an average length of 60 mm. The prepared CFF samples are demonstrated in Figure 2. The shear strength parameters were studied to observe the improvement achieved by CFF in the sand sample. In many studies on the reinforcement of sand soils with fibers, samples were prepared by reinforcing them with different fibers in the range of 0.1 to 2% by weight (Anagnostopoulos et al., 2013; Benziane et al., 2019; Islam et al., 2021; Liu et al., 2017; Noorzad and Zarinkolaei, 2015; Yetimoglu and Salbas, 2003). Based on this, 0%, 0.2% and 0.4% fiber content by weight were used.

2.3. Method

Test samples were prepared with 0%, 0.2% and 0.4% fiber content and 80% relative density. Since the samples were prepared and tested in dry condition, no water was added to the shear box cell. Since larger fibers were used compared to the fiber size used in many studies, experiments were conducted using a large-sized shear box. Since the test equipment used transferred the horizontal deformation, vertical deformation and applied shear stress values read during the test to the computer with an automatic system, data loss was minimal during the test. Shear box tests were conducted by taking TS 1900-2/T3 (2019) as reference.Dried sand and CFF were randomly mixed and compacted into three layers and placed in the shear box to prepare the samples. The samples were cut in a cutting box with dimensions of 116x116x60 mm at a speed of 1 mm/min. The experiments were carried out under three different normal stresses of 29 kPa, 58 kPa and 116 kPa.

3. Results and Discussion

Many studies on fiber reinforcement have indicated that fiber reinforcement provides improvement in the shear strength parameters of the soil. For example, Yetimoglu and Salbas (2003) and Anagnostopoulos et al. (2013) did not observe a significant increase in peak shear strength in their studies with polypropylene fibers. Both studies have worked on poorly graded sand (SP) samples with polypropylene fibers (φ:0.03-0.05mm; l:12-20mm) in the range of 0.1-1.0% by weight. Although the normal stress values used do not fully coincide, they have tested their samples within the limits of 50-800kPa. While Anagnostopoulos et al. (2013) observed a decrease in cohesion value with fiber addition, Yetimoglu and Salbas (2003) did not observe a positive contribution. The authors observed a decrease in the friction angle value, although not at a significant level. While the authors did not express an opinion on the mechanism of this situation, Yetimoglu and Salbas (2003) stated that small-sized experiments were insufficient to observe the fiber effect and that larger-sized fibers should be used.

Noorzad and Zarinkolaei (2015)also worked on poorly graded sand (SP) samples with polypropylene fibers (φ:0.03 mm; l:6, 12 and 18 mm) in the range of 0.1-1.0 wt%. For this purpose, they tested the samples with direct shear and triaxial compression tests. In the study, it was stated that fiber reinforcement generally increased the shear strength of the soil sample (the increase became more pronounced with the increase in vel if length in the range of 106-435%). However, it was stated that the peak strength ratio decreased as the normal pressure increased and that the fiber content increased. The author explained this situation by the fact that while the unreinforced soil already had high strength under high normal stress, the addition of fibers under low normal stress provided lower peak strength ratio and the interaction between the fiber and the soil decreased.

Benziane et al. (2019) also tested poorly graded polypropylene fibres (φ:0.03 mm; l:12 mm) on samples of sand (SP) with 0.1 - 1.0% by weight. The author also stated that a limited improvement in the shear strength has generally been achieved with increasing fibre content and an increase in the coherence and friction angle has also been observed. The author worked with relative densities of 30%, 50% and 80% and found that increasing relative density increased the interaction between fibre and soil. All three authors discussed in this paragraph have noted that with increasing fibre, residual shear strength increases. For example, at 80% relative density, peak and residual shear strengths were increased by about 20% Based on this, it can be concluded that the increase in normal stress increases the fiber-soil interaction and the use of large-sized fibers increases the shear strength by increasing the soil-fiber interaction.

Adlin Rose et al. (2022), studied poorly graded sand (SP) samples with chicken feather fibers (sorted as stem-feather and prepared in l:5mm length) in the range of 0.0-3.0% by weight. In the study, the maximum shear strength increased by 27% (σ=150kPa) - 56% (σ=50kPa) depending on the normal stress in the range of 1.5-2.5%. An increase of up to 13% was achieved in the friction angle.

