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Increasing Strength of Clay Soils with the Use of Basalt Fiber: An Experimental Study

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Abstract: Due to the increase in population, the demand for buildings increases. The engineering properties of the soils on which these structures will be built may not always meet the desired conditions. In such cases, soil improvement methods are used. One of these methods is additive used stabilization, in which additives such as lime, fly ash, volcanic ash and tuff, silica fume, and blast furnace slag are used. This method has been used successfully for years. However, in recent years, interest in the use of different types of fibers has increased. Some of these fibers are glass, basalt, polypropylene, and carbon. Basalt fibers have begun to attract attention in soil reinforcement applications due to the properties of their raw material, basalt rock, which is widely distributed in nature, natural, and has high strength. In this study, the effect of basalt fiber reinforcement on the unconfined compressive strength of high plasticity bentonite clay was revealed. For this purpose, 12 mm long basalt fiber in different proportions (1%, 2%, 3%, 4%, and 5%) was used as reinforcement in bentonite clay, and the optimum fiber ratio that provided the maximum increase in strength was determined. According to the results of the study, when 12 mm long basalt fiber was used as reinforcement in bentonite clay, the maximum strength value was obtained at a 4% basalt fiber ratio. However, the strength value decreased in the sample where 5% BF was used. It has been determined that basalt fiber reinforcement improves the strength properties of bentonite clay.

Key words: Basalt fiber, bentonite clay, reinforcement, unconfined compressive strength.

Bazalt Fiber Kullanımı ile Killi Zeminlerin Dayanımının Artırılması: Deneysel Bir Çalışma

Öz: Nüfusun artışına bağlı olarak yapılara olan talepte artmaktadır. Bu yapıların inşa edileceği zeminlerinde mühendislik özellikleri her zaman istenilen şartları sağlamayabilir. Böyle durumlarda zeminlerin iyileştirilmesi yöntemlerine başvurulmaktadır. Bu yöntemlerden biri de kireç, uçucu kül, volkanik kül ve tüf, silis dumanı, yüksek fırın cürufu gibi katkıların kullanıldığı katkılı stabilizasyondur. Bu yöntem yıllardır başarılı bir şekilde uygulanmaktadır. Fakat son yıllarda farklı türde fiberlerin kullanımına olan ilgi artmıştır. Bu fiberlerden bazıları cam, bazalt, polipropilen ve karbondur. Özellikle bazalt fiberler, hammaddesi olan bazalt kayacının doğada geniş yayılım göstermesi, doğal olması ve dayanımın yüksek olması gibi özelliklerinden dolayı zemin güçlendirme uygulamalarında oldukça dikkat çekici olmaya başlamıştır. Bu çalışmada yüksek plastisiteli bentonit kilinin serbest basınç dayanımında bazalt fiber takviyesinin etkisi ortaya konmuştur. Bu amaçla 12 mm uzunluğunda ve farklı oranlarda (%1, %2, %3, %4 ve %5) bazalt fiber, bentonit kilinde takviye olarak kullanılmış ve dayanımda maksimum artışı sağlayan optimum fiber oranı belirlenmiştir. Çalışmanın sonuçlarına göre, 12 mm uzunluğundaki bazalt fiber bentonit kilinde takviye olarak kullanıldığında maksimum dayanım değeri %4 bazalt fiber oranında elde edilmiştir. Ancak %5 BF kullanılan örnekte dayanım değeri azalmıştır. Bazalt fiber takviyesinin bentonite kilinin dayanım özelliklerini iyileştirdiği belirlenmiştir.

Anahtar kelimeler: Bazalt fiber, bentonit kili, güçlendirme, serbest basınç dayanımı.

1. Introduction

The use of fiber (glass, polypropylene, basalt, etc.) as an alternative to traditional methods in soil improvement has shown remarkable development in recent years. Ekincioğlu [1] defines fibers as materials that can be found naturally or produced by humans, one dimension of which is much larger than the other dimension, and has a higher strength and elasticity modulus than the larger shape of the same material. Of the two types of fibers, natural and artificial, the artificial one is used more. Artificial fibers are preferred because they have high strength, are light, flexible and highly resistant to environmental effects [2]. Glass fiber [3-8], polypropylene fiber [8-12] and carbon fiber [13] are used as reinforcement in several studies and studies using these fibers as reinforcement stated that improvements in soil properties occurred.

