Investigation and Comparison of Changes in the Hydraulic Conductivity of Clay Minerals Modified with Polypropylene Fibers

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ABSTRACT

In this study, the hydraulic conductivity of illite and kaolinite clay modified with polypropylene fibers was investigated. For this research, polypropylene fibers were mixed with illite and kaolinite clay separately at different weight percentages (0.5%, 1%, 2%, and 4%) and tested accordingly. After comparison and analysis, the sample of illite clay modified with 2% polypropylene fibers and the sample of kaolinite clay modified with 1% polypropylene fibers were found to be more effective in altering hydraulic conductivity compared to other samples. These fiber percentages were determined to be the optimal values for these two types of clay.

Keywords*:* Illite Clay, Kaolinite, Hydraulic Conductivity, Polypropylene Fibers

1. INTRODUCTION

Mokhtari (2011) *investigated flood control strategies. Based on the reviewed results, he concluded that due to the sudden onset of floods, proactive measures are highly effective. Additionally, considering the general public's fear of this natural disaster, proper awareness and explanation of preventive actions can help reduce and control flood risks [1].*

Masoumi et al. (2011) *studied the behavior of granular and loose soils reinforced with synthetic polypropylene fibers. In this study, to examine and measure the effects of various variables such as fiber type, weight percentage (ratio of dry fiber weight to dry soil weight), and fiber length on the load-bearing improvement of loose sandy soil (randomly distributed reinforcement), synthetic fibers such as polypropylene were used in the CBR test. A key finding of these experiments was the increase in load-bearing resistance of the sand-fiber mixture at an optimum moisture content of 13.8%. However, at higher moisture levels, the behavior of the reinforced soil changes. Increasing the fiber length up to 12 mm, along with varying fiber percentages, enhances load-bearing resistance, whereas further length increases lead to a reduction in strength.*

Additionally, ***Kapana Maheshwari et al. (2013)*** *examined the effects of polyester fibers on the strength properties of clay soil. In this study, polyester fibers were mixed with clay soil at different weight percentages (0%, 0.25%, 0.50%, 0.75%, 1.00%, and 1.50% of the dry clay weight) to investigate the reinforcement effects on the soil in terms of...*

...compaction, CBR, mixing, free compression, shear parameters, and the stabilization of various other parameters [2,3,4].

***Abdi and Ebrahimi (2011)** studied the effect of polypropylene fiber length and content on the mechanical properties of kaolinite. The results indicated that the random distribution of fibers significantly increased the maximum differential stress, shear strength, and ductility of kaolinite clay. The increase in strength was dependent on the length and amount of mixed fibers [5]. In general, increasing fiber length and content led to an increase in shear strength and ductility.*

***Hamed Haghshehno and Mahyar Arabani** conducted a study on the effect of polymer fiber waste on the strength properties of cement-stabilized sand. They concluded that adding fibers up to a certain limit enhanced the compressive and shear strength of cement-stabilized sand [6]. Additionally, fibers generally improved residual strength and altered the brittle behavior of the samples to a more ductile response.*

***Mohammad Hossein Noori et al.** investigated the mechanical characteristics of lime- and fiber-stabilized soil. Their findings showed that the presence of fibers along with lime improved the soil's strength parameters and ductility, while the passage of time further enhanced its mechanical properties [7].*

*Similarly, **Mohammad Asadi and Fereydoun Zeinali** studied the mechanical properties of fiber-reinforced and cement-stabilized soil. They concluded that the combination of fibers and cement in the soil led to an increase in both strength parameters and ductility [8].*

***Feng Jian Chen et al.** investigated the strength and mechanical behavior of clay soil reinforced with short polypropylene fibers and stabilized with cement. They concluded that adding fibers to both cemented and non-cemented soil increases unconfined compressive strength, shear strength, and shear strain while reducing stiffness [9]. Cemented soil exhibited greater ductility compared to non-cemented soil.*