3.1. Change in Shear Strength Values

Shear stress-horizontal displacement curves for the tests with and without CFF reinforcement are shown in Figure 3. In this study, an increase in peak and residual shear strength values was observed with fiber reinforcement. With 0.2% fiber reinforcement, peak shear strength values of 43 kPa, 75 kPa and 137 kPa; residual shear strength values of 39 kPa, 70 kPa and 121 kPa were obtained under normal stresses of 29 kPa, 58 kPa and 116 kPa, respectively. With 0.2% fiber addition, peak shear strength values increased by 16%, 29%, 24.5% and residual shear strength values increased by 34%, 34.6% and 23.5%, respectively. Increasing the CFF content to 0.4% did not provide a significant increase. Considering the studies mentioned in the previous paragraph, while no improvement was observed in two studies conducted with polypropylene fibers (Anagnostopoulos et al., 2013; Yetimoglu and Salbas, 2003), an increase of up to 20% was observed in one study (Benziane et al., 2019), and an increase of up to four times was observed in the other (Noorzad and Zarinkolaei, 2015) In the study conducted by Adlin Rose et al. (2022), with chicken feathers, an average of 30% improvement was achieved at very high fiber rates compared to our study. When compared to the findings obtained from our study, it is seen that a very good performance is achieved with a recycled organic and waste fiber compared to the studies conducted with synthetic fibers. The fact that similar performance was achieved with the use of chicken feathers at a lower weight compared to the study conducted with chicken feathers is also a positive gain. In addition, using the fiber sizes in larger sizes and as a whole will save on fiber processing processes.

Table 2. Summary of experimental data

	Amount of fiber by weight (%)	Shear Strength (kPa)						Friction Angle (°)	
		Peak			Residual			Peak	Residual
		29kPa	58kPa	116kPa	29kPa	58kPa	116kPa		
UR	0.0	37	63	110	29	52	98	38.6	32.9
0.2%CF	0.2	43	75	137	39	70	121	47.8	37.2
0.4%CF	0.4	45	76	132	40	75	121	43.6	36.7

When the other mentioned studies were examined, it was observed that in some studies, peak strengths increased with the increase in fiber (Yetimoglu and Salbas, 2003), while in some studies, although an increase in strength was observed at the beginning, a decrease in peak strengths was observed with the increase in fiber (Noorzad and Zarinkolaei, 2015). However, in this study, the highest peak and residual shear strength values were obtained at 116 kPa normal stress with 0.2% CFF reinforcement. The increase obtained by increasing fiber supplementation from 0.2% to 0.4% is not significant. Considering the curves in Figure 3, the highest stress value for each experiment was taken as peak shear stress and the stress value at the end of the experiment was taken as residual shear stress. Peak shear stress and residual shear stress values obtained from the experimental results are illustrated in Figure 4. It was stated that the reason for the increase in shear strength with fiber additive is based on the interaction between fiber and soil. The reason why the fiber additive rate we observed in our study did not provide a significant increase after 0.2% is that while the fiber-soil interaction reached the most ideal rate at a certain fiber percentage, the increase in the subsequent fiber ratio negatively affects the fiber-soil interaction. For this reason, the idea that the fiber-soil interaction is shaped depending on the soil grain size and fiber type comes to mind. Therefore, it is recommended that the appropriate fiber size selection for each soil sample be tested and selected in applications related to fiber reinforcement.

