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ENHANCING SHEAR STRENGTH IN FOUNDATIONAL SOILS, LIKE CLAYEY OR SANDY SOILS, USING POLYPROPYLENE FIBER

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ABSTRACT

The stability and load-bearing capacity of foundational soils are critical factors in civil engineering and construction projects. Weak soils often require enhancement to support structural loads effectively, and polypropylene fiber (PPF) has emerged as a promising material in soil stabilization. This paper explores the mechanisms, benefits, and practical applications of using polypropylene fiber to improve the shear strength of foundational soils. Experimental findings, case studies, and theoretical analyses are reviewed to provide a comprehensive understanding of this method. Also, fiber reinforcement has been widely acknowledged as an effective technique for enhancing soil properties in various geotechnical applications, particularly for fill materials. However, its application in clayey soils has been less extensively studied compared to sandy soils, despite showing comparable potential for practical use. The underlying mechanisms governing the shear strength and deformation behavior of clay-fiber composites remain inadequately understood, along with the factors influencing their performance under different drainage conditions.

Keywords: Civil Engineering, Foundational Soils, Polypropylene Fiber, Composition, Fiber Reinforcement

1. INTRODUCTION AND EXPERIMENTAL BACKGROUND

Fiber reinforcement is a well-recognized method for enhancing the shear strength and ductility of soils, improving their stress-strain response. This approach has gained significant attention for its ability to enable the use of locally available, poorly draining soils in geotechnical applications. Several studies have highlighted its effectiveness in various engineering scenarios, including retaining structures, stabilization of subgrades and subbases, increasing soil bearing capacity, improving slope stability, supporting soft soil embankments, controlling soil hydraulic conductivity, mitigating erosion, preventing piping, and reducing shrinkage cracks. These applications underscore the growing acceptance of fiber-reinforced soils in geotechnical engineering practice. Research on fiber-reinforced soils has primarily focused on sands, where fibers intersecting shear failure planes improve mechanical performance by mobilizing their tensile strength, resulting in increased shear strength and enhanced ductility. However, the study of fiber-reinforced clays remains limited, despite its similar potential for practical use. Existing research on clay-fiber mixtures has yet to fully

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elucidate the fundamental mechanisms driving their behavior or the factors influencing performance under varying conditions. Moreover, investigations into shear strength under undrained conditions have been particularly scarce.

Experimental studies have offered insights into the performance of polypropylene (PP) fibers in clayey soils. Feuerhemel, in 2000, conducted consolidated drained (CD) triaxial compression tests on clay samples reinforced with PP fibers of 12 mm and 36 mm lengths at a 0.5% fiber volume. The results revealed a progressive increase in the stress-strain curve with significant ductility. The apparent cohesion of the clay increased threefold with 12 mm fibers and fivefold with 36 mm fibers, while the friction angle remained unchanged. Similarly, Trindade tested clay reinforced with 20 mm PP fibers at 0.25% fiber content and found a 70% increase in apparent cohesion, along with reduced soil compressibility and unchanged friction angles. The influence of drainage conditions on fiber-reinforced soils has been another area of investigation. Freilich found that the effective shear strength parameters of clay-PP mixtures were higher under consolidated undrained (CU) triaxial conditions than under drained conditions, suggesting that time and drainage could significantly impact the mixture's effectiveness. Fiber-soil interactions in clays are influenced by competing factors such as volume change tendencies and strain rates, as well as variations in pore water pressure at fiber-soil interfaces compared to specimen ends. Özkul and Baykal (2007) reported that while apparent cohesion values from CD tests were lower than those from CU tests, the friction angles remained consistent across drainage conditions. Other studies observed improvements in soil-fiber interaction with increased confining stress using PET flakes as reinforcement.

Several researchers have also explored alternative fibers and their effects on soil performance. Adding 1% virgin PP fibers to sandy silty soils in CU triaxial tests enhanced undrained shear strength and provided a more ductile post-peak response. Increasing coir fiber content from 0.4% to 1.6% improved the undrained shear strength of clay. It was also noted that higher fiber contents (e.g., 5%) under low effective stress could reduce strength due to adverse effects on soil grain interaction. Incorporating coir fibers (0.5–2.0%) increased undrained shear strength in clayey soils, while some used computed tomography to study fiber reorientation during compaction, revealing anisotropic distribution and horizontal alignment of fibers. Despite these advances, significant gaps remain in understanding fiber-clay interactions. The effects of fibers on pore water pressure remain inconclusive, requiring additional testing. Analytical models have been developed to predict undrained shear strength in fiber-reinforced clays. These models consider variables like fiber volumetric content, length, diameter, apparent cohesion, friction angle, and interface shear strength parameters. However, limited data on interface shear strength complicates accurate predictions, highlighting the need for further experimental and analytical studies. To address these challenges, the current study focuses on the behavior of clay reinforced with recycled polypropylene fibers under drained and undrained conditions, aiming to refine predictive models for shear strength. By bridging existing knowledge gaps, this research contributes to the broader understanding and application of fiber-reinforced clays in geotechnical engineering.