***W. An Jiu et al.** studied the effects of fibers and lime on the engineering properties of clay soil. They found that the amount of lime, fibers, and curing duration significantly affected the soil's characteristics. Increasing the lime content resulted in a slight reduction in unconfined compressive strength, cohesion, and the internal friction angle of the soil, while also decreasing soil creep and swelling. In contrast, increasing fiber content enhanced strength and creep but also led to greater soil swelling. Additionally, a longer curing period improved compressive strength and shear strength parameters [10].*

***Sang Sik Park** in his study, using unconfined compressive tests on sand, investigated the effect of fiber distribution in cement-stabilized sand. He concluded that increasing the number of fiber layers enhances the resistance [11].*

***Santoni and Tingel (2001)** conducted unconfined compressive tests on sand reinforced with discontinuous fibers in a random arrangement and demonstrated that the presence of fibers significantly increases the unconfined compressive strength of the samples. They also identified an optimal fiber length of 51 mm for the fibers used [12].*

***Furumoto et al. (2002)**, during large-scale permeability tests, concluded that reinforcing slopes with short fibers significantly increases resistance to boiling and enhances stability against seepage [13].*

***Tang and his colleagues (2006)** recognized the important role of fibers in soil reinforcement and were able to modify the compressive strength and behavior of soil using polypropylene fibers. By considering 12 soil samples and varying fiber percentages, they increased the shear strength and triaxial strength of the soil to a maximum of 229 kPa [17].*

2. MATERIALS USED

In this study, two types of materials were used to evaluate the effect of fibers on the hydraulic conductivity of soil. The soils used in this research are illite and kaolinite clay, while the fiber material employed is polypropylene, which was used to modify the mentioned soils.

The soils selected for this study are illite and kaolinite clay. Since most areas affected by flooding consist of fine-grained soils, saturated illite and kaolinite clay were used in this research.

The characteristics and appearance of ***kaolinite clay*** *are presented in* ***Table and Figure 1****, while the properties and form of* ***illite clay*** *are shown in* ***Table and Figure 2****.*

Table 1 *- Properties of the Kaolinite Clay Used*

Specifications	Amount
Specific Gravity	2/76
Melting Point (°C)	1785
Color	Off-white to yellowish
Chemical Formula	(OH)8 (Si4O10) Al4
Maximum Dry Density (g/cm^3)	1/7
Optimum Moisture Content (%)	8

Fig 1 – *Kaolinite Clay*

The fibers used for reinforcing the illite and kaolinite samples are ***polypropylene****. In terms of composition, polyolefin fibers consist of at least* ***85% by weight of ethylene, propylene, or other similar types****.* ***Polypropylene and polyethylene*** *are the most important olefin fibers, belonging to the category of synthetic fibers.*

*The first olefin fibers were made from **low-density polyethylene** in the **late 1930s in England**, initially used for automobile seat covers. Over time, the application of these polymeric materials expanded into various industries.*

*As shown in **Figure 3**, the fibers appear as **thin strands**, which are cut to the desired lengths for use.*

Table 2 *- Properties of the Illite Clay Used*

Specifications	Amount
Specific Gravity	2/71
Melting Point (°C)	1300
Color	white
Chemical Formula	Al4Si8O20(oH)4.nH2O
Maximum Dry Density (g/cm^3)	1/79
Optimum Moisture Content (%)	9/25

Fig 2 – *Illite Clay*

*These fibers are straight, with a smooth surface, a diameter of approximately **0.3 mm**, a density of **0.91 g/cm^3**, a tensile strength of **400 MPa**, and a tensile modulus of **3200 MPa**. The length of the fibers used is **12 mm**, and the fiber content percentages are **0.5%, 1%, 2%, and 4% by weight**. The specifications of the polypropylene fibers are shown in **Table 3**.*

