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Research Article

A Review on Soil Reinforcement Technology by Using Natural and Synthetic Fibers

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Abstract
Soil reinforcement techniques are frequently used to improve the engineering properties of soils in geotechnical engineering applications. For this purpose, natural and synthetic fibers have managed to attract the attention of geotechnical engineerings as an alternative reinforcement technique to traditional stabilization methods due to their sufficient strength, low cost and easily availability. The purpose of this study is to create a review on the effects of parameters such as fiber type, physical and mechanical properties of fiber, fiber quantity, fiber length and fiber surface roughness on the engineering properties of different types of soils, according to data of scientific studies on the reinforced-soils using different types of natural and synthetic fibers. Besides, this study contains information about the effects of water in the soil matrix on the behavior of natural fibers and the recommended treatments, in addition to the mechanical behavior of the fiber-soil composite.

Keywords: Natural fiber, synthetic fiber, soil reinforcement

Zeminlerin Doğal ve Sentetik Lifler ile Güçlendirilmesi Üzerine Bir Derleme Çalışması

Öz
Geoteknik mühendisliği uygulamalarında zeminlerin mühendislik özelliklerinin geliştirilmesi amacıyla sıklıkla zemin güçlendirme teknikleri kullanılmaktadır. Bu amaç için son zamanlarda yeterli dayanımları, düşük maliyetleri ve kolay ulaşılabilirliklerinden dolayı doğal ve sentetik lifler, geleneksel stabilizasyon yöntemlerine alternatif bir güçlendirme tekniği olarak araştırmacıların dikkatini çekmeyi başarmıştır. Bu araştırmanın amacı; literatürde farklı türde doğal ve sentetik lifler ile zeminlerin güçlendirilmesi üzerine yayınlanmış bilimsel çalışmaların verilerini kullanarak lifin türü, fiziksel ve mekanik özellikleri, miktarı, uzunluğu ve yüzey pürüzlülüğü gibi paremetrelerin farklı türdeki zeminlerin mühendislik özellikleri üzerine etkileri hakkında bir derleme çalışması oluşturmaktır. Ayrıca bu çalışmada zemin ortamındaki suyun, doğal liflerin davranışı üzerine etkileri ve alınabilecek önlemler ile lif-zemin kompozitinin mekanik davranışı hakkında bilgiler verilmektedir.

Anahtar Kelimeler: Doğal lif, sentetik lif, zemin güçlendirme

1. Introduction

Nowadays, as a result of rapid industrialization and population growth, with the decrease of existing field resources especially in city centers, civil engineering structures are increasingly being built on almost all kinds of problematic soils, including loose and soft soils (Cai et al., 2006). If such soils are encountered within a shallow depth, the soil is usually removed and a suitable filling material is placed. However, if such soil is encountered at a great depth from the surface, it would be an uneconomical solution to carry out a large volume excavation. This situation raises the need to identify and develop a relatively more economical soil stabilization technique. In addition, in geotechnical engineering applications such as slope stability problems

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and stabilization, swelling and shrinkage effects, bearing capacity of road pavements and embankment, liquefaction, reinforcement of soils with high compressibility and very low shear strength, increasing the durability of soils under freeze-thaw cycles, soil stabilization techniques are frequently used. Soil stabilization methods used in geotechnical engineering applications can be grouped under three separate titles: i) Mechanical stabilization, ii) Chemical stabilization, iii) Combination of mechanical and chemical stabilization (Salim et al., 2018; Estabragh et al., 2012; Soltani et al., 2018). Chemical stabilization is carried out by adding materials such as cement, lime or polymer (resin) into the soil and the real chemical structure of the soil is changed with this method (Al-Rawas, 2002; İsmail et al., 2002; Tremblay et al., 2002; Bahar et al., 2004; Basha et al., 2005). From past to present, cement is generally the most preferred traditional additive material to improve the mechanical properties of soils such as strength and stiffness. However, there are some disadvantages associated with using cement for the chemical stabilization of soils. The waited curing time to gain sufficient strength, the need for high energy during the production of cement, the increase in the consumption of non-renewable resources, the damage to the ecological balance and the environment can be given as examples of these disadvantages (Sakaray et al., 2012; Dilrukshi et al., 2016). Conventional mechanical stabilization methods generally consist of placing planar reinforcement elements such as geosynthetic strips, reinforcement bars, geogrids or geotextiles into the soil. In traditional mechanical stabilization methods, reinforcements are generally made layer by layer and reinforcement elements are oriented horizontally, vertically or in both directions (Estabragh et al., 2012). With the use of oriented reinforcement elements, additional frictional resistance is provided in the reinforced planes, while the planes without reinforcement elements remain relatively weak planes. Additionally, according to Gowthaman et al. (2018), the worldwide capacity of geosynthetic plastic products was 0,36 million tons in 2007 and 2,33 million tons in 2013, while these values are expected to increase to approximately 3,45 million tons in 2020. Besides, since corroded steel is an environmentally toxic material, the use of steel reinforcement bars in the soil as a reinforcement element is a non-environmentally friendly approach (Gaw et al., 2011). For all these reasons, the need for an alternative environmentally friendly, sustainable and economical stabilization technique is increasing for geotechnical engineering applications. Recently, natural and synthetic fibers have attracted the attention of researchers as an alternative method of mechanical stabilization due to their sufficient strength, low cost and easily availability. Since the reinforcement of soils with natural and synthetic fibers is a relatively new technique, soil-fiber composites should be investigated in the laboratory or field to understand the mechanism of the soil-fiber composite and to observe the effects of parameters such as fiber amount, fiber aspect ratio, fiber surface roughness, the specific surface area of the fiber and fiber distribution on the engineering properties of the soil.

1.1. Brief history of the fiber reinforcement mechanism

The use of fibers as reinforcement was mainly achieved by observing the behavior of plant roots consisting of fibers randomly embedded in the soil matrix. This observation has led to the use of natural fibers in soil reinforcement. The first examples of fiber reinforcement technique, which is one of the most popular research topics today, date back to 5000 years. The use of branches of trees as tensile elements in the Great Wall of China and the use of woven mats in the ziggurats of Babylon, the addition of barley straw or horse hair into mudbrick in the Ancient Egyptian period, the use of barley straw carpets as a reinforcement element in ancient Chinese and Japanese shelter constructions are examples representing the applications with fibers in ancient constructions (Hejazi et al., 2012; Ramkrishnan et al., 2018; Salehan and Yaacob, 2011; Mansour et al., 2007). When modern history is examined, the soil reinforcement technique and principles used today were first put forward by Vidal in 1969 (Vidal, 1969; Akbulut et al., 2007). Vidal has shown that the shear strength of the medium can be increased by adding reinforcement elements into soil and as a result, almost tens of thousands of structures have been built with the soil reinforcement technique all over the world since 1969 (Hejazi et al., 2012).

1.2. Classification of fibers

Fiber reinforced soils can be divided into two classes, depending on the method of application: i) Oriented distributed fiber reinforced soil (ODFRS) and ii) Randomly distributed fiber reinforced soil (RDFRS) (Figure 1). The mechanism of ODFRS is similar to conventional geosynthetic applications in which materials were introduced to weaker planes of the soil as geogrids, geocells, geomats, geotextiles and so forth. Additional frictional resistance is provided along the reinforced planes with the oriented distributed fiber reinforcement, whereas the relatively weaker unreinforced regions have to resist failure by their strength. For this reason, the probability of failure planes occurring is relatively higher in unreinforced regions (Gowthaman et al., 2018). In soils reinforced with randomly distributed discrete fibers, isotropic strength increase is provided without potential planes of weakness that can develop parallel to oriented reinforcement (Anagnostopoulos et al., 2013; Estabragh et al., 2011; Gray and Maher, 1989; Maher, 1990; Yetimoglu and Salbas, 2003; Tang et al., 2010; Ates, 2016; Ghazavi and Roustaie, 2010; Hejazi et al., 2012). In addition, in the RDFRS method, fiber-soil composite can be obtained by easily mixing fibers into the soil as in other additives such as cement, lime, calcium sulphate, fly ash, silica fume, etc. (Ahmad et al., 2010).

In practice, fibers are generally divided into two parts as natural and synthetic fibers. Figure 2 shows the fiber types studied in the literature.

2. Fiber Studies Available in the Literature

To increase the bearing capacity and reduce settlements on weak, soft or organic soils with low bearing capacity or high compressibility, to prevent serious damage to structures such as one or two-storey light-weight structures, pavements, channel beds, retaining structures that were built on clays with high swelling pressure and in order to increase the durability of soils under freeze-thaw cycles, the technique of soil reinforcement is widely preferred by geotechnical engineers In the technique of soil reinforcement with fiber addition, which is one of the most popular research topics today, the engineering properties of fiber-soil composites are generally based on the aspect ratio or length, quantity, structure, orientation, rigidity, surface roughness of fibers (Ranjan et al., 1996; Chauhan et al., 2008; Gowthaman et al., 2018). Compared to conventional geosynthetic materials, the RDFRS method provides many advantages. Some of these advantages are that fibers can be simply added to the soil and mixed easily, that strength isotropy can be achieved without creating potential weakness planes with randomly distributed fibers, that only the physical properties of the soil are changed with the addition of fibers and that they are environmentally friendly material (Soundara ve Kumar, 2015). There are generally studies on RDFRS in the literature due to these advantages. (Gao et al., 2015). Therefore, only literature research on RDFRS will be given in this paper. Basically, the use of randomly distributed discrete fibers mimics the behavior of plant roots and the fibers contribute to the stability of the soil mass by increasing the strength of soils near the surface where effective stress is low (Wu et al., 1988; Greenwood et al., 2004). As a result, fiber length or aspect ratio and fiber amount are the most preferred variable parameters in the literature and some of these studies are given below.