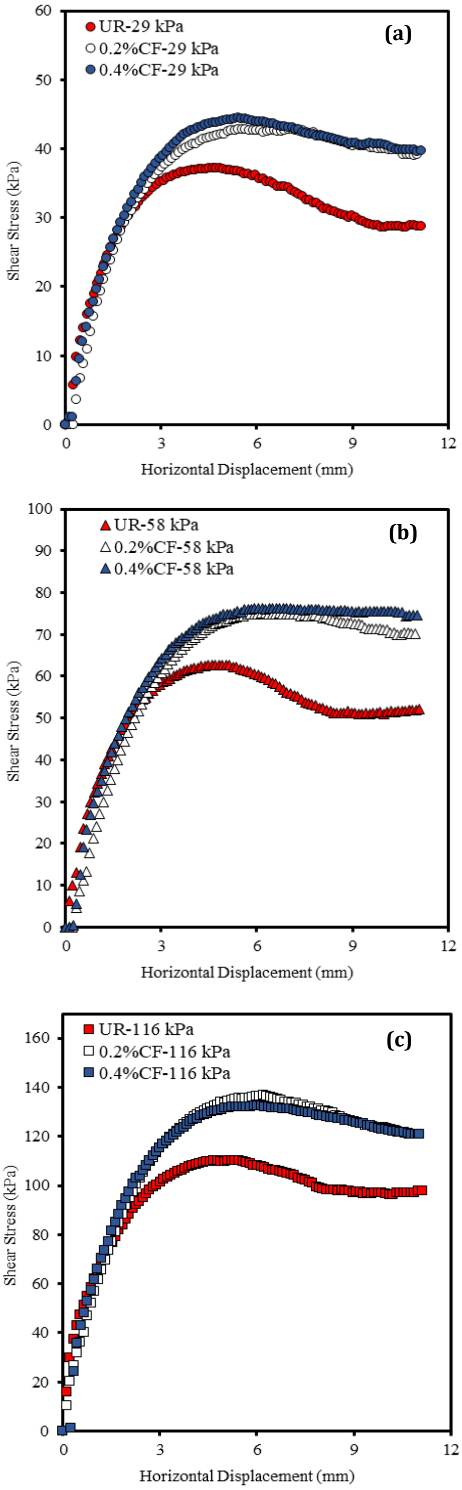

Figure 3. Load-deformation behavior of unreinforced, 0.2% CFF and 0.4% CFF reinforced specimens under different normal stresses (a) 29 kPa (b) 58 kPa (c) 116 kPa.

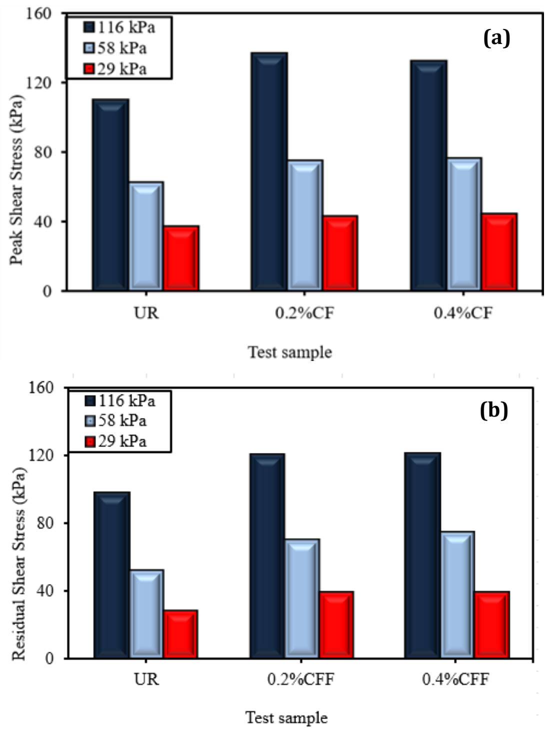

Figure 4. Shear strength values of the samples at different normal stresses (a) Peak shear stress (b) Residual shear stress.

3.2. Mohr Failure Envelopes and Friction Angle Variation

In most studies on reinforcing sands with fibers, the friction angle increased with increasing fiber reinforcement (Anagnostopoulos et al., 2013; Islam et al., 2021; Noorzad and Zarinkolaei, 2015). The results of Yetimoglu and Salbas (2003) are in the opposite direction. However, Yetimoglu and Salbas (2003) stated that fiber supplements only increased residual values.

The peak and residual friction angle values obtained from the experimental results are demonstrated in Figure 5. Additionally, Mohr failure envelope curves are given in Figure 6. In this study, the fracture envelopes of the samples with CFF reinforcement were positioned higher and with a greater slope. Therefore, with fiber reinforcement, an increase in both peak and residual friction angle values was observed along with the increase in shear strength. The highest friction angle values were observed at 0.2% fiber content. At 0.2% fiber content, the peak friction angle value increased from 38.6º to 47.8º; the residual internal friction angle value increased from 32.9º to 37.2º. With reinforcement, an increase of approximately 23.8% in peak friction angle value and approximately 19% in residual friction angle value was observed. Adlin Rose et al. (2022) observed that the friction angle increased by 13% from 39.9º to 45º by reinforcing a poorly graded sand soil (SP) with CFF. The effect of the increase in fiber content from 0.2% to 0.4% on the change of peak and residual friction angle is quite limited. It is known that the friction angle is a parametric expression of the mechanical interaction between soil grains. It is expected that the friction between grains will increase with the increase in fiber-soil interaction and therefore the increase in the friction angle. The statement that the increase in shear strength with fiber contribution discussed in the previous paragraph is due to the interaction between fiber and soil is consistent with the findings of the friction angle change.

