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Hydraulic Response of Sandy Soil to Fungi-Biopolymer Treatment

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Abstract. This study explores a novel technique combining biopolymers with fungi to modify the hydraulic behaviour of a sandy soil. Fungi are known for inducing water repellence in soil by producing hydrophobic compounds, while biopolymer hydrogels, such as xanthan, exhibit hydrophilic properties. The combined action of these two agents is hypothesised to create a dynamic system influencing soil-water interactions. Liquid cultures of two saprotrophic fungal strains, *Pleurotus eryngii* and *Pleurotus ostreatus*, were separately applied in conjunction with xanthan biopolymer to treat a sandy soil. Fungal mycelia interact with soil particles to form a network that modifies pore structure and water movement pathways. Simultaneously, biopolymers retain water through their hydrogel properties, enhancing the soil's water-holding capacity. Soil water retention curves (SWRC) were obtained by measuring suction at different drying stages using a WP4c dew point potentiometer for untreated, biopolymer-treated, and fungi-biopolymer-treated soils. Results showed a significant increase in saturated gravimetric water content (θ_s) and air-entry suction (lower α) for treated soils, allowing increased water retention. A notable reduction in the desaturation rate (n), particularly in fungi-biopolymer-treated soils, indicated reduced moisture loss, which might be critical for limiting shrinkage cracks and maintaining soil strength during dry conditions. Additionally, the suction at residual water content (θ_r) was found to increase, suggesting prolonged moisture availability in treated soils. These findings suggest potential application of fungi-biopolymer soil treatment for slope stabilisation, pavement subgrade improvement, and erosion control, where retaining moisture and reducing desaturation is crucial and to enhance long-term soil stability under unsaturated conditions.

1 Introduction

Soil moisture management is a critical aspect of geotechnical engineering, as it directly influences the stability, strength, and durability of soils used in infrastructure projects. In particular, soil desiccation—the process of water loss from the soil—can lead to significant issues such as cracking, reduced shear strength, and loss of cohesion, which ultimately compromise the integrity of pavements, embankments, foundations, and landfills. Consequently, enhancing water retention in soils and controlling their moisture content is essential for mitigating these risks and ensuring long-term stability [1].

Traditionally, soil stabilisation techniques have involved the use of cement, lime, and fly ash, which improve soil strength and reduce permeability. However, these methods are highly carbon-intensive, contributing significantly to CO_2 emissions during production [2, 3]. Further many of them are known to disrupt soil ecology and irreversibly alter soil properties such as the soil pH and chemical composition which in turn may increase pollution of surface runoff and groundwater [4]. Recently, biopolymers, such as agar, xanthan and gellan, have emerged as a promising alternative to the traditional carbon intensive materials like cement. These natural, hydrophilic polymers can increase soil's water-holding capacity by formation of a hydrogel matrix that alters soil's pore structure by reducing macropores, increasing micropores, and creating soil particle aggregates [5, 6, 7]. Likewise, fungal treatments have gained attention due to their ability to modify soil structure through the formation of fungal mycelial networks and the secretion of extracellular polymeric

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substances (EPS). These contribute to soil aggregation and cohesion, surface water repellence, and subsurface water retention by disrupting capillary rise and continuous water films [8, 9, 10, 11, 12] The growth of fungi and the hyphae proliferation depends largely on the nutrient supply and environmental conditions. This study investigates a synergistic application of fungi and biopolymer to assess its impact on the hydraulic properties of amended sandy soil. Here the biopolymer would serve as a nutrient supply for the fungi, along with contributing to modification of the water retention behaviour of soil. Such hybrid and complementary approaches are being explored in recent studies with the aim of developing cost-effective, durable, and more sustainable alternatives for soil improvement [13].

To achieve study objectives, we investigated the impact of biopolymer (BP) and fungi-biopolymer (fungi-BP) treatments on the soil water retention behaviour, focusing on key parameters such as saturated gravimetric water content (θ_s), residual water content (θ_r), air-entry value (α), and the rate of desaturation (n). By comparing the behaviour of untreated soils with BP-treated and fungi-BP-treated soils, the study explores the practical significance of these treatments in improving soil performance, particularly in terms of water retention. The findings from this preliminary study provide valuable insights on the water retention behaviour of fungi-biopolymer treated soils which are particularly not available in the literature. The findings would further the knowledge needed for practical applications in geotechnical applications where water retention becomes a crucial aspect.

2 Materials and Methods

2.1 Materials

The materials used for the study were sandy soil, xanthan biopolymer and fungi liquid cultures of *Pleurotus* genus.

2.1.1 Soil

For this study, uniformly graded [14] Leighton Buzzard sand, which is a high-purity silica sand, was used, with most of the particles ranging in size from 0.6 to 1 mm, as shown in Fig. 1. It had a specific gravity of 2.64. Sand was chosen as it is an inert material, unlike fine grained soils which are chemically active and can potentially interact with biopolymers. To avoid any potential conflict in having a thorough understanding on the behaviour of fungi-biopolymer synergy, fine-grained soils was not considered in this study. The sand was made initially sterile by autoclaving at 121°C for 20 minutes. This process effectively eliminated soil bacteria, other fungi, or unwanted microorganisms that could potentially interfere with the experiment. The sterilised sand was then allowed to cool before use in subsequent experiments.