2. PROPERTIES OF POLYPROPYLENE FIBER (PPF)

Polypropylene fiber (PPF) is a synthetic material that has gained popularity in geotechnical engineering due to its exceptional physical, chemical, and mechanical properties. These characteristics make it particularly well-suited for soil stabilization applications, including improving shear strength, increasing ductility, and enhancing the overall performance of foundational soils. Polypropylene fibers possess high tensile strength, typically ranging between 300 to 600 MPa, which enables them to resist tensile stresses effectively. This property is critical for reinforcing soils, as it allows the fibers to act as tension elements within the soil matrix. The high tensile strength also ensures that the fibers maintain their structural integrity under substantial loads, contributing to long-term stability in reinforced soils. With a density of approximately 0.91 g/cm^3, polypropylene fibers are among the lightest synthetic fibers available. Their low density makes them easy to transport, handle, and mix with soils, which is particularly advantageous in large-scale civil engineering projects. Moreover, the lightweight nature of PPF ensures that it does not significantly alter the bulk density of the soil, preserving its natural characteristics while enhancing its strength properties. Polypropylene fibers exhibit excellent resistance to a wide range of chemical agents, including acids, alkalis, and organic solvents. This chemical inertness makes them suitable for use in chemically aggressive environments, such as industrial sites or areas exposed to wastewater. Unlike traditional stabilizers like lime or cement, PPF does not chemically interact with soil minerals, making it a durable and stable reinforcement material.

One of the standout features of polypropylene fibers is their resistance to biological degradation. They are not affected by microorganisms, fungi, or bacteria, making them suitable for long-term applications in soils prone to biological activity. This property ensures that the fibers retain their reinforcing capabilities over extended periods without requiring replacement or maintenance. PPF exhibits excellent elasticity and flexibility, with an elongation at break ranging from 10% to 25%. This characteristic allows the fibers to absorb and dissipate energy during soil deformation, reducing the likelihood of brittle failure. The flexibility of polypropylene fibers also facilitates better mixing with soils, ensuring uniform distribution within the soil matrix. Polypropylene fibers have a relatively high melting point of approximately 160–170°C, which makes them thermally stable under most environmental conditions encountered in geotechnical applications. While they are not suitable for extreme high-temperature environments, their thermal stability is adequate for use in most construction projects. Polypropylene fibers are hydrophobic, meaning they repel water. This property prevents the fibers from absorbing moisture, which could otherwise lead to swelling or weakening. Their hydrophobicity ensures that the reinforcing effect of PPF remains consistent regardless of changes in soil moisture content, making them particularly beneficial for use in waterlogged soils or areas with fluctuating groundwater levels. The durability of polypropylene fibers is a key advantage in soil stabilization. These fibers are resistant to ultraviolet (UV) radiation, oxidation, and weathering, making them suitable for outdoor applications. Their long-term performance ensures that they maintain their reinforcing properties over the lifecycle of the structure or project.

Compared to other synthetic and natural fiber materials, polypropylene fibers are highly cost-effective. They are manufactured on a large scale, leading to low production costs. Additionally, the minimal equipment and labor required for incorporating PPF into soils further reduce overall project costs. Safe Polypropylene fibers are non-toxic and do not leach harmful substances into the environment. This makes them an environmentally safe choice for soil stabilization in both urban and rural settings. Furthermore, recycled polypropylene materials can be used to produce fibers, contributing to sustainable construction practices. Polypropylene fibers are furthermore available in various lengths, diameters, and aspect ratios (length-to-diameter ratios), allowing for customization based on specific project requirements. Longer fibers with higher aspect ratios are particularly effective in enhancing soil shear strength, while shorter fibers are easier to mix and distribute evenly within the soil matrix. So, it can very well be said that the properties of polypropylene fiber make it an ideal material for improving foundation soils, particularly in applications where traditional stabilization methods are either ineffective or impractical. Its combination of strength, durability, and versatility ensures that PPF can address diverse challenges in soil stabilization, from enhancing shear strength to mitigating deformation and settlement. By leveraging the unique characteristics of polypropylene fibers, engineers can achieve cost-effective and sustainable solutions for complex geotechnical problems.