One of these fiber is basalt fibers (BF), which has attracted attention in recent years and is produced from basalt rock. The raw material of BF is basalt rock, which is a volcanic rock that is widely distributed in nature and easy to access. BFs have superior properties such as high chemical resistance and resistance to temperature and microorganism effects. The fact that no additives are used during production is also an advantage for BFs. When

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soil reinforcement studies with BF reinforcement are examined, it is seen that BF length and rate are important for successful reinforcement.

As a matter of fact, Gao et al. [14] used BF reinforcement in clayey soil and stated that the fiber ratio in which the maximum strength was determined was 0.25% and the fiber length was 12 mm. Gisymol & Ramya [15] found that the maximum increase in the strength of the organic soil with 10 mm length and 0.05% BF reinforcement occurred after 28 days of curing, while Kenan & Özocak [16] found that the optimum fiber ratio was 1.5% in their study on a silty soil. Pandit et al. [17] showed that according to the results of experimental studies using BF reinforcement in the soil, the maximum dry unit weight value of the soil increased and the optimum water content value decreased with the 4% ratio of BF. Moreover, Ocakbaşı [18] reported that the maximum strength value in the soil was increased by 2% BF and she stated that the fiber length was determined as 24 mm. Sungur et al. [19], determined that the shear strength increases up to a fiber length of 15 mm in BF reinforced clay soil, and the shear strength values decrease at a fiber length greater than that. Terzi [20] added 6 mm, 12 mm and 24 mm long BF to high plasticity clay at the rate of 0, 1.0, 1.5, 2.0 and 2.5% by weight. As a result of experimental studies, the maximum cohesion value was determined in the 12 mm long 1.5% BF reinforced sample, and the maximum internal friction angle was determined in the 24 mm long 2% BF reinforced sample. Zhao et al. [21] examined the reinforcing effect of BF and polypropylene fiber on low plasticity clay in their study. In the study, it was suggested that the effect on strength could be maximized when the fiber length was 10 - 13 mm and the additive ratio was 0.2%. Also, Jia et al. [22] determined that the shear strength and cohesion of silty clay increased with basalt fiber reinforcement. It has been noted that the shear strength of reinforced silty clay is maximum when the fiber content is approximately 0.2%. The researchers stated that a single fiber is tightly surrounded by the surrounding clay particles, which creates a gripping effect that can increase soil strength. It has been stated that the fibers in certain areas are interwoven to form a fiber network, and the binding effect of this fiber network can effectively restrain the surrounding soil particles and increase the strength of the soil. It has been stated that the gripping effect and the binding effect are the main mechanisms of fiber reinforcement. Gürocak and Aslan Topçuoğlu [23] conducted experimental studies on the samples prepared by using 20, 25, 30 and 35% water content in kaolin clay by using BF (0, 1, 2, 3%). According to the test results, they stated that the maximum strength value was obtained with 1% BF reinforcement and 25% water content. Aslan Topçuoğlu and Gürocak [24] carried out experimental studies using 6 mm long BF reinforcement in different proportions in bentonite clay. According to the results obtained from the study, the optimum fiber ratio that provides the maximum improvement in unconfined compressive strength was determined to be 4%. Song et al. [25] stated that the use of basalt fiber in low plasticity clay soil increased the shear and compressive strength of the soil and that the fiber ratio that provided the maximum increase in strength was 0.3%.

When fiber is added to the soil, the mechanism between the fiber and the soil is explained as follows; When the appropriate amount of fiber is added to the soil, the fiber binds to the soil particles and forms a fiber - soil column. When exposed to external forces, discrete soil-fiber columns interact with each other to form an approximately three-dimensional fiber - soil network and serve to limit the displacement and deformation of soil particles. Thus, the mechanical properties of the soil improve [25]. When the fiber ratio in the soil is very low, the fiber spacing is wide and the intersection between fiber - soil columns is difficult, so an effective fiber - soil network does not form. When the soil is exposed to external force, the stress is mainly transferred and carried by the scattered fiber - soil columns and the forces between the soil particles themselves. Gradually, as the fiber ratio increases, the fiber spacing decreases, which enables adjacent fiber to soil columns to easily intersect to form an effective fiber to soil network. Thus, when the soil is subjected to external force, the force is mainly carried by the forces between the fiber - soil network and the soil particles. When the fiber ratio is high, it becomes difficult to distribute the fibers properly due to the accumulation of many fiber filaments in clusters on the soil due to electrostatic interaction [14].