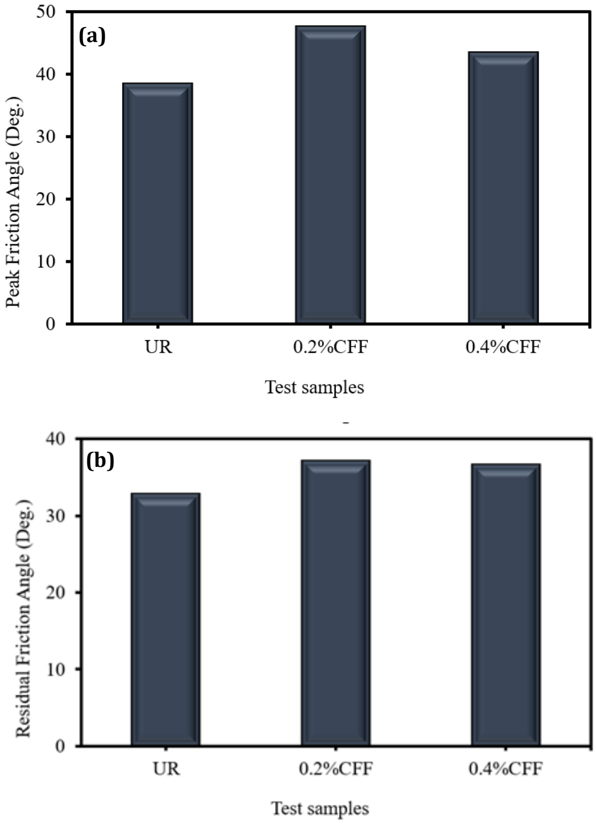

Figure 5. Friction angle values (a) Peak (b) Residual.

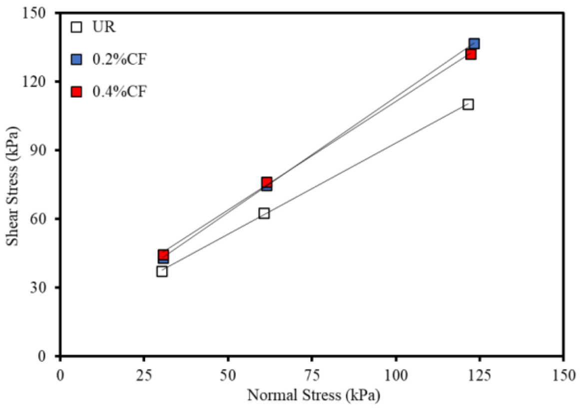

Figure 6. Mohr failure envelops for peak state values.

Benziane et al. (2019) stated that fiber reinforcement prevents expansion at low density ratios but increases it at high density ratios. Furthermore, many studies have been conducted at high density ratios and it has been observed that the expansion increases with increasing fiber reinforcement and normal stress (Anagnostopoulos et al., 2013; Benziane et al., 2019; Noorzad and Zarinkolaei, 2015). The vertical deformation-horizontal deformation curves obtained from the experiments are given in Figure 7. The findings in this study are consistent with the literature that expansion increases with increasing fiber reinforcement. While the increase in expansion is evident at low normal stresses, it loses its significance at high normal stresses. Our findings also indicate that the tendency of the soil to expand under the effect of shear forces increases with the increase in fiber content and normal stress. This indicates that the fibers increase the friction between the grains and cause the soil to behave as if it were in a more compact state than it actually is. For a better evaluation, the fiber effect should be monitored with visual monitoring tools. Considering the findings of this study and the literature, it is clearly revealed that the fibers mechanically strengthen the soil in terms of resistance to shear forces. However, both in the literature and in this study, it is important to emphasize the fact that peak and residual strength values can occur at different normal stresses or fiber ratios. It is clear that there will be differences in the unit volume weights of the fiber-sample mixtures, especially depending on the fiber unit volume weights. On the other hand, differences in fiber lengths, dimensions and textural properties cause the fiber-soil adhesion to vary with unit volume weight. Similarly, the increase in the expansion tendency of the samples with the addition of fibers is due to the same reasons. In other words, the sand matrix changes due to the fiber effect. Both the shear strength increases and the unit volume weight changes. Just as excess water prevents compressibility during compaction, fiber added beyond a certain amount reduces the mechanical strength of the soil rather than contributing. It would therefore make sense to determine the ideal amount of fiber in the laboratory when carrying out studies with fiber additives.