2.1. Natural Fibers

Recently, natural fiber technology, which is referred to as "Eco-composite" in the modern industry due to its high strength, low cost, lightweight, high stiffness, sustainability and environmental friendliness, has become a popular research subject in geotechnical engineering (Hejazi et al., 2012; Hanafi and Few, 1998; Marandi et al., 2008). Natural fibers consist of animal, vegetable and mineral fibers. In this study, only the literature studies about plant fibers will be shared. In general, many factors such as test method, sample length, soil conditions, climate, time of harvesting, what part of the plant the fiber came from, fiber separation process, the hygroscopic structure of the fiber and storage conditions affect the mechanical behavior of plant fibers. (Ghavami et al., 1999; Rowell et al., 2000). For this reason, these points should be considered in the selection of plant fibers to be used for reinforcement.

2.1.1. Palm fiber

Marandi et al. (2008) found that the maximum and residual strengths of the silty sand soil increased but the difference between residual and maximum strengths is decreased with the increase of palm fiber length from 20 mm to 40 mm and the fiber amount from 0,25% to 2,5%. Moreover, they reported that the stiffness of the soil decreased and ductility increased with the increase in fiber content and length.

Jamellodin et al. (2010) stated that with the addition of palm fiber at the content of 0,25-1%, a significant improvement was obtained in the deviator stress value and shear strength parameters of soft soil at failure. They also observed that using more than 0,75% palm fiber reduces the shear strength.

Ahmad et al. (2010) stated that the shear strength parameters with introducing palm fiber in the amount of 0,25% and 0,50% and the length of 15-45 mm into the silty soil, improved significantly and the soil performed a more ductile behavior with the increase in fiber content. They stated that with the increase of fiber length up to 30 mm, the shear strength increased non-linearly, the use of longer and higher fiber content reduced the interlocking of the soil particles and fiber-soil particles do not act as a single coherent mass.

Bateni et al. (2011) stated that with the increase of fiber length up to 30 mm in silty sand samples prepared by using 15-35 mm palm oil empty fruit fibers at the content of 0,25-0,50% the deviator stress value at failure increased. They observed that maximum improvement was achieved by using fiber with 30 mm length at the content of 0,5%. They also concluded that with the increase in fiber content, the failure load significantly increased, especially at high confining pressures.

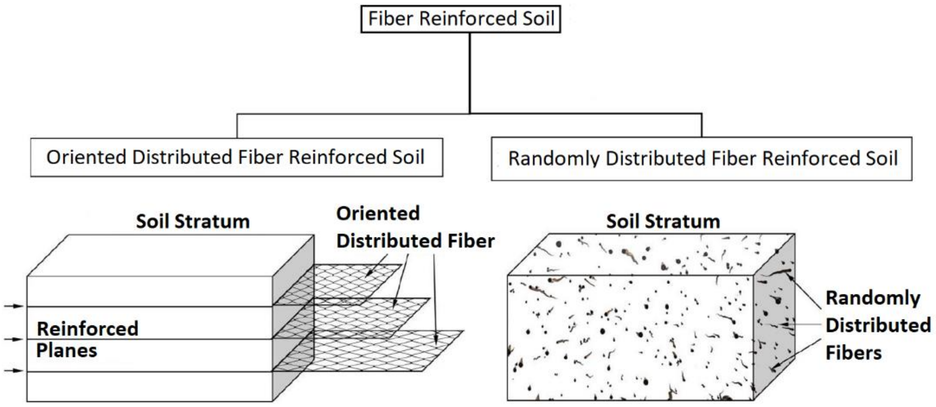

Figure 1. Classification of the fiber reinforcement mechanism in soil (Gowthaman et al., 2018)

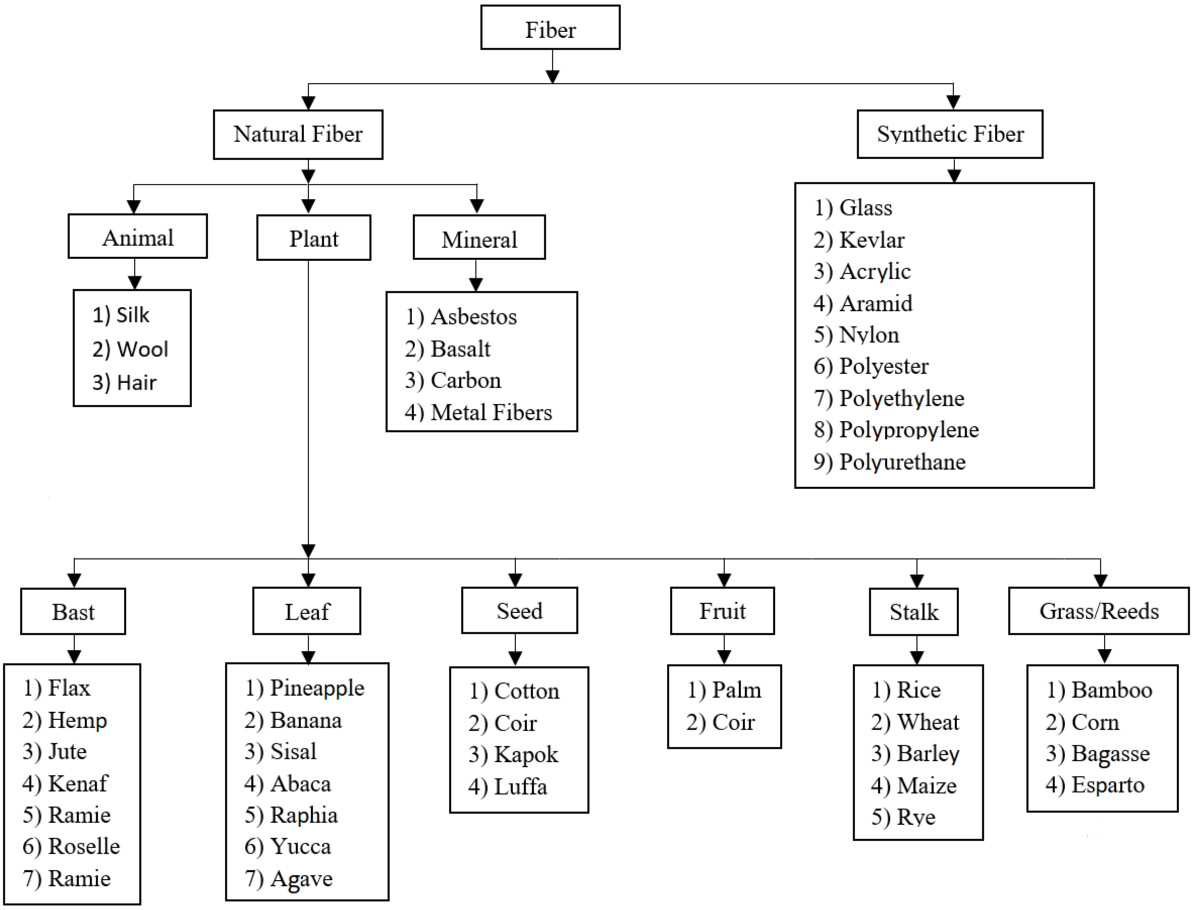

Figure 2. Classification of natural and synthetic fibers (Sathishkumar et al., 2014; Aral, 2006)

2.1.2. Coir fiber

Currently, there are coconut geotextiles with a wide variety of properties that can be economically used for temporary reinforcement purposes (Subaida et al., 2009). Since some coconut fibers have a higher coefficient of friction, they show a better resilient response relatively to synthetic fibers. For example, Chauhan et al. (2008) showed that coconut fibers (47,5%) gave greater enhancements than synthetic fibers (40%) in the resilient modulus or strength of the soil. In addition, Ayyar et al. (1989) and Viswanadham (1989) reported the efficacy of randomly distributed coir fibers in reducing the swelling potential of soil.

Ravishankar and Raghavan (2004) suggested that the maximum dry unit weight (MDW) of the soil decreased and the optimum water content (OWC) value increased with the increase of the fiber content in coir fibers reinforced lateritic soils. They also suggested that the optimum fiber content in the compressive strength of the soil was 1%.