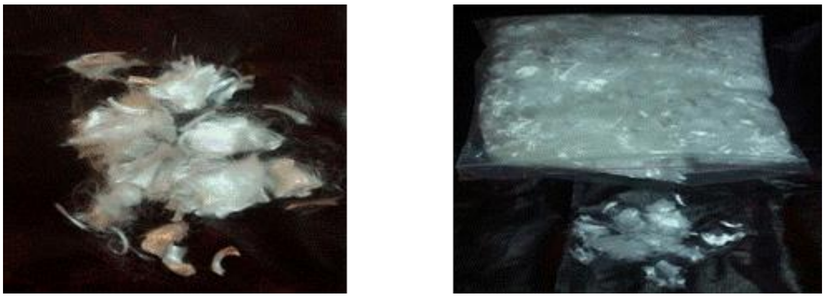

Fig 3 – *Fibers Used in Clay Soil*

Table 3 *- Properties of Polypropylene Fibers*

specification	Amount
Apparent Color	white
Fiber Type	single
Specific Gravity (g/cm³)	0/91
Diameter (mm)3/0	0/3
Tensile Strength (MPa)	400
Melting Range (°C)	160 – 165
Thermal Conductivity	Low
Electrical Conductivity	Low
Resistance to Acids and Alkalis	High
Resistance to Salt	High

3. STUDY METHOD IN THIS RESEARCH

In this study, the obtained results were analyzed using various laboratory methods, as described below. According to existing standards, the one-dimensional consolidation test was conducted to evaluate the effect of reinforcing the mentioned soils with polypropylene fibers on soil settlement. A brief explanation of this test is provided below.

4. TEST PROCEDURE

In. this study, the ***one-dimensional consolidation test*** *was used to measure settlement variations according to* ***ASTM standard (D 2435)****. This test was conducted on* ***10 soil samples*** *of* ***illite and kaolinite*** *modified with* ***polypropylene fibers****, where the fibers were randomly mixed into the soil.*

When ***saturated soil*** *with* ***low permeability*** *is subjected to stress, a* ***gradual decrease in volume*** *occurs due to the* ***drainage of pore water****. Since this drainage continues until the* ***excess hydrostatic pressure*** *is eliminated, the* ***volume reduction*** *also persists for an extended period. Naturally, the* ***excess hydrostatic pressure*** *results from an* ***increase in total stress****.*

Additionally, soil may ***expand*** *due to the* ***absorption of pore water*** *or the presence of* ***negative pore water pressure****. The* ***first phenomenon*** *is called* ***consolidation****, while the* ***second phenomenon*** *is known as* ***swelling****. The processes of* ***consolidation and swelling*** *lead to* ***settlement or expansion*** *at the soil surface.*

If ***lateral deformation*** *in the sample is* ***zero****, and the entire* ***volume change*** *(caused by the rearrangement and gradual filling of voids by soil particles) occurs in the* ***vertical direction****, it is referred to as* ***one-dimensional consolidation****. Otherwise, if deformation occurs in multiple directions, it is called* ***multi-dimensional consolidation****.*

*If the soil sample is **not saturated**, the **air escapes faster** during loading. Initially, the **air is expelled (compaction)**, and this process continues (provided that the applied pressure is sufficient) until the sample becomes **fully saturated**. Once saturation is achieved, the **consolidation process** begins, similar to the previous case (**primary consolidation**).*

*Even after **primary consolidation** is fully completed, **compression does not stop** and continues **slowly** over time. In this phase, there is **no excess hydrostatic pressure** or its dissipation. This phenomenon is known as **secondary compression or secondary consolidation**.*

*The **cause of secondary consolidation** is likely due to **the gradual adjustment of soil particles to the new stress conditions, the progressive breakdown of interparticle bonds, or the drainage of adsorbed water** from the surface of soil particles. For example, **organic soils** undergo a **significant portion of their compression** due to **secondary consolidation**.*

*Therefore, the **consolidation process** consists of three phases: **compaction, primary consolidation, and secondary compression (secondary consolidation)**. For a **fully saturated sample**, **compaction does not occur significantly**, and the process **directly starts with consolidation**.*

*This **test is conducted on fine-grained soils** (as it does not apply to coarse-grained soils). It can be performed on both **undisturbed and disturbed soil samples**. However, due to the **sensitivity of fine-grained soils to disturbance**, it is preferable to perform the test on **undisturbed soil samples**.*