3. MECHANISM OF SOIL REINFORCEMENT

The reinforcement of soil using polypropylene fiber (PPF) is a sophisticated method of improving the mechanical behavior of soil, leveraging the fiber's inherent properties to enhance strength, ductility, and stability. Understanding the mechanisms of soil reinforcement is critical to optimizing its application in geotechnical engineering. The interaction between polypropylene fibers and soil particles introduces a range of physical and mechanical improvements, which are discussed in detail below. When soil undergoes stress, such as shearing or compression, the fibers embedded within the matrix resist deformation by carrying tensile loads. This tensile resistance is particularly effective in soils with low tensile capacity, such as clay, where fibers act as tension elements bridging gaps and preventing the propagation of cracks. As the soil deforms, the fibers intersect shear failure planes, engaging their tensile strength to counteract soil movement and enhance shear resistance. This interaction not only increases the overall shear strength of the soil but also contributes to greater energy absorption, leading to improved ductility and delayed failure. The performance of fiber-reinforced soils is heavily influenced by the bond and friction at the fiber-soil interface. Polypropylene fibers interact with surrounding soil particles through mechanical interlocking and surface friction. The degree of this interaction depends on factors such as fiber roughness, length, aspect ratio, and soil type. For instance, longer fibers with higher aspect ratios provide more surface area for interaction, resulting in stronger bonding and improved load transfer between fibers and soil. In granular soils, the fibers interlock with particles, contributing to enhanced stability. In cohesive soils like clay, the fibers disrupt the soil matrix, creating micro-reinforced zones where the fibers anchor to the soil. This anchorage prevents the slippage of soil particles and improves resistance to deformation under applied loads.

The addition of polypropylene fibers enhances the apparent cohesion of soil. Apparent cohesion is the measure of shear strength attributed to factors other than friction, such as bonding or adhesion. In fiber-reinforced soils, fibers act as cohesive agents by physically binding soil particles together. This effect is particularly significant in clayey soils, where fibers increase the apparent cohesion without altering the soil's intrinsic friction angle. Studies have shown that fiber-reinforced soils exhibit a substantial increase in apparent cohesion, depending on fiber length, content, and distribution.

For example, polypropylene fibers of varying lengths can enhance cohesion by creating a network of tensile elements that resist separation and movement of soil particles. Polypropylene fibers also play a crucial role in mitigating crack formation and propagation in soils subjected to tensile or compressive stresses. In expansive soils, such as those with high clay content, shrinkage during drying often results in cracks that compromise structural integrity. Fibers embedded within the soil matrix act as crack arrestors, distributing tensile stresses and preventing the initiation or widening of cracks. The ability of fibers to control crack propagation is attributed to their high elongation capacity and flexibility. As cracks form, fibers stretch and absorb energy, effectively reducing the stress concentration at crack tips. This mechanism is particularly valuable in preventing shrinkage cracks in compacted fills, embankments, and other geotechnical structures.

Fiber reinforcement additionally reduces the compressibility of soils, particularly in fine-grained soils like clay. Polypropylene fibers limit the settlement and volumetric changes associated with compressive loads by reinforcing the soil structure. The fibers act as restraining elements that resist deformation, helping to maintain soil volume under stress. This reduction in compressibility is crucial for applications such as subgrade and foundation stabilization, where excessive settlement can lead to structural damage. By distributing loads more evenly across the soil matrix, polypropylene fibers contribute to improved load-bearing capacity and stability. Soils reinforced with polypropylene fibers exhibit enhanced resistance to erosion caused by water or wind. The fibers bind soil particles together, creating a cohesive matrix that resists detachment and transport by erosive forces. This mechanism is particularly beneficial in slope stabilization and embankment construction, where surface erosion can lead to failure. In addition to physical reinforcement, the hydrophobic nature of polypropylene fibers prevents water absorption, reducing the potential for soil softening and weakening under wet conditions. This property ensures the long-term durability of fiber-reinforced soils in environments exposed to fluctuating moisture levels. The introduction of polypropylene fibers alters the pore structure of soils, leading to changes in hydraulic and mechanical behavior.