In the studies briefly summarized above, fiber reinforcement of different lengths and rates was used in different soil types. In these studies, it is clear that the effect of fiber reinforcement depends on the type of soil, fiber ratio and length. Unlike the soil type chosen in the studies, bentonite clay (B) was preferred in this study because it has higher plasticity. It has been tried to reveal the importance of basalt fiber reinforcement, especially in the unconfined compressive strength of clay soils with high plasticity. The fiber ratio was kept within a wide range (1%, 2%, 3%, 4%, 5%), thus aiming to reveal more clearly the effect of the fiber ratio on unconfined compressive strength. For this purpose, different amounts of BF with a length of 12 mm were used as reinforcement in bentonite and the changes in the strength values were determined. The fiber ratio that gives maximum strength on the soil was determined and the effectiveness of fibers used less or more than this ratio was evaluated separately. The results obtained from the study will contribute to future studies on the use of BF in soil reinforcement.

2. Materials and Methods

In this study, bentonite was used as the clayey soil, and BF, whose use has increased in recent years and whose database still needs to be strengthened with new studies, was used as the reinforcement material.

2.1. Bentonite clay and basalt fiber

Bentonite clay, which is a clay mineral that belongs to the montmorillonite family and is formed as a result of the chemical decomposition or degradation of volcanic ash, lava and tuff rich in aluminum and magnesium content Önem [26], Akbulut [27], consists of chemically hydrated aluminum and magnesium silicates. In the experimental studies, pure bentonite clay produced in the Tokat - Reşadiye (Turkey) clay quarry was used (Figure 1), and according to the results of the XRF analysis performed on the clay, it was determined to be Na - Bentonite type clay [28].

Figure 1. Bentonite clay used in the study.

BF produced from basalt, which is a hard, fine - grained, dark - colored volcanic rock widely found in the world, is used for reinforcement soils due to its economical, natural, and high strength properties. Basalt has the property of melting when heated, like thermos - plastic materials [29]. BF with a length of 12 mm was used in the study (Figure 2) and was purchased from a fiber selling company. The physical and mechanical properties of BF are given in Table 1.

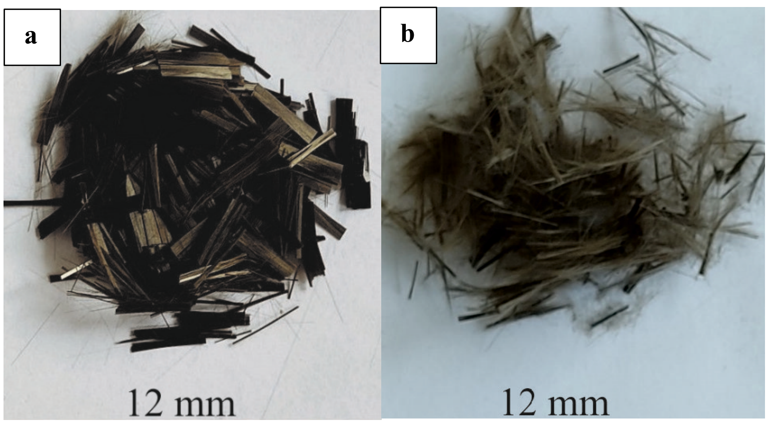

Figure 2. Unseparated (a) and separated (b) basalt fiber used in the study.

Table 1. Mechanical and physical properties of BF were used in the study.

Feature	Value
Length fiber (mm)	12
Diameter of monofilament (µm)	15 ±1,5
Humidity, Max (%)	2
Modulus of elasticity (GPa)	90
Tensile strength (MPa)	3000
Thermal conductivity (W/mK)	0.031- 0.038
Elongation at break (%)	3.5
Density (g/cm^3)	2.63

2.2. Laboratory studies

Firstly, liquid limit (LL), plastic limit (PL), and standard proctor tests were carried out on bentonite in the laboratory studies. In the second stage, unconfined compressive strength tests were carried out after the mixtures in which different amounts of BF were used as reinforcement in B were compressed at optimum water content. Laboratory studies were carried out at Fırat University, Department of Geological Engineering, Rock - Soil Mechanics Laboratory.