Chauhan et al. (2008) investigated the effects of fly ash, coconut fiber and polypropylene (PP) fiber on the mechanical properties of a subgrade layer consisting of silty sand soil. First, they added 10%, 20%, 30% and 40% fly ash into the silty sand soil and determined the OWC and MDW values for each of the mixtures prepared in different proportions. In addition, they carried out an unconfined compression test on the samples prepared. They found that the content of fly ash which gives the greatest unconfined compression strength (UCS) was 30%. Later, they added 0,5-2% of coconut fiber and PP fibers by dry weight of soil to the mixture of 70% silty sand and 30% fly ash. They observed that the optimum content for coconut fiber was 0,75%, while this value was 1% for PP fiber. Then they carried out static and cyclic triaxial compression tests on samples prepared with optimum contents (0,75% coconut fiber, 1% PP fiber, 30% fly ash). As a result, they reported that the axial stress of unreinforced soil at failure under the confining pressure of 25 kPa was 720 kPa, 990 kPa when reinforced with PP fiber and 1180 kPa when reinforced with coconut fiber. Based on this, they stated that by using synthetic and natural fibers at optimum contents in a subgrade layer with silty sand under static loading, the stress-strain response was improved by 37,5% and 63,88%, respectively, compared to the pure soil. Furthermore, they stated that under cell pressure of 25 kPa and deviator stress of 169 kPa, when 100 cycles of load are applied, permanent axial strain of unreinforced soil, PP fiber reinforced soil and coir fiber reinforced soil are 3,5%, 2,4% and 2,15% respectively. Finally, they observed that in the event of cell pressure of 25 kPa, deviator stress of 169 kPa and a strain of 0,41%, the resilient modulus value for unreinforced soil after 100 cycles of load is 41219 kPa. resilient modulus of PP and coir reinforced soil are 54516 kPa and 58275 kPa respectively. Based on these results, they argue that coir fiber gave better results than PP fiber.

2.1.3. Sisal fiber

Prabakar and Siridihar (2002) stated that the dry density of the soil decreased with the increase of both the length and the content in the mixture prepared with the addition of sisal fiber in the length of 10-25 mm at the content of 0,25-1%. They also observed that the shear strength increased non-linearly with the increase in fiber length up to 20 mm, and decreased with the use of longer fibers. They argued that the highest shear strength value was obtained by using 0,75% amount of sisal fiber in 10 mm length.

2.1.4. Jute fiber

Aggarwal and Sharma (2010) added jute fibers with 0,5-2 cm length at the content of 0,2-1% into the soil, and as a result they found that with the addition of jute fiber the MDW value decreased and the OWC value increased. On the other hand, they observed that the maximum California Bearing Ratio (CBR) value of the soil reinforced with 0,8% jute fiber in a length of 10 mm increased 2,5 times compared to the unreinforced soil.

Bairagi et al. (2014) conducted tests to investigate the effects of jute fibers on the engineering properties of a local lime reinforced clay soil. They stated that the shrinkage limit of the soil increased from 13,75% to 28,68% with the increase in the jute fiber percentage in the samples stabilized with 5% lime. They also reported that the OWC value increased from 16,2% to 19,6%, and the MDW value decreased from 1,68 gr/cm^3 to 1,58 gr/cm^3. On the other hand, they observed that with the increase in fiber content, the CBR value increased from 3,1% to 4,95% and the UCS increased from 1,09 kg/cm^2 to 1,35 kg/cm^2.

2.1.5. Barley straw fiber

Bouhicha et al. (2005) carried out shrinkage and compressive strength tests on clayey silt, clayey sand and silty sand soil samples prepared with barley straw fiber with the lengths of 10-20 mm, 20-40mm and 40-60 mm at the content of 1-3,5%. Therefore, they concluded that the linear and volumetric shrinkage limit values of each soil decreased with the increase of both fiber content and fiber length. In addition, they stated that the highest compressive strengths were obtained that fiber length is 20-40 mm and fiber percentage is 1,5% in clayey silt and clayey sand soils and that fiber length is 20-40 mm and fiber content is 1% in silty sand soil.

2.1.6. Bamboo fiber

Kanayama and Kawamura (2019), in the samples prepared by adding 1-5% bamboo fiber into soil, observed that the liquid limit and plastic limit values tended to increase with the increasing fiber content whereas the plasticity index did not change. On the other hand, based on the compaction test results, they concluded that with the increase in fiber content, the MDW value decreased and the OWC value increased. According to this result, the researchers stated that the unit weight of the mixtures prepared with bamboo fiber at optimum density would be relatively lower than the unreinforced soil, and this material would be very lightweight as a building material. According to the results of the unconfined compression test (UCT), they stated that the UCS increases with the increase in the fiber content and that the maxsimum improvement occurs at 5% content.

2.1.7. Hemp fiber

Najjar et al. (2014) found that the ductile behavior of the clay increased with the increase in the fiber percentage in samples prepared by adding the hemp fibers in length of 25 mm at the content of 0,15-1% into a low plasticity clay soil. They reported that a more significant improvement in this behavior at fiber contents greater than 0,4%. In addition, they stated that as the fiber content increased, the undrained shear strength of the soil increased, and the highest strength increase were obtained especially in fiber content between 0,3% and 0,5%. They also observed that with the addition of more than 0,4% fiber, the values of Young's Modulus corresponding to 1% axial strain increased.

2.1.8. Cotton straw fiber

Liu et al. (2020), in order to investigate the effects of freeze-thaw cycles on the strength of 0,2% and 0,4% cotton straw fiber reinforced clay soil they placed specimens for 12 hours in a freezing container at -20°C, then removed and placed in thawing container at 20°C for 12 hours. As a result, they reported that the cotton straw fiber not only increased the UCS of the soil, but also reduced the softening degree of the soil exposed to freeze-thaw cycles in the absence of confining pressure conditions. Based on the electron microscope images, they stated that after the freeze-thaw cycles, the soil surrounding a fiber is less tight and this is evidence of the strength reduction at the soil-fiber interface.

2.1.9. Cornsilk fiber

Tran et al. (2018) investigated the mechanical properties of cornsilk fiber reinforced low plasticity silt soil. In their research, they used fibers of 10-50 mm length and 0,5-2% amount. They observed that with the increase of fiber content up to 1,5%, the value of MDW increased, the value of OWC decreased, while the value of MDW decreased and the value of OWC increased with increases after 1,5%. They also stated that the increase in fiber length caused a decrease in MDW value and an increase in OWC value. On the other hand, they reported that the fiber content that caused the highest increase in UCS was 1%, and the most effective fiber lengths were 10 and 30 mm.

2.1.10. Papyrus fiber

Al-Adili et al. (2012) investigated the effects of adding 5-25% papyrus fiber on the mechanical properties of sandy clayey silt soil. Based on the results of the direct shear test, the researchers stated that with 10% fiber addition, the greatest values of internal friction angle, cohesion and modulus of elasticity were obtained. In addition, they reported that the stiffness of the soil was significantly increased with the addition of fiber, and consequently the immediate settlement of the soil was reduced.

2.1.11. Kenaf fiber

Ghadakpour et al. (2020) conducted tests on composite samples prepared by adding 3% and 6% cement, 8-16 mm kenaf fiber at the content of 0,25-0,75% to a sandy soil. Besides, they investigated the effects on the engineering behavior of the sand soil of the hybrid fiber mixture, which they formed by mixing fibers with 8 and 16 mm lengths. They used the brittleness index (IB) to measure the ductility behavior of the samples (Equation 1).

$$I_B = \frac{q_{max}}{q_{res}} \tag{1}$$

Here q_{max} and q_{res} represent peak and residual stress values obtained from the stress-strain curve, respectively. As a result, they stated that as the fiber content and length increased, the UCS, splitting tensile strength, energy absorption capacity and residual shear strength of the cemented soil increased, while the elasticity modulus, brittleness index and ultrasonic wave velocity decreased. On the other hand, they observed that the UCS, splitting tensile strength and energy absorption capacity increased, whereas the brittleness index decreased in the hybrid fiber reinforced samples compared to the 8 mm long fiber reinforced samples.

2.1.12. Hemp fiber

Ozdemir (2019) investigated the effects of hemp fiber, straw fiber, polyester fibre and fly ash on the engineering behavior of a high plasticity clay soil. The researcher added straw, hemp and polyester fiber with 2 and 5 mm lengths at the content of 0,5-1,5% to the clay soil. In addition, he added 10% fly ash to specimens with 1% fiber content. On the other hand, he investigated the durability of fiber-soil composites under freeze-thaw cycles. As a result, he concluded that the value of the liquid limit increases with the increase in the percentage of hemp or polyester fiber in samples with or without fly ash. He was observed that the highest liquid limit value occurred in 2 mm hemp at 1,5% fiber content. He also stated that unreinforced soil classified as CH according to the unified soil classification system exhibits the behavior of MH class soil as a result of the change in consistency limits with the addition of fiber. Besides, he claimed that with the increase in fiber content, the UCS of the soil generally increased, and the strength increased more with the addition of 2 mm length fibers compared to 5 mm length in straw and polyester fiber reinforced samples. He stated that the maximum UCS in hemp fiber was obtained by adding of 5 mm long hemp fiber at 1,5% content. He also stated that the maximum UCS after freeze-thaw cycles was obtained by using 2 mm hemp fiber at the content of 1,5%.