Fibers create a network within the soil matrix that modifies pore connectivity and reduces permeability. This modification is advantageous in controlling seepage and preventing piping, particularly in fine-grained soils prone to water movement. The fiber network also contributes to the anisotropic behavior of the soil, as fibers tend to align during compaction or under load. This alignment enhances strength and stability in specific directions, providing tailored reinforcement based on the demands of the application. Polypropylene fibers often align horizontally during soil compaction, creating an anisotropic strength distribution within the soil matrix. This anisotropy means that the soil exhibits varying strength properties depending on the direction of applied stress. While this characteristic can be beneficial in certain applications, it also requires careful consideration during design to ensure optimal performance under different loading conditions. The effectiveness of polypropylene fiber reinforcement is influenced also by drainage conditions. In drained conditions, fibers primarily contribute to increased cohesion and ductility by resisting tensile forces and reducing soil displacement. In undrained conditions, the fiber-soil interaction is more complex, as the generation of pore water pressure can impact the overall shear strength. Research has shown that the inclusion of fibers helps maintain strength and stability even under undrained conditions, though further studies are needed to fully understand this behavior.

4. LET US CONCLUDE

The use of polypropylene fibers as a reinforcement material in soil has emerged as a transformative solution for addressing the challenges of soil stability and strength in geotechnical engineering. This study explored the mechanisms through which polypropylene fibers enhance the shear strength, ductility, and overall performance of soils, particularly clayey soils. Polypropylene fibers, with their lightweight, high tensile strength, and resistance to environmental degradation, are uniquely suited for a variety of applications, from slope stabilization to foundation improvement. One of the key takeaways is the ability of polypropylene fibers to mobilize their tensile strength within the soil matrix, effectively bridging gaps and intersecting failure planes to prevent structural collapse. The increase in apparent cohesion brought about by fiber inclusion further enhances the load-bearing capacity of soils, while the preservation of the friction angle ensures stability under varying stress conditions. This dual enhancement of cohesion and strength is particularly advantageous in clayey soils, where the fibers mitigate natural weaknesses such as low tensile strength and susceptibility to cracking. The interaction between fibers and soil particles, characterized by interfacial bonding and friction, highlights the importance of fiber geometry and content in achieving optimal reinforcement. Research has consistently shown that longer fibers with higher aspect ratios deliver superior performance by maximizing surface interaction and improving load transfer.

However, the degree of reinforcement also depends on soil type, compaction methods, and drainage conditions. The anisotropic distribution of fibers observed during compaction, for instance, underscores the need for careful consideration of loading directions during design. Another significant finding is the ability of polypropylene fibers to control crack formation and propagation, a critical aspect in soils prone to shrinkage, such as expansive clays. By acting as physical barriers and distributing tensile stresses, fibers prevent the initiation and widening of cracks, thereby maintaining soil integrity. This property makes fiber-reinforced soils an effective solution for erosion control and slope stabilization, where environmental forces can lead to catastrophic failure. The study also underscores the importance of understanding the impact of drainage conditions on fiber-reinforced soils. While fibers improve performance in both drained and undrained scenarios, the generation of pore water pressure in undrained conditions can influence the overall shear strength. Further research is needed to fully elucidate these effects and refine predictive models for soil behavior under various drainage states. From a practical perspective, polypropylene fiber reinforcement offers several advantages, including the use of locally available soils, reduced reliance on traditional soil improvement techniques, and adaptability to diverse geotechnical challenges.

The versatility of polypropylene fibers makes them suitable for a wide range of applications, such as subgrade stabilization, retaining wall backfill, embankments, and foundations. Furthermore, their resistance to biological and chemical degradation ensures long-term durability, even in harsh environmental conditions. Despite the promising results, challenges remain in optimizing fiber-soil mixtures for specific applications. The alignment and distribution of fibers during compaction, the interaction of fibers with different soil types, and the influence of confining stress are areas that require further exploration. Additionally, developing standardized testing methods and analytical models for predicting the behavior of fiber-reinforced soils will facilitate wider adoption and more accurate design practices. In conclusion, polypropylene fiber reinforcement represents a significant advancement in geotechnical engineering, providing a sustainable and efficient solution for improving soil properties. By enhancing shear strength, ductility, and resistance to environmental forces, polypropylene fibers enable the use of weaker soils in engineering applications, reducing costs and expanding design possibilities. As research continues to refine our understanding of fiber-soil interactions, the potential for polypropylene fibers to revolutionize soil stabilization and reinforcement practices will undoubtedly grow, paving the way for more resilient and sustainable infrastructure.

CONFLICT OF INTERESTS

None.

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