2.2.1. Liquid and plastic limit tests

At this stage of laboratory studies, the LL and PL values of unreinforced B were determined according to the ASTM D4318 - 17e1 [30] standard. For this purpose, a total of 15 tests were carried out. According to the test results, the average LL and PL values of unreinforced B were found to be 507% and 41%, and the plasticity index (PI) value was calculated to be 466%. It was determined that the clay used in this study was the high plasticity (CH) clay according to the Unified Soil Classification System (USCS) (Table 2).

Table 2. Results of consistency limits

Feature	Value
LL (%)	507
PL (%)	41
PI (%)	466
Soil class (USCS)	CH

2.2.2. Sample preparation and standard proctor experiments

Firstly, BF separated by compressor was added to the clay, which was dried in an oven at 105^{o}C for 24 hours and mixed with the help of a mixer (Figure 3). B samples reinforced with BF were mixed again with a mixer by spraying distilled water at optimum water content, and a separate manual mixing process was applied in order to ensure homogeneous distribution of the fibers in B and to prevent fiber aggregation/agglomeration. In this study, the mixing time was determined to be 10 minutes and five separate mixtures were prepared. BF ratios used in the mixtures are shown in Table 3. The optimum water content (w_{opt}) value and maximum dry density (γ_{dmax}) value of B were determined by standard proctor tests performed in accordance with the ASTM D698 - 12e2 [31] standard. The test was carried out by letting a 2.5 kg load fall freely from a height of 30.5 cm on the soil and compressing the soil in three layers in the formwork (Figure 4). According to the proctor test results, w_{opt} value was determined as 38.50% and γ_{dmax} value was determined as 12.36 kN/m^3 (Figure 5).

Figure 3. Preparation of B and BF mixtures.

Figure 4. Proctor test and taking cylindrical samples.

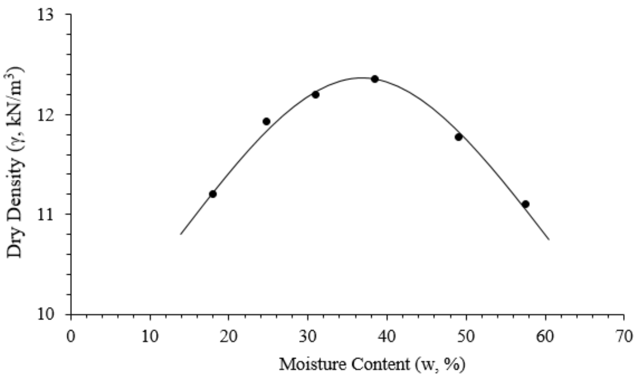

Figure 5. w - γ graph of the clay used in the study.

Table 3. BF rates used in experimental studies.

BF Length (mm)	BF Rate (%)	Sample Name
12	0	B
	1	B + 1% BF
	2	B + 2% BF
	3	B + 3% BF
	4	B + 4% BF
	5	B + 5% BF

2.2.3. Unconfined compressive tests

According to the ASTM D2166M - 16 [32] standard, unconfined compressive tests were carried out on cylindrical soil samples whose length is twice the diameter length to determine the compressive strength (q_u) of the soil. Experiments were carried out on 35 cylindrical specimens compressed to optimum water content and reinforced with 12 mm long BF (Figure 6).

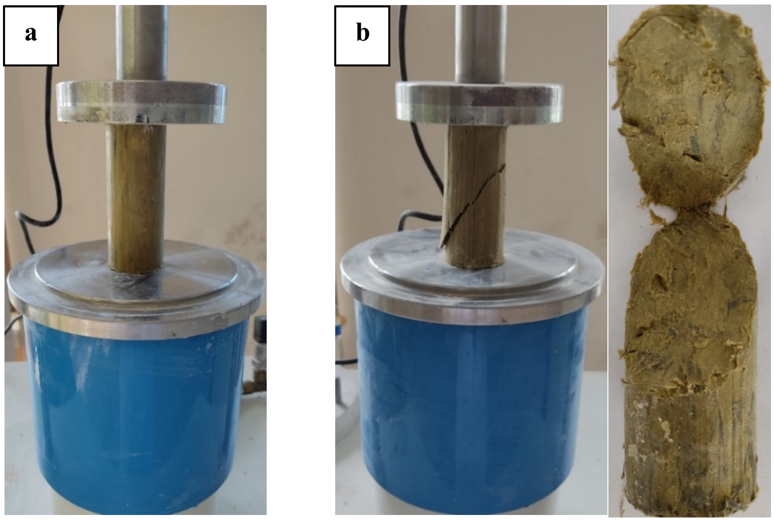

Figure 6. Unconfined compressive strength (a) before sample and (b) after sample.