2.1.13. The effect of water on natural fiber-soil composite

Natural fibers are exposed to wetting and drying cycles in the soil and show swelling and shrinkage behavior (Hejazi et al., 2012; Bordoloi et al., 2017; Gowthaman et al., 2018). The changes in width and length of the fibers due to temperature and humidity affect the adhesion and friction properties occurring at the fiber-soil interface. During the mixing of the fibers with the soil, the fibers swell by absorbing the water in the soil and the swelling of the fibres pushes away the soil at least at the micro-level. Then at the end of the drying process, the fibers lose the moisture and shrink back almost to their original dimensions leaving very fine voids around themselves (Figure 3). For this reason, it is necessary to determine the water absorption rate and dimensional changes of the fibers (Ghavami et al., 1999; Marandi et al., 2008). For this purpose, many researchers have examined the water absorption rate of the fibers by immersing them in water for a certain period time (48 hours-(Marandi et al., 2008), 18 days-(Ghavami et al., 1999)). In addition, they measured the width and length changes of the fibers immersed in water at certain time intervals.

The water absorption capacity (w) of naturally dried fibers can be determined from Equation 2 (Ghavami et al., 1999):

$$w = \frac{P_h - P_d}{P_d} \qquad (2)$$

Here P_h is the weight of the soaked fibers in drinking water at the end of the relevant period, and P_d is the weight of the air-dried fiber.

2.1.14. Measures to be taken against the degradation of the natural fibers

Natural fibres degrade faster than synthetic fibres in natural environments, minimizing environmental pollution. However, as a result of this degradation, natural fibers cannot be used as long-term reinforcement material, and this situation is a disadvantage of natural fibers (Bateni et al., 2011; Jishnu et al., 2020).

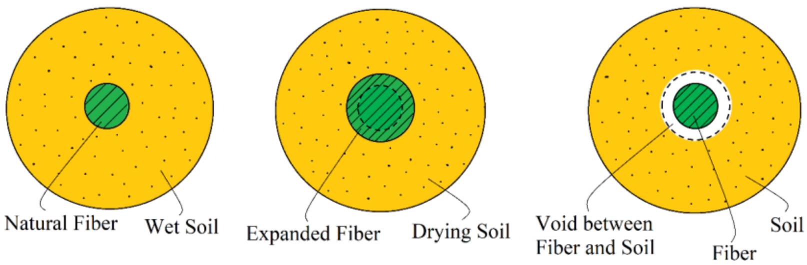

Figure 3. Effect of fiber deformation caused by moisture changes (Ghavami et al., 1999; Gowthaman et al. 2018; Segetin et al., 2007)

The fibers must be covered with a water-repellant materail to prevent degradation of natural fibers and to ensure that they can be used for long-term reinforcement purposes. Bateni et al. (2011) stated that the presence of water in the fiber increases the biodegradation potential of the fiber material. The studies carried out to protect natural fibers against biological degradation, reduce their water absorption capacity and increase the fiber-soil interface friction forces are given in Table 1. As a result of the increase in the surface area of the fiber due to the water-repellant material surrounding the fiber in natural fibers treated coating materials, the interface friction between the soil and the fibers increases and thus the strength of the fiber-soil composite increases (Ahmad et al., 2010; Bateni et al., 2011).

2.2. Synthetic fiber

Synthetic fibers are widely used as reinforcement materials due to their corrosion resistance, non-toxicity, high tensile strength and stiffness (Taha et al., 2020; Soganci, 2015).

2.2.1. Glass fiber

Ahmad et al. (2012) proved that the use of glass fibers as a long-term reinforcement technique, especially in the reinforcement of soft soils is an advantage due to their easily availability, lightweight, high strength and non-biodegradable structure.

Table 1. Recommended treatments for natural fibers

Fiber Material	Recommended Treatment	Reference
Palm Fiber	Acrylic Butadiene Styrene Coating with thermoplastic material	Ahmad et al. (2010) Bateni et al. (2011)
Flax Fiber	Coating with enamel paint	Segetin et al. (2007)
Coir and Sisal Fiber	Coating with liquid bitumen	Ghavami et al. (1999)
Jute Fiber	Coating bitumen	Aggarwal and Sharma (2010)
Sisal Fiber	Coating gum rosin	Kafodya and Okanta (2018)
Bamboo Fiber	Coating with bitumen or water-based paint	Javadian et al. (2016) Chacko and Joseph (2016)

Baruah (2015) stated that the UCS of the samples obtained by adding glass fiber material of 10 mm length at 0,5-1,5% content into the red soil increased with the increase of fiber content. He also reported that glass fiber reinforced red clay soil can be used in subgrade layer for road construction and slope stability because fiber increases the strength of the soil and decreases the plasticity index.

Saha and Bhowmik (2018) investigated the effects of 0,5-1,5% glass fiber addition and water content on the shear strength properties of the sand-clay mixture. They prepared the soil samples by mixing clay and sand in dry conditions. They subjected the prepared samples to unconsolidated-undrained (UU) triaxial compression test under confining pressures of 50, 100 and 150 kPa. Therefore, they reported that the maximum value of the shear strength was obtained at a water content smaller than the OWC value in both reinforced and unreinforced soils. In addition, they stated that 1% fiber content was the optimum value in terms of the shear strength enhancement of the soil. They argued that the compaction behavior of the soil is affected due to the formation of lumps during mixing at fiber contents greater than %1 and this situation may reduce the strength.

Asadollahi and Dabiri (2017) conducted an experimental program on the shear strength and permeability of glass fiber reinforced clay soil. They used glass fiber material with the length of 10 mm and at the content of 0,2-1% by dry weight of soil in their research. They stated that 0,8% fiber content is the optimum content in terms of strength. They also observed that the behavior of fiber-reinforced soils changed from brittle to ductile. In addition, the researchers reported that permeability which is an important parameter in drainage performance in subgrade and pavement design increases with the increase of fiber content.

2.2.2. Polypropylen (PP) fiber

PP fibers are one of the most preferred synthetic fiber materials due to their non-toxicity, corrosion resistance, high acid and alkali resistance, low cost, hydrophobic and chemically inert material and high tensile strength (Taha et al., 2020; Puppala and Musenda, 2001; Maher and Ho, 1994; Al-Wahab and El-Kedrah, 1995; Nataraj and McManis, 1997).

Yetimoglu and Salbas (2003) investigated the shear strength of PP fiber reinforced sands at the fiber content of 0,1-1% and a relative density of 70% by direct shear test. As a result, they concluded that the peak shear strength angle value in reinforced soil was similar to that of unreinforced soil. They observed that the fiber reinforcement had no noticeable effect on the initial stiffness of the sand and partially changed the brittle behavior of the sand to a more ductile one. They also stated that the residual shear strength angle of sand increases with the addition of fiber.

Chen and Loehr (2008) conducted consolidated-drained (CD) and consolidated-undrained (CU) triaxial compression tests carried out on medium-dense (D_r=55%) and loose (D_r=10%) composite samples prepared by adding 0,4% PP fiber to Ottawa sand. They observed that with the addition of fiber, the effective cohesion value of the soil increased from 0 to 87 kPa from CU tests, and from 0 to 21 kPa from CD tests compared to unreinforced soils. They also observed that the internal friction angle value increased by 42% from CU tests and by 52% CD tests.

Mousa and Tamimi (2010) conducted shear box tests to investigate the effects of adding two types of PP fiber (type A and type B) with different aspect ratios at 1-4% content on the shear strength parameters of sandy soil. Type A has a flat profile and high flexibility, B type fiber has high relative stiffness and crimped profile. As a result, they stated that with the increase of both fiber content, the internal friction angle value and ductility of the sand increased. They explained that with the increase in the aspect ratio, both the shear strength and the internal friction angle increased. They emphasized that with the increase of A type fiber content, the shear strength of sand always increased, whereas with the increase of B type fiber content it increased only under high normal stress.

Falorca and Pinto (2011) observed that the initial stiffness decreased with the increase of fiber content in PP fiber reinforced sand soil, whereas there was no significant change in the PP fiber reinforced clay soil. They stated that the increase in shear strength was more significant at lower normal stress levels in the shear box test in both reinforced soils. They also suggested that the amount of fiber in the shear plane is a very important parameter.

Taha et al. (2020) investigated the effect of adding PP fiber with 12 mm length and at the content of 0,75-3% on the mechanical behavior of the CH soil. As a result of the tests, they stated that as the fiber content increased, the plasticity index decreased, and the decrease in the plasticity index increased the stability and workability of the soil. Based on the results of the triaxial compression test, they reported that with the increase of fiber content, the internal friction angle value increased and the cohesion value decreased. They also reported that the maximum internal friction angle and minimum cohesion values were obtained at 3% fiber content. From the consolidation test results, they concluded that the void ratio, coefficient of consolidation and hydraulic conductivity of the soil decreased as the fiber content increased.

Malekzadeh and Bilsel (2012) conducted experimental studies evaluating the effect of PP fiber addition on the mechanical behavior of expansive soils. They stated that due to the decrease in the average weight of the solid part in the fiber-soil mixture, the MDW value of the fiber-soil composite decreased with increasing fiber content, whereas the OWC value was not affected by the fiber content. They also stated that the swelling potential of the soil was significantly reduced with the addition of 1% fiber. On the other hand, they observed that the UCS increased with the increase in the fiber content, and the cohesion value in 1% fiber reinforced soil increased by 1,5 times compared to the pure soil and reached its maximum value.

Soganci (2015) thought that as an alternative to excavating an expansive soil and filling granular material instead, stabilizing the expansive soil with PP fiber could reduce the cost and the swelling percentage. Based on this idea, the researcher prepared samples by adding 0,5-1% of PP fiber material into the expansive soil and carried out swelling tests. As a result, he stated that with the addition of 1% fiber, the one-dimensional swelling percentage of the soil decreased from 11,6% to 5,3%.