*The **settlement of the saturated soil sample** is measured under a **specific vertical load**. After applying necessary corrections, the **results obtained** are used to estimate **soil settlement in the field**.*

*As shown in **Figure 4**, the **soil sample is placed inside a relatively rigid ring**, and pressure **P** is applied **only from the top surface**, without any **lateral pressure**. This setup closely **resembles the in-situ conditions** of the soil sample.*

Fig 4 – *One-Dimensional Consolidation Test Apparatus*

5. *RESULTS OF THE RESEARCH*

In this research, laboratory studies were conducted. The laboratory results show the effects of polypropylene fibers on the hydraulic conductivity of ***illite*** *and* ***kaolinite*** *soils at different fiber percentages (0.5%, 1%, 2%, 4%). These results reflect the impact of polypropylene fibers on the hydraulic conductivity of illite and kaolinite soils.*

6. *THE EFFECT OF FIBER PERCENTAGE ON PERMEABILITY COEFFICIENT OR HYDRAULIC CONDUCTIVITY OF SOIL*

Permeability coefficient is the unit of flow velocity. The term "permeability coefficient" is commonly used by geotechnical engineers, while geologists refer to it as "hydraulic conductivity." In the SI unit system, the permeability coefficient is expressed in centimeters per second or meters per day. The permeability of soils depends on several factors, including the viscosity of the fluid, the size and distribution of pores, the particle size distribution curve, the porosity ratio, the roughness of the particles, and the degree of soil saturation. In clayey soils, the soil structure plays a significant role in the permeability coefficient. Other important factors influencing the permeability of clays include ion concentration and the thickness of the water layer retained around clay particles.

$$K = 10^{-3}.\gamma_{\text{water}}\ .\mathrm{m}_{v}.\mathrm{c}_{v} \tag{1}$$

m_v :*Volumetric Compressibility Coefficient*

c_v *: Consolidation coefficient*

γ_{water}: *water Density*

As shown in Figure 5, the changes in hydraulic conductivity of unreinforced Illite soil due to changes in pressure were investigated.

The horizontal axis represents the changes in pressure, while the vertical axis represents the hydraulic conductivity. The effect of adding polypropylene fibers to Illite soil on its permeability coefficient was also studied.

The horizontal axis shows pressure changes, and the vertical axis shows the permeability coefficient. With increasing pressure, the permeability coefficient initially increased at low pressures.

It is important to note that fiber-reinforced samples had a higher permeability coefficient compared to the untreated sample, which is attributed to the presence of fibers and the creation of water flow channels.

Additionally, at high pressures, as compression reached its maximum, the water flow channels became fully blocked, causing a decrease and stabilization of the permeability coefficient.

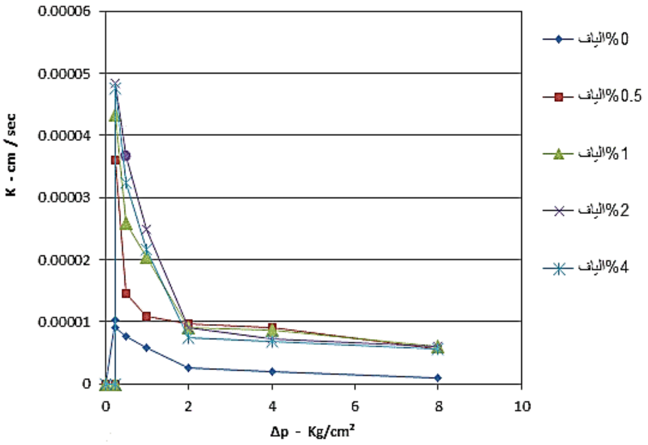

Fig 5 – *Comparison of the effect of Illite soil reinforcement with different percentages of polypropylene fibers on hydraulic conductivity.*

Figure 6 – Changes in the hydraulic conductivity of Kaolinite soil without fibers due to pressure variations are investigated. The horizontal axis represents pressure changes, while the vertical axis represents hydraulic conductivity.