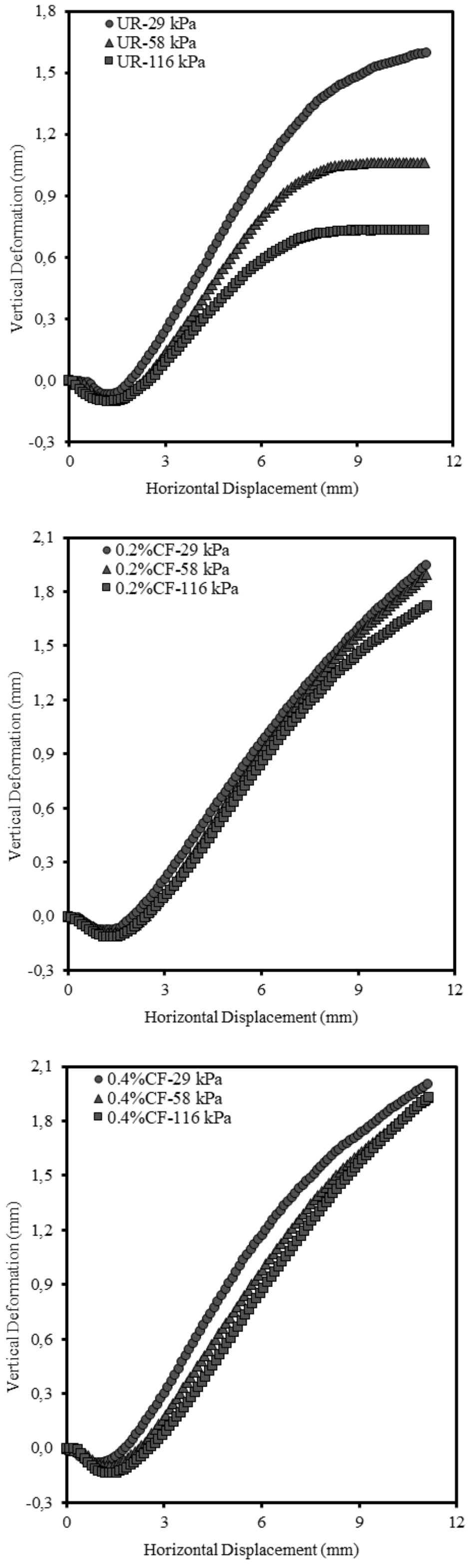

Figure 7. Variation of vertical displacement with respect to horizontal displacement.

4. Conclusion

The amount of waste feathers generated by chicken production and consumption reaches millions of tons worldwide. Disposal methods of waste chicken feathers harm nature and therefore human health. For this reason, waste chicken feathers need to be removed from nature and disposed of with sustainable approaches. In this study, the use of waste chicken feathers as soil improvement fiber was investigated by direct shear tests. The obtained results reveal that chicken feathers, which are increasingly becoming a burden on the environment, make sense to be used for soil reinforcement. It provides reinforcement as effective as synthetically produced polypropylene fibers. Once the appropriate amount of fiber for the soil is determined, it can be used with the highest benefit. To summarize all the results obtained in a few points:

- CFF fibers, like many other fibers, provide satisfactory mechanical strength increases.
  - With 0.2% fiber reinforcement, peak shear strength values of 43kPa, 75kPa and 137kPa; residual shear strength values of 39kPa, 70kPa and 121kPa were obtained under normal stresses of 29kPa, 58kPa and 116kPa, respectively. With 0.2% fiber addition, increases of 16%, 29%, 24.5% were observed in peak values and 34%, 34.6% and 23.5% in residual values, respectively.
  - At 0.2% fiber content, the peak friction angle value increased from 38.6^o to 47.8^o; the residual friction angle value increased from 32.9^o to 37.2^o.
  - Fiber reinforcement improved mechanical behavior. However, increasing fiber reinforcement from 0.2% to 0.4% did not provide significant improvement.
- As we recommend for many fibers, the best results can be achieved by determining the most appropriate amount of fiber for the soil to be reinforced based on normal loading.
- It offers a great advantage that the waste generated by eating chicken every year is disposed of in a natural way and has the power to compete with the synthetic fibers that are harmful to nature.

Finally, one of the problems with reinforcement using natural fibres is the time to degrade and the rate of degradation of natural materials. In almost all existing studies, degradation processes of natural materials in soil reinforcement with natural fibre studies were not investigated. Although this is a costly and time-consuming process, the investigation of the degradation processes of the materials used is itself a subject of research. This should be explored in future studies.

Author Contributions

The percentages of the authors' contributions are presented below. All authors reviewed and approved the final version of the manuscript.

	M.Ö.	U.E.Y.
C	50	50
D	50	50
S	50	50
DCP	50	50
DAI	50	50
L	50	50
W	50	50
CR	50	50
SR	50	50
PM	50	50
FA	50	50

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The authors declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

Acknowledgement

The authors thanks to Beyza Piliç company for supply of chicken feather.

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