Ghazavi and Roustaie (2010) investigated the effects of freeze-thaw cycles on the UCS of 1-3%.PP fiber reinforced kaolinite clay. Finally, they observed that before and after freeze-thaw cycles the UCS of the sample prepared at 3% PP fiber content relative to the unreinforced soil increased by 160% and 60%, respectively.

Claria and Vettorelo (2016) investigated the effects of flat and crimped PP fiber addition on the behavior of loose fine to medium alluvial sand. As a result, they stated that the shear strength and ductility at large strain levels of the fiber-reinforced sand soil increased. They stated that the maximum internal friction angle value of the soil occurs at 2% fiber content. They also observed that the increases in the shear strength of the crimped fiber reinforced soil were slightly higher than that of the flat fiber reinforced soil. On the other hand, they reported that as the fiber length increased, the shear strength of the soil increased. Besides, they concluded that with the increase of fiber content, the elasticity modulus defined at large ($\varepsilon=10^{-2}$), medium ($\varepsilon=10^{-3}$) and small ($\varepsilon=10^{-5}$) strain levels decreased. They argued that this behavior may be the result of a reduction in friction due to loss of contact between particles resulting from increased fiber content.

Murray et al. (2000) conducted compaction and triaxial compression tests to evaluate the compaction characteristics and stress-strain behaviour of recycled carpet and PP fibers reinforced sandy silt soil. As a result, they reported that with the addition of carpet fibers and PP fibers, the MDW value of the sandy silt soil decreased, whereas the OWC value decreased with the addition of carpet fiber, and that the OWC value did not change with the addition of PP fiber. They also stated that with both fiber addition, peak shear strength and ductility increased, post-peak strength loss decreased. They stated that an optimum fiber content was not observed in samples reinforced with carpet fiber, whereas the optimum content was 1% in those reinforced with PP fiber.

Zaimoglu (2010) conducted tests to investigate the effects of PP fiber addition with 12 mm length and at 0,25-2% content on the engineering properties of high plasticity silt soil exposed to freeze-thaw cycles. As a result, the researcher was reported that UCS of the soil exposed to the freeze-thaw cycle increased with the increase of fiber content and the reinforced soil showed a more ductile behavior compared to the unreinforced soil. He also stated that the initial slopes of the stress-strain curves were not significantly affected by fiber reinforcement.

Kucukkcongar (2015) conducted model tests investigating the bearing capacity and optimum reinforcement depth of a strip foundation resting on a crimped PP fiber reinforced medium-dense sand soil. In his research, the researcher used fiber with 20 mm length at 1% content by dry weight of soil. The researcher investigated the change in bearing capacity and settlement values of the foundation by using fiber reinforcement at depths B, 2B, 2,5B and 3B from the ground surface. Here, B is the width of the foundation. As a result, the researcher observed that with the reinforcement depth increases up to 2B depth, the bearing capacity increases and settlements decrease.

2.2.3. Polyvinyl alcohol fiber (PVA)

Kutanaei and Choobbasti (2016) conducted laboratory tests evaluating the effects of adding PVA fiber with the length of 12 mm at the content of 0,3-1% on the UCS of cemented sand soil. Therefore, they stated that with the increase of fiber content, the UCS of cemented soil increased and this increase was higher in low cement content.

Park (2011) conducted a series of tests to investigate the effects of 0,3-1% PVA fiber content on the UCS of sand stabilized with 2-6% cement. As a result, researcher stated that fiber reinforced sand with 2% cement ratio has 3,5 times strength more than cemented sand without fiber addition. On the other hand, the researcher used the equation of deformability index (D) to evaluate the ductility behavior of the soil (Equation 3).

$$D = \frac{\Delta_f}{\Delta_{nf}} \tag{3}$$

Here Δ_f represents the axial strain at peak strength in fiber reinforced cemented sand and Δ_{nf} represents the axial strain at peak strength in unreinforced cemented sand. Accordingly, the researcher has concluded that the deformability index increases with the increase in fiber content, and the deformability index is not affected by the cement ratio in fiber content less than 1%.

Park (2009) conducted a series of UCT to evaluate the effects of fiber addition and distribution on the strength of PVA reinforced cemented sand soil. The researcher used a very different sample preparation method than the one used in the literature. They mixed 4% cement by dry weight of soil with sand at an OWC value of 14%. Then the researcher compacted the samples in to 5 layers in the mold. At this stage, the researcher prepared samples by adding fiber only to the middle layer (case I), adding fibers only to the top, bottom and middle layers (case II) and adding fibers to five layers (case III). The researcher named the samples with 0,2% fiber content in these mixtures as L series. In addition, the strength of T series samples prepared using 1% fiber content for the I case, 0,33% for the II case and 0,2% for the III case were investigated. While determining the fiber content in the T series, the researcher paid attention to the total fiber content in 5 layers to be equal to 1% by dry weight of sand. As a result, the researcher was observed that with the increase in the number of fiber reinforced layers in the L series, the strength increased 120% for the I. case, 158% for the II. case and 195% for the III. case. In the T series, he stated that the strength of the sample in III. case increased 1,5 times compared to the I. case. On the other hand, the researcher suggested that the change in the number of fiber reinforced layers or the fiber content did not affect the secant modulus of elasticity of the soil.

2.2.4. Nylon fiber

Akhras et al. (2008) investigated the effects of natural and synthetic fiber addition in 25-100% aspect ratio at the content of 1-5% on the swelling properties of clay soils. For this purpose, they mixed with nylon and palmyra fibers with different aspect ratios into three types of clay soils with different physical properties. As a result, they stated that with the increase of fiber content of both types, swelling pressure and swelling potential decreased significantly. They observed that the palmyra fiber has a greater effect on swelling pressure than nylon fiber. Besides, they reported that in both fiber types, lower aspect ratios had a greater effect on reducing swelling pressure.

Estabragh et al. (2012) investigated the effects of adding 5-10% cement and 0,5-1,25% nylon fiber on the UCS of clay soil. As a result, they stated that 1% fiber content was the optimum content in strength enhancement and the initial stiffness of fiber reinforced soil was not affected by fiber content. They explained that the initial stiffness of the cement-fiber-soil mixture was less than that of the cemented-soil and that the stiffness decreased with the increase of cement content in the cement-soil-fiber mixture.

Salim et al. (2018) used recycled nylon fibers obtained from waste nylon bags to stabilize a soft clay soil with low bearing capacity and high compressibility. They used fibers of 6 mm length at the content of 1-5%. As a result, they stated that with the addition of fiber, the liquid limit of the soil decreased and the plastic limit increased slightly. Thus, they stated that the plasticity index of the soil decreased and the workability of the soil increased. They also reported that with the increase in fiber content, the OWC value of the soil increased and the MDW value decreased. On the other hand, they observed that as the fiber content increased, the specific gravity and undrained shear strength of the fiber-clay composite decreased and the increased, respectively. However, they observed that with increasing fiber content, the compression index decreased and an approximately 35% reduction occurred in 5% nylon fiber content.

2.2.5. Polyester fiber

Kumar et al. (2006) investigated the effect of adding plain and crimped polyester fiber at the content of 0,5-2% on the UCS of highly compressible soft clay. They stated that with the inclusion of 2% of 6 mm plain fibers or 1% of 12 mm plain fibers or 1,5% of 6 mm crimped fibers, the UCS of the soil increased approximately 100%.

Information on physical and mechanical properties, quantities, lengths of fiber materials commonly used and tests conducted, mixture preparation method in the literature are given in Table 2.

3. Sample Preparation

In the literature, different procedures have been adopted in the preparation of samples to avoid segregation of fibers, to allow uniform distribution and isotropic orientation of fibers in the soil.

For this purpose, the soil dried the oven or in the air is mixed with the fiber material first and then the required amount of water is added to this mixture (Sogancı, 2015; Liu et al., 2020; Tran et al., 2018; Gao et al., 2015; Motiram et al., 2018). Some researchers prepared mixtures using different methods from this procedure. Sadeghi and Beigi (2014) stated that it is more important to add the water before adding the fibers to the soil in order to prevent the floating of the fibers during the preparation of the mixture. Marandi et al. (2008) first mixed the whole dry soil with half of the amount of water corresponding to the OWC value and half of the fiber, then slowly added the remaining water and fiber to this mixture. Murray et al. (2000) prepared their mixtures by mixing the soil, fiber and water simultaneously. Ghazavi and Roustaie (2010) stated that it is very difficult to compact the mixtures obtained by first mixing the clay soil with water and then adding fiber. In contrast, they suggested that by mixing the dry clay and fibers first and then adding water, most of the water is absorbed by the fibers and non-homogeneous mixtures were obtained. Therefore, they first mixed half of the amount of clay and water to be used and then added half of the clay and water and all the fiber material to this mixture. Researchers argued that this method is the best method for the preparation of fiber reinforced clay soils.