According to the results of the unconfined compressive tests, the average q_u value of the unreinforced B was determined as 206.93 kPa. The average q_u values of the BF reinforced samples were found to be in the range of 202.74 - 267.66 kPa (Table 4). The failures that occurred in the samples after the unconfined compressive tests are given in Figure 7.

Figure 7. Samples after unconfined compressive test.

Table 4. q_u values of unreinforced and BF reinforced samples.

BF Length (mm)	Sample Name	Average q_u (kPa)	Standard Deviation (SD)
12	B	206.93	6.27
	B + 1% BF	223.64	7.06
	B + 2% BF	229.00	5.13
	B + 3% BF	247.42	8.10
	B + 4% BF	267.66	5.69
	B + 5% BF	202.74	4.82

3. Results and Discussion

With the experimental studies, it was tried to determine the changes in the unconfined compressive strength values of the unreinforced and BF reinforced B samples. In addition, the optimum fiber ratio, which provides the best improvement in strength, was determined. The average q_u value of unreinforced B is 206.93 kPa. The sample in which the maximum strength was determined with BF reinforcement is B + 4% BF, and its q_u value is 267.66 kPa. The lowest q_u value was determined as 202.74 kPa in the B + 5% BF sample (Table 4, Figure 8). This BF ratio was determined as 4%.

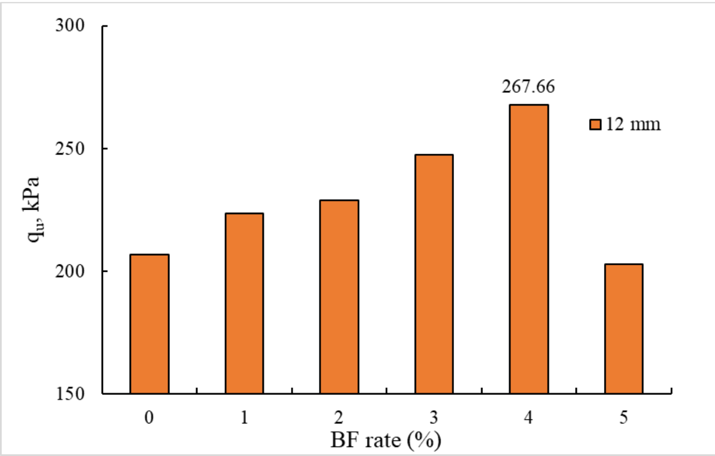

Figure 8. Relationship between q_u - BF ratio in unreinforced and BF reinforced clay samples.

The increases in the q_u values of the reinforced samples with 1, 2, 3, and 4% BF compared to unreinforced B were found as 8.08, 10.67, 19.57, and 29.35%, respectively. However, there is a decrease of 2.02% in the 5% BF reinforced sample (Table 5, Figure 9).

Table 5. Percentage changes in q_u values of unreinforced and reinforced clay samples.

BF Length (mm)	Sample Name	q_u (% Change)
12	B	-
	B + 1% BF	8.08
	B + 2% BF	10.67
	B + 3% BF	19.57
	B + 4% BF	29.35
	B + 5% BF	-2.02

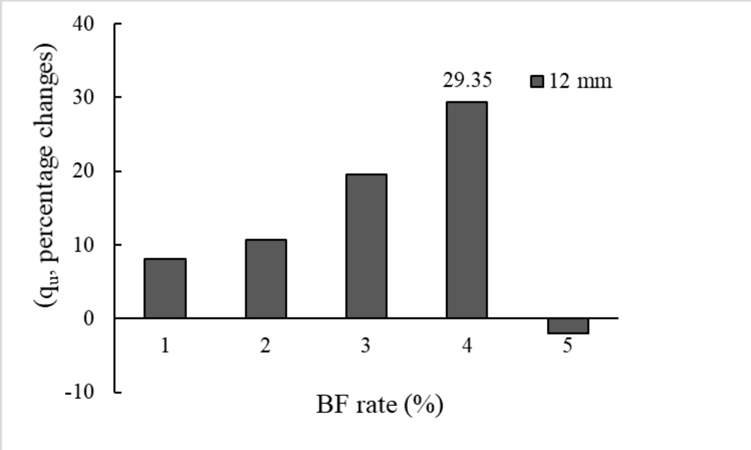

Figure 9. The relationship between percentage changes of q_u - BF ratio of unreinforced and reinforced clay samples.