The effect of adding polypropylene fibers to Kaolinite soil on hydraulic conductivity is examined. The horizontal axis indicates pressure variations, and the vertical axis represents permeability coefficient.

At lower pressures, with an increase in pressure, the permeability coefficient increases, and this increase is higher in the fiber-modified samples compared to the regular samples.

Furthermore, as loading continues up to a pressure of 2 kg/cm², the permeability coefficient decreases in all samples. During this pressure variation, with the increase in fiber content, the permeability coefficient increases, which is due to the presence of more fibers, a fact that can be justified at lower pressures.

Additionally, with an increase in pressure at higher pressures, the flow rate decreases due to the complete compaction of the samples, leading to a reduction and stabilization of the permeability coefficient.

As observed, at lower pressures, the fiber-reinforced samples of Kaolinite soil exhibit higher permeability coefficients compared to regular soil samples without fibers, due to the fibers' presence. The fibers act as channels for water flow in the soil, which explains the increase in permeability at the initial stage of loading.

As compaction completes and the channels become fully blocked, the flow rate decreases, causing the permeability coefficient to decrease as well. This process helps to prevent floods, allowing rainwater to infiltrate the soil initially in pastures and areas exposed to rainfall.

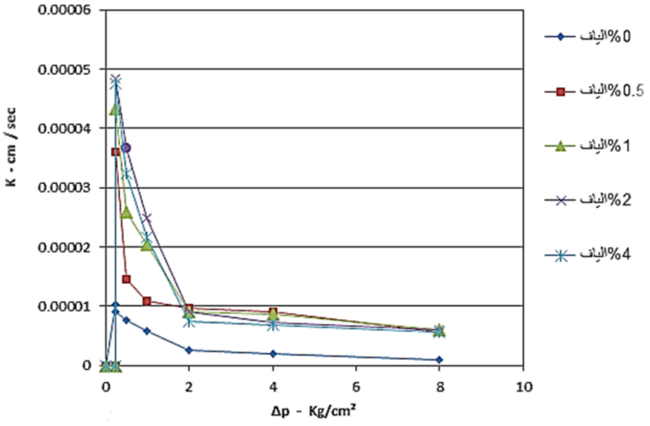

Fig 6 – *Comparison of the effect of modifying Kaolinite soil with different percentages of polypropylene fibers on hydraulic conductivity.*

7. CONCLUSION

The results presented in this study can be summarized as follows:

- *The results show that the use of polypropylene fibers and soil modification significantly increased the hydraulic conductivity of Illite and Kaolinite soils.*
- *It was also observed that modifying soil with synthetic fibers increases hydraulic conductivity, which allows more water to infiltrate during rainfall, thereby preventing potential floods. The presence of fibers between soil particles enhances the cohesion between them.*
- *The lifespan of synthetic polypropylene fibers is significantly long, providing long-term load-bearing capacity compared to natural fibers.*
- *The use of fibers is very simple, as they can be easily added to the soil, and resins can also be mixed with water and incorporated into the soil*
- *Based on laboratory results, increasing fiber content at all tested percentages leads to an increase in soil hydraulic conductivity. It should be noted that this effect is observed at pressures lower than 2 kg/cm². At higher pressures, due to the soil reaching its final compaction, the voids between the particles get filled, reducing and stabilizing permeability.*
- *The optimal fiber content for Illite and Kaolinite soil samples modified with polypropylene fibers ranges between 1% and 2% by weight.*
- *Although all fiber percentages increased hydraulic conductivity, the question arises as to why higher percentages were not selected as optimal. The answer, based on observations during testing, is that in samples with 4% fiber content or higher, the large volume of fibers, while increasing hydraulic conductivity, also obstructed water infiltration.*
- *Today, various flood control methods are used, but they are often not cost-effective and require extensive implementation time, which is critical in emergency flood situations. Soil modification is a practical method for improving drainage paths. Given the low cost of synthetic fibers and minimal labor requirements, this approach is economically viable and time-efficient, helping to mitigate flood risks effectively.*

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