Obtaining a homogeneous mixture depends largely on the mixing method. For this purpose, mixing methods such as manual (with hand), mixer, mechanically stirring, mortar mixer, drum mixer etc. are used. The most preferred mixing method in the literature is the manual mixing method (Yetimoglu and Salbas, 2003; Choo et al., 2017; Falorca and Pinto, 2011; Sujatha et al., 2020; Ates, 2016; Bouhicha et al., 2005; Najjar et al., 2014; Taha et al., 2020; Soltani et al., 2018). The manual mixing method is sufficient especially in small-scale applications such as laboratory tests, and the ability to observe the distribution of fibers during mixing is an advantage of this method. On the other hand, in large-scale works such as field applications, due to the manual mixing method will require a lot of labor, it is more appropriate to choose other mixing methods (Park, 2009; Segetin et al., 2007). In addition, Falorca and Pinto (2011) suggested that manual mixing is difficult and impractical when the fiber content and fiber length are greater than 1% and 100 mm respectively. Besides, they stated that the required mixing time in clays is independent of the fiber structure and that the mixing time is longer when the crimped fiber is used in sands.

Two types of methods are used to determine the amount of fiber in the sample preparation phase: I) Gravimetric and II) Volumetric fiber content. Gravimetric method is generally used in the literature and fiber selection according to this method is made from Equation 4 (Estabragh et al., 2012; Sogancı, 2015; Li, 2005; Park, 2011; Sadeghi and Beigi, 2014). The determination of the volumetric fiber content is made according to Equation 5 (Anagnostopoulos et al., 2013; Li, 2005).

$$P_f = \frac{M_f}{M_d} \tag{4}$$

$$P_v = \frac{V_f}{V} \tag{5}$$

Table 2.Summary of studies with natural and synthetic fibers commonly used to reinforce the soil

	Mechanical and Physical Properties of Fiber									
Fiber Type	**B or D (µm)**	**Specific Gravity (gr/cm^3)**	**E (GPa)**	**T (MPa)**	**Percentage of Fiber (%)**	**Fiber Length (mm)**	**Soil Type**	**Mixture Preparation Method**	**Tests**	**Reference**
PP Glass	32 47	0,90 2,50	3,4 69	550-760 ort.2400	1; 2; 3; 4; 5w 1; 2; 3; 4; 5w	2,5-20 6,4-25,4	Kaolinit clay	Motorizedrotary mixer	UCT, Split tensile	Maher and Ho (1994)
Sisal Coconut	150 270	1,07 1,08	18 3	580 150	4w 4w	50-65	Clay	Mixer	UCT	Ghavami et al. (1999)
PP Carpet	4300 450	0,91 1,12	- -	- -	1; 2; 3w 1; 2; 3w	30,7 17	Silt (ML)	Mixer	Compaction, Triaxial ct	Murray et al. (2000)
PP	-	-	-	-	0,3; 0,6; 0,9w	-	Clay	-	UCT, Shrinkage, Free swelling	Puppala and Musenda (2001)
PET	190	1,06	7	207-230	0,1; 0,22; 0,5; 0,78; 0,9w	12-36	Sand (SP)	Manual	UCT, Split tensile, Triaxial ct	Consoli et al. (2002)
Sisal	215	1,422	-	0,138	0,25; 0,5; 0,75; 1; 1,25w	5-15	CH and CL	-	Triaxial ct, CBR	Prabakar and Siridihar (2002)
PP	50	0,91	3,7	320-400	0,1; 0,25; 0,5; 1w	20	Sand	Manual	Direct shear	Yetimoglu and Salbas (2003)
BS	1000-4000	1,20	-	-	1; 1,5; 2; 2,5; 3; 3,5w	10-60	Four different fine grained soils	Manual	Shrinkage, Compression, Direct shear	Bouhicha et al. (2005)
PP	34	0,91	3,5	350	0,05; 0,15; 0,25w	12	Clay (CL)	-	UCT, Direct shear, Swelling, shrinkage	Cai et al. (2006)
PP	-	0,91	1,5	200	0,25; 0,5w	25-100	Sandy clay (CL)	Manual	Direct shear, Ring shear	Falorca et al. (2006)

Table 2.Summary of studies with natural and synthetic fibers commonly used to reinforce the soil (Continue)

Fiber Type	B or D (µm)	Specific Gravity (gr/cm^3)	E (GPa)	T (MPa)	Percentage of Fiber (%)	Fiber Length (mm)	Soil Type	Mixture Preparation Method	Tests	Reference
PP PE	2500 1000	0,92-0,96 0,90	- 3-4,5	200-400 500-900	0,1; 0,2; 0,3; 0,4; 0,5w 0,1; 0,2; 0,3; 0,4; 0,5w	5-60 5-60	Clay (CH)	-	UCT, Direct shear, Resonant frequency	Akbulut et al. (2007)
Polyester	-	1,34-1,40	-	400-600	0,5; 1; 1,5; 2w	3-12	Fly ash+Clay	-	Compaction, UCT, Splite tensile	Kumar et al. (2007)
Flax	-	-	-	-	0,6; 0,8w	70-85	Silty sand (cemented)	Manual, Concrete mixer, Tumble mixer	Third point loading, Modified cube method	Segetin et al. (2007)
Nylon Palmira	200 400	1,10 0,73	4,1 16,5	790 177	1; 2; 3; 4; 5v 1; 2; 3; 4; 5v	5-20 10-40	CH, CL	-	Free swelling	Akhras et al. (2008)
PP Coir	48 200	0,91 0,85	3 2	150 100	0,5; 0,75; 1; 1,5; 2w 0,5; 0,75; 1; 1,5; 2w	20 80	Silty sand (SM)	-	Triaxial ct, Compaction, UCT	Chauhan et al. (2008)
PP	-	0,91	4,83	310	0,4w	51	Ottawa sand (SP)	-	CD and CU	Chen and Loehr (2008)
Palm	350	0,92	0,6008	63,32	0,25; 0,5; 0,75; 1; 1,5; 2; 2,5w	20-40	Silty sand (SM)	-	Compaction, UCT, KBR	Marandi et al. (2008)
PVA	100	1,30	-	1078	0,2; 0,33; 1w	12	Cemented river sand	Manual	UCT	Park (2009)
Jute	2000-8000	1,12	-	-	0,2; 0,4; 0,6; 0,8; 1w	5-20	Clay (CL)	-	Compaction, CBR	Aggarwal and Sharma (2010)
Palm	400	1,46	-	283	0,25; 0,5w	15-45	Silty sand (SM)	Manual	CU, CD	Ahmad et al. (2010)
PP	-	-	-	-	0,5w	-	Silty clay	Manual	CD and CU	Freilich et al.(2010)
PP	100	0,90	-	-	1; 2; 3w	12	MH	-	UCT	Ghazavi and Roustaie (2010)

Table 2.Summary of studies with natural and synthetic fibers commonly used to reinforce the soil (Continue)

Fiber Type	B or D (µm)	Specific Gravity (gr/cm^3)	E (GPa)	T (MPa)	Percentage of Fiber (%)	Fiber Length (mm)	Soil Type	Mixture Preparation Method	Tests	Reference
Palm	-	-	-	-	0,25; 0,5; 0,75; 1w	-	Soft clay	-	Compaction, UU	Jamellodin et al. (2010)
PP (f) PP (c)	130 480	- -	- -	1004 250	1; 2; 3; 4w 1; 2; 3; 4w	5-20 5-20	Sandy soil	-	Direct shear	Mousa and Tamimi (2010)
PP	23	0,91	3	120	0,5w	24	Sand	-	CD	Santos et al. (2010)
PP	50	0,91	4	320-400	0,25; 0,5; 0,75; 1; 1,25; 1,5; 2w	12	Silt (MH)	-	UCT	Zaimoglu (2010)
Palm	300-500	-	0,55	283	0,25; 0,5w	15-45	Silty sand (SM)	-	CD	Bateni et al. (2011)
PP	32	0,91	1,5	200	0,25; 0,5w	25-100	Sand (SP), Clay (CL)	Manual	Direct shear	Falorca and Pinto (2011)
PVA	100	1,30	2,5	1078	0,3; 0,6; 1w	12	Cemented sand (SP)	Manual	UCT	Park (2011)
Glass	50-100	-	42-55	1300-2100	-	100	Clay (S-CL), SP-SM, Peat soil	-	Direct shear	Ahmad et al. (2012)
Nylon	280	0,91	2,35	400	0,5; 0,75; 1; 1,25w	20	Clay (CL)	Manual	UCT	Estabragh et al. (2012)
PP	60	0,91	-	-	0,5; 0,75; 1w	20	Clay (CH)	Mixer	Compaction, UCT, Split tensile, Free swelling	Malekzadeh and Bilsel (2012)
PP	34	0,91	-	350	0,3; 0,6w	12	Silty clay	-	UCT, Triaxial ct, Direct shear	Ple and Le (2012)
PP	25	0,91	-	-	0,5; 1; 1,5; 2w	12	Clay (CH)	-	UCT, KBR, Permeability, Swelling pressure, Compaction	Sabat (2012)

Table 2.Summary of studies with natural and synthetic fibers commonly used to reinforce the soil (Continue)