The q_u value of clay increased up to 4% BF reinforcement but decreased with 5% BF reinforcement. The reason for this is the difficulty in aggregating and dispersing the fibers in the soil as the fiber ratio increases. When the fiber ratio is high in the soil, electrostatic interaction occurs between the fibers. For this reason, the fibers that are not homogeneously dispersed in the soil are collected in clusters, and thus the strength decreases [14, 25].

In addition, the fibers clustered in increasing fiber ratios do not have direct contact with the soil particles; thus, the grip effect between the fibers and the soil weakens. Excessive fiber concentration tends to create a weak structural surface in the soil, resulting in a decrease in soil strength [13]. In this study, q_u values increase up to 4% BF, and at 5% BF addition, the strength decreases as the grip effect between the fiber and the soil decreases due to fiber agglomerations. When the literature is examined, if the soil type is clay, the optimum BF ratio changes due to the type of reinforced clay.

When BF reinforcement is used in a low plasticity clay soil, the optimum BF ratio that provides maximum improvement in soil properties varies between 0.2 and 1.5% [14, 19, 21, 23, 25]. In high plasticity clays, the optimum BF ratio varies between 1.5 and 4% [18, 20, 24]. These studies showed that not only the BF ratio but also the type of reinforced soil and fiber length are important in soil reinforcement. The bentonite clay used in this study has much higher plasticity than the clays used in the literature. Therefore, the optimum BF ratio of 4% can be recommended for maximum strength in this bentonite clay with such high plasticity. In the study conducted by Aslan Topçuoğlu and Gürocak [24] using BF reinforcement in bentonite clay, 6 mm long BF was used. The optimum BF ratio that provides maximum strength with BF reinforcement was found to be 4%. The maximum strength value is 237.48 kPa. In this study, BF with a length of 12 mm was used and the optimum BF ratio was determined as 4%. However, the maximum q_u value corresponding to the optimum BF ratio is 267.66 kPa. The maximum q_u value determined by using a 12 mm long BF is 12.71% higher than the maximum q_u value determined by using a 6 mm long BF. In other words, using the same ratio but different lengths of BF resulted in obtaining different q_u values. In this study, increasing the BF length has a significant effect on obtaining higher q_u values. Accordingly, the plasticity of the clay, the fiber ratio and length affect the unconfined compressive strength.

4. Conclusions

In this study, using BF as reinforcement, the effect of BF ratio on the strength properties of high plasticity clay soil was determined. In unconfined compressive tests, the average strength value of unreinforced B was determined as 206.93 kPa. The average q_u values of BF reinforced mixtures vary between 202.74 - 267.66 kPa. In BF reinforced samples, q_u values increased up to 4% BF addition. By using 4% BF, the q_u value increased by 29.35% compared to unreinforced clay. However, with 5% BF reinforcement, there was a decrease of 2.02% compared to the q_u value of unreinforced clay. As the increasing fiber ratio caused fiber aggregation, the strength values decreased. Since the clustered fibers do not have direct contact with the soil particles, the grip effect between the fibers and the soil is weakened and excessive fiber concentration reduces the strength of the soil [13]. This study also revealed that q_u values increase with increasing BF length. In this study using 12 mm BF on the same type of soil and in another study using 6 mm BF [24], different strength values were determined and higher strength values were obtained in samples using 12 mm BF. Additionally, based on the findings of this study, one can assert that the optimum fiber ratio rises with an increase in the soil's plasticity. In studies where BF reinforcement was used, it is clear that the soil type, fiber ratio and length have an effect on the strength of the soil. In addition, mixing soil and BF homogeneously during the preparation of samples for experimental studies is very important in obtaining healthier and more reliable results. This experimental research on the reinforcement of high plasticity bentonite clay with basalt fiber is important in terms of providing a theoretical basis for engineering applications. The data obtained from this study will contribute to the studies and literature on the use of BF, which is abundant and naturally found in nature, has high strength and is environmentally friendly, in soil reinforcement and road base improvement in engineering.

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