Fiber Type	B or D (µm)	Specific Gravity (gr/cm^3)	E (GPa)	T (MPa)	Percentage of Fiber (%)	Fiber Length (mm)	Soil Type	Mixture Preparation Method	Tests	Reference
PP PP	30 25	0,91 0,91	7 4	500 400	0,3; 0,5; 0,7; 0,9; 1,1w 0,3; 0,5; 0,7; 0,9w	12 12	Sandy silt, Silty clay	Manual	Direct shear	Anagnostopoulos et al. (2013)
Jute	-	-	-	-	1; 2; 3; 4; 5w	50	Lime treatet clay	-	Compaction, CBR, Consistency limits, UCT	Bairagi et al. (2014)
PP	23	0,91	7,4	500	0,5; 1w	12	River sand (SC)	Manual	Cyclic triaxial	Sadeghi and Beigi (2014)
PP	48	0,91	3,5	350±20	-	150	Clay	-	Single fiber pull-out	Tang et al. (2014)
Glass	150	2,57	112,3	1530	0,5; 1; 1,5w	10	Red soil	-	UCT, Consistency limits, Compaction	Baruah (2015)
Carbon	-	1,74	243	3535	0,01; 0,02; 0,03; 0,05; 0,1; 0,15; 0,25; 0,35; 0,5w	9	CL	-	UCT	Gao et al. (2015)
Basalt	17	2,65	85,9	2611	0,05; 0,1; 0,15; 0,2; 0,25; 0,3; 0,35w	4-15	Clay	-	UCT	Gao et al. (2015)
Polyester	-	1,38	-	-	0,5; 1; 1,5w	70	Clay sand (SC)	-	Direct shear	Nguyen et al. (2015)
PP	34	0,91	3,5	350	0,5; 0,75; 1w	12	Clay (CH)	Manual	Compaction, UCT, Free swelling	Sogancı (2015)
Glass	2000	2,68	72	1000-1700	1; 2; 3; 4w	4	Sand	Manual	Compaction, UCT, Direct shear	Ates (2016)
PVA	100	-	-	-	0,3; 0,6; 1w	12	Cemented sand	-	UCT	Kutanaei and Choobbasti (2016)
Basalt	14±2	-	-	-	1; 1,5; 2w	6-24	Silt (ML)	-	UU	Ndepete and Sert (2016)
Carbon	10-14	-	27,5-41	≥24	0,2; 0,4; 0,6; 1,2w	3, 6	Clay	Mortar mixer	Compaction, Direct shear	Wang et al. (2016)

Table 2.Summary of studies with natural and synthetic fibers commonly used to reinforce the soil (Continue)

Fiber Type	B or D (µm)	Specific Gravity (gr/cm^3)	E (GPa)	T (MPa)	Percentage of Fiber (%)	Fiber Length (mm)	Soil Type	Mixture Preparation Method	Tests	Reference
Glass	13	-	-	-	0,2; 0,4; 0,6; 0,8; 1w	10	Clay (CL)	-	Compaction, Direct shear, UCT	Asadollahi and Dabiri (2017)
PP	40	0,91	3,9	360	0,5; 1; 2w	6 12	Sand	Manual	Modified oedometer	Choo et al. (2017)
Basalt	0,16	2,65	85,9	2611	0,05; 0,1; 0,15w	10-30	Organic soil (OH)	-	UCT, Compaction	George and Ramya (2017)
Carbon	7	1,80	230	4900	1; 2; 3w	3	Silty soil	Mixer	Direct shear	Cui et al. (2018)
Carbon	-	-	243	3535	0,05; 0,1; 0,15w	15	Clay	-	Resonant column	Gao et al. (2018)
Basalt PP	12-14 12-13	2,60 0,91	75 35	3500 600	0,25; 0,5; 0,75w 0,25; 0,5; 0,75w	12 12	Clay (CL)	-	UU	Kravchenko et al. (2018)
Basalt	-	2,80	90-110	3500-4000	0,4w	9	Clay	-	UCT	Ma et al. (2018)
Basalt	0,16	2,65	85,9	2611	2; 4; 6; 8w	12	Clay (CH)	-	Compaction	Motiram et al. (2018)
Glass	-	-	-	-	0,5; 0,75; 1; 1,5w	-	Clay (CH)+Sand (SP) karışımı	Manual	UU	Saha and Bhowmik (2018)
Nylon	17	0,98	3,4-3,8	>350	1; 3; 5w	6	Clay (CL)	Manual	Consistency limits, Compaction, Vane, Oedometer	Salim et al. (2018)
PP PP	10 30	0,72 0,85	7 5	1250 3000	0,5; 1; 1,5w	15-30	Clay (CH)	Manual	Swelling pressure	Soltani et al. (2018)
COS	300	-	-	8,3	0,5; 1; 1,5; 2w	10-50	Silt (ML)	Manual, Mixer	UCT, Compaction, Split tensile	Tran et al. (2018)
Basalt	13	2,70	90-110	4000-4800	0,3; 0,6; 0,9; 1,2w	9	Clayey soil	Automatic mixer	UCT, Dynamic compression	Cao et al. (2019)

Table 2.Summary of studies with natural and synthetic fibers commonly used to reinforce the soil (Continue)

Fiber Type	B or D (µm)	Specific Gravity (gr/cm^3)	E (GPa)	T (MPa)	Percentage of Fiber (%)	Fiber Length (mm)	Soil Type	Mixture Preparation Method	Tests	Reference
Bamboo	-	-	-	-	1; 3; 5w	-	Fine grained soil	-	Consistency limits, Compaction, UCT	Kanayama and Kawamura (2019)
Kenaf	100	1,30	18	380	0,25; 0,5; 0,75w	8-16	Cemented sand	Electric mixer	UCT, Split tensile, Ultrasonic wv	Ghadakpour et al. (2020)
Coconut	25000	-	-	-	1; 2; 3w	25	River sand	-	UU	Jishnu et al (2020)
CS	102	1,55	5,5	290	0,2; 0,4w	10	Clay	ManuAl	UCT, Single fiber pull-out	Liu et al. (2020)
Glass EWG	19 19	2,70 2,57	72 73,5	1700 3500	0,25; 0,5; 0,75; 1w (for atterbeg limits, compaction and UCT) 0,1; 0,2; 0,3; 0,4; 0,5; 0,6w (fot KBR)	12 12	Clay	Manual	Consistency limits, UCT, KBR	Sujatha et al. (2020)
PP	34	0,91	-	-	0,75; 1,5; 2,25; 3w	12	Clay (CH)	Manual	Compaction, Triaxial ct, Oedometer, CBR	Taha et al. (2020)

B, D= Fiber width or diameter

T= Tensile strength value of fiber

PET: Polyethylene terephthalate

BS= Barley straw

COS= Cornsilk

UCT= Unconfined compression test

E: Elasticity modulus of fiber

v= Fiber content by volume of soil

PP= Polypropylene

CS= Cotton straw fiber

w= Fiber content by dry weight of soil

ct= Compression test

wv= Wave velocity

f=Flat

PVA= Polyvinyl alcohol

c=Crimped

PE= Polyethylene

EWG=E-waste glass

Here, P_f is the gravimetric fiber content, M_f is the weight of fibers, M_d is the dry weight of soil, P_v is the volumetric fiber content, V_f is the volume of fibers and V is the total volume of the soil-fiber composite.

Dry unit weight (γ_d) of fiber-reinforced soil is defined as in Equation 6. By using Equations 4, 5 and 6, relationship between P_f and P_v can be defined as in Equation 7 (Li, 2005):

$$\gamma_d = \frac{M_f + M_d}{V} \tag{6}$$

$$P_v = \frac{P_f \gamma_d}{(1+P_f) G_f \gamma_w} \tag{7}$$

$$G_f = \frac{M_f}{V_f \gamma_w} \tag{8}$$

In the literature, in the laboratory tests where the stress-strain behavior of fiber-reinforced soils are investigated and the swelling pressure and potential are determined, the samples are generally prepared by either static (Sogancı, 2015; Estabragh et al. 2012; Consoli et al., 2002; Murray et al., 2000; Malekzadeh and Bilsel, 2012; Soltani et al., 2018; Cai et al., 2006) or dynamic (Saha and Bhowmik, 2018; Calik, 2017; Ocakbasi, 2019) compaction method in OWC and MDW values. Samples for sand soils are usually prepared with the desired relative densities (Consoli et al., 2002), whereas in clay, silt and clayey soils, samples are usually prepared at OWC and MDW values (Malekzadeh and Bilsel, 2012; Soltani et al., 2018; Estabragh et al. 2012) or 95% relative compaction value (Ghazavi and Roustaie, 2010; Attom and Al-Tamimi, 2010; Mousa and Tamimi, 2010). Falorca and Pinto (2011) stated that a water content at or below OWC value is generally used in the literature for mixing sand and fibers, whereas a high quality mixture can be obtained by using water content around the PL limit for clays.

4. Mechanical Behavior of Fiber-Soil Composite

As the soil samples deform under axial pressure, the fibers in the soil are forced. The modulus of elasticity of natural and synthetic fibers generally takes values ranging from 0,55 to 243 GPa which is higher than the elasticity modulus of the soil. Due to this difference between the elasticity modules, inconsistent deformations occur between the fibers and the soil and therefore the fibers are in tension. When the soil is under load, the internal stress of the fiber changes, resulting in uneven tension stress. As can be seen from Figure 4, the magnitude of the tensile stress to which the fiber is exposed is T_1-T_2. Accordingly, if this tensile stress is less than the tensile strength of the fiber and interface friction and/or adhesion force, the reinforced soil composite can remain stable. The magnitude of the stress to which the fiber material in reinforced soil composite is subjected depends on the magnitude of the friction and adhesion forces occurring in the interface between the fiber and the soil particles (Tang et al., 2007; Gao et al., 2015; Gao et al., 2018).

When the fiber-soil composite is loaded, shear stresses in the soil mobilize the tensile strength of the fibers and thus the strength of the soil increases (Jamshidi et al., 2010; Abtahi et al., 2008; Ma et al., 2018).

Most of the fiber materials used for reinforcement purposes have free bending flexibility, which makes the fibers turn randomly distributed in the soil to form a large number of curved structures. When the fibers are in tension, the concave side of bending fiber in the soil squeezes the soil particles (Figure 5). This situation creates a binding effect on the soil particles and reduces the deformation of the soil (Gao et al., 2018; Gao et al., 2015).

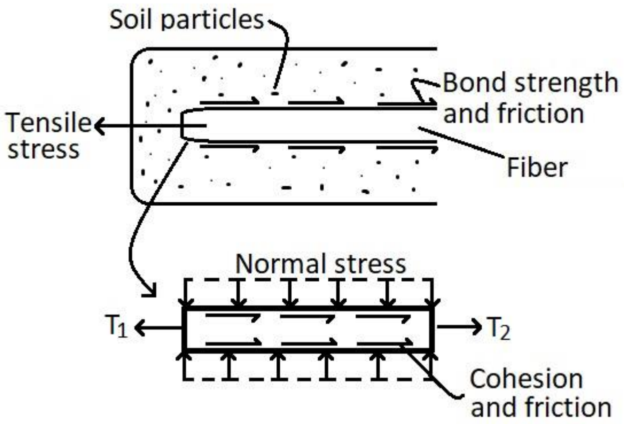

Figure 4. Fiber-soil interface microsection

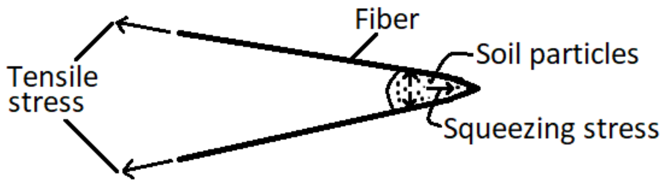

Figure 5. Microsection of the interface of the bending fiber and soil

In a randomly distributed fiber reinforced soil, when the fibers are pulled out (when the orientation of the fiber coincides with the shear plane of the soil), the fibers leave linear grooves. This situation reduces the tensile strength and the reinforcement effect of the fiber material. However, as the overall fiber distribution is uniform in randomly distributed fiber reinforced soils, only a small amount of fiber would be aligned with the shear plane direction and the negative effect of this situation on the reinforcement mechanism is negligible (Gao et al., 2018).

With the use of more than a certain amount of fiber material, a decrease in the strength of the fiber-soil composite occurs because the fibers are not distributed uniformly in the soil. In addition, at high fiber content, the fibers form clusters rather than uniformly distributed, resulting in a decrease in the strength of the fiber-soil composite (Cui et al., 2018).

5. Discussion

Based on the results of the one-dimensional free swelling test (Malekzadeh and Bilsel, 2012; Akhras et al., 2008; Soganci, 2015; Soltani et al., 2018) carried out in the literature on soils classified as CH according to the unified soil classification system, it was observed that the swelling potential decreased by approximately 54-58% with the addition of PP fiber and 79% with the addition of nylon fiber and 82% with the addition of palmyra fiber. Moreover, the undrained shear strength of CH soils reinforced with PP fiber with the length of 12-20 mm at the content of 1% by weight increased approximately by 35-40%.

As a consequence of the examination of the effects of fiber addition on the stress-strain behavior of soils classified as CL according to the unified soil classification system (Asadollahi and Dabiri, 2017; Salim et al., 2018; Prabakar and Siridihar, 2002; Al-Adili, 2012; Najjar et al., 2014; Ple and Le, 2012), it was observed that the UCS, cohesion and internal friction angle values of the soil with the addition of glass fiber with 10 mm length and the content of 0,8% by weight are increased approximately 33%, 33% and 24%, respectively. Moreover, with the addition of 6 mm length of 5% nylon fiber by volume, the undrained shear strength of the soil increased approximately 120%, and with the addition of 20 mm length of 0,75% sisal fiber by weight the undrained cohesion and internal friction angle values increased approximately 267% and 11%, respectively. With the addition of papyrus leaf fibers with the length of 0,5-1,5 mm at the content of 10% by volume, the effective cohesion and effective internal friction angle and elasticity modulus of the soil improved by approximately 1700%, 12,5% and 47%, respectively. On the other hand, with the addition of 1% hemp fiber with the length of 25 mm, the undrained shear strength of the soil and the undrained Young's Modulus corresponding to 1% axial strain increased by approximately 118% and 147%, respectively. With the use of 12 mm PP fiber at the content of 0,6% by weight, the undrained cohesion decreased by 26%, and the undrained internal friction angle and Young Modulus values increased by 68% and 49%, respectively.

As a result of the examination of effects of fiber addition on the stress-strain behavior of soils classified as SP according to the unified soil classification system (Jishnu et al., 2020; Chen and Loehr, 2008; Yetimoglu and Salbas, 2003; Falorca and Pinto, 2011), it was seen that with the addition of 0,4% PP fiber by weight the effective cohesion value of the soil increased and that the effective internal friction angle value increased by 42-52% compared to the unreinforced state. Furthermore, it was observed that the maximum improvement in the shear strength of the SP soil occurred by mixing PP fiber with the length of 50-75 mm at the content of 0,4-1% by weight. However, with the addition of coconut fiber with 25 mm length at the content of 3% by weight, the peak shear strength of the SP soil increased by approximately 80% and the axial strain at failure increased with the addition of more than 1% coconut fiber.

6. Conclusions

In this article, a review was conducted on randomly distributed discrete fiber reinforced soils. For this purpose, widely used natural (palm, coir, sisal, jute, barley straw, bamboo, hemp, cotton straw, cornsilk, papyrus, kenaf and hemp) and synthetic (glass, PP, PVA, nylon and polyester) fibers in the literature have been researched. As a result, fibers at the content of 0,01-8% by weight and 1-25% by volume for natural fibers, 0,05-5% by weight and 1-5% by volume for synthetic fibers are added and mixed to clay, silt, sand and cement or lime stabilized soils. In addition, the effects of fiber lengths varying between 2,5-100 mm for synthetic fibers and 1,5-85 mm for natural fibers on the engineering properties of fiber-soil composites were generally investigated.

The studies reviewed have shown that adding both natural and synthetic fiber into soil generally increases the strength of soils. Moreover, based on these studies, it can be concluded that the fiber-induced changes in the fiber-soil composite are dependent on the aspect ratio or length, content, surface roughness and mechanical properties of the fibers. Besides, soil characteristics such as soil classification and gradation, test conditions such as the normal stress applied in the direct shear test and the magnitude of the confining pressure applied in the triaxial compression test change the stress-strain behavior of fiber-soil composites.

According to the results obtained from these studies investigating the stress-strain behaviour of fiber-soil composites using direct shear test, UCT and triaxial compression test, it is possible to say that the addition of randomly distributed discrete fibers increases the shear strength of soils and ductile behaviour, also decreases the post-peak strength loss and the swelling potential. In addition, because they are lightweight and have a small specific surface area, adding the fibers to the soil generally decreases the MDW value and increases the OWC value. Hereby, the use of fiber reinforcement in road embankments and subgrade layers can provide advantages, as the fiber reinforced soil has a lower unit weight and higher mechanical properties relative to the unreinforced soil.

It has been observed that PP, nylon and palmyra fiber are effective reinforcement elements in reducing the swelling potential of high plasticity clays and the highest improvement is achieved by using palmyra fiber.

According to these studies, it is seen that the undrained shear strength and stiffness of CL soils can be increased significantly by using natural and synthetic fibers as reinforcement elements. In addition, it is observed that the addition of natural fibers such as sisal and papyrus leaves is highly effective in increasing the cohesion value of low plasticity clay soils and the highest improvement is achieved with the addition of papyrus fiber. Besides, it is seen that the initial stiffness of hemp, sisal and PP fiber reinforced soils significantly increased compared to the pure soil.

Synthetic fibers are generally preferred in geotechnical engineering applications as a reinforcement element due to their non-toxicity, hydrophobic, lightweight, high tensile strength, elasticity modulus and chemical resistance. On the other hand, natural fibers are also preferred as alternative reinforcement elements due to sufficient strength and stiffness, low cost, low density, resource abundance, being a sustainable material, minimal energy consumption and especially eco-friendliness.

Natural fibers exposed to wetting-drying cycles exhibit swelling-shrinkage behavior and thus they leave micro voids around them. Due to these voids, the fiber-soil contact decreases and for this reason strength of the fiber-soil composite decreases. Moreover, the presence of water in the soil matrix increases the degradation of natural fibers. As a consequence, an effective and economical water-proof coating material can be used to protect natural fibers from degradation and to eliminate these swelling-shrinkage effects.

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