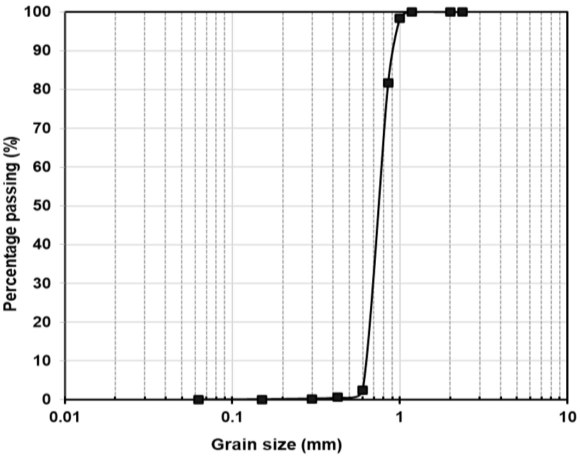

Fig. 1. Grain size distribution of Leighton Buzzard sand

2.1.2 Fungi

Fungi liquid culture obtained from the manufacturer, Mycelia, supplied by UrbanFarmit was used in these experimental studies. Two different fungal strains were used in this study, namely, *Pleurotus eryngii* and *Pleurotus ostreatus*. Both are filamentous fungi that belong to the genus *Pleurotus*, also known as oyster mushrooms. The fungal strains obtained were stored in a refrigerator at a temperature between 2 and 5 °C, as recommended by the supplier.

2.1.3 Biopolymer

Xanthan gum, a high-molecular-weight polysaccharide, was used as the biopolymer in this study. It was obtained from M/s Sigma-Aldrich, United Kingdom and has a general chemical formula of $(C_{35}H_{49}O_{29})_n$. Xanthan gum consists of repeating pentasaccharide units composed of glucose, mannose, and glucuronic acid, with side chains containing acetyl and pyruvate groups. It was selected to evaluate the water retention behaviour of the sandy soil, acting as a nutrient source to the fungi based on its known ability to influence microbial growth and sand cohesion [15, 16]. The biopolymer was avalable in powder form and was stored in air tight container at room temperature.

2.2 Experimental program

2.2.1 Laboratory Experiments

To study the hydraulic behaviour of the fungi-biopolymer amended soil, total suction measurements were carried out in this study using WP4c dew point potentiometer. Dew point potentiometer was selected primarily for its simplistic approach in determining total suction for a wide range of suction up to its residual level. Further, given the complexity of fungi growth on soil sample, attaching tensiometers would pose difficulty; hence dew point potentiometer, was a suitable option for suction measurements. Both treated and untreated soil samples were analysed using the same device to ensure consistency and enable direct comparison. Soil specimens were carefully placed in the sample cups provided, which were then inserted into the measurement chamber of the WP4c potentiometer for equilibrium and dew point determination. Disc-shaped soil specimens (3.5 cm in diameter and 0.5 cm thick) were prepared using prefabricated moulds specifically designed for WP4c tests. The specimens were compacted to a dry density of 1.4 g/ cm^3, a low density chosen to provide sufficient pore space availability for fungal mycelium growth [17]. For untreated soil specimens, dry soil was placed in the suction cups at the target density and levelled inside the cup. A preliminary optimisation study was undertaken to understand the optimal quantities of biopolymer content and fungal suspensions similar to the previous work conducted by the authors [15, 18]. Based on this study, the optimal biopolymer content of 2.5% and moisture content of 10% were selected. For fungi-biopolymer treated specimens, oven-dried and autoclaved sand and 2.5% (w/w) xanthan biopolymer were first dry-mixed. Then, fungi liquid culture, adjusted to 10% moisture content, was added using a dropper pipette. For biopolymer treated soil, instead of fungi culture, 10% distilled water was used for making the specimens. The mixture was thoroughly mixed, placed in the mold and levelled using a tamper to ensure uniform sample height (desired density). This approach was adopted to replicate loose, uncemented field conditions. They were carefully transferred to the measurement cups, which were then kept covered using aluminium foil inside climate chamber set at temperature of 25 ºC and a relative humidity of 50% to provide optimum conditions for fungi belonging to *Pleurotus* species [19]. During the biopolymer curing and fungi growth stages, no significant swelling of the soil samples was observed. The specimens maintained their original volume with only minimal surface irregularities due to biological activity. Any minor changes were negligible and did not impact the sample integrity or testing procedures.

The specimens, after seven days of treatment, were gradually wetted using a pipette. For this, water was added in small increments, ensuring uniform distribution across the sample, allowing time for absorption by the hydrogel. To expedite the process and promote uniform water permeation, at each incremental water addition, the specimens were placed inside a vacuum desiccator during the waiting periods to remove any residual entrapped air. Once saturation was achieved, total suction was measured using the WP4c dew point potentiometer. The specimen's mass was also recorded at this stage. The specimens were then left to air dry under laboratory conditions (T = 21°C; RH = 40-50%). Periodic total suction measurements and mass recordings were taken until the mass variation was negligible, indicating equilibrium with residual conditions. Following this, the specimens were oven-dried to determine their dry weight, allowing for the calculation of gravimetric water content at each stage of suction measurement.

2.2.2 Modeling

The soil water retention curve (SWRC) is considered a reliable approach to represent the relationship between soil suction and water content [20]. SWRC was plotted as gravimetric water content vs. total suction for the following conditions: untreated soil, xanthan biopolymer-treated soil (BP only), *Pleurotus eryngii* + BP treated soil (PE+BP), and *Pleurotus ostreatus* + BP treated soil (PO+BP). The experimental data were fitted using the van Genuchten [21] model, employing gravimetric water content (θ). Although the van Genuchten model was originally formulated for volumetric water content, it can also be applied to gravimetric data when interpreted appropriately, as the shape of the soil water retention curve remains valid [22]. The model describes the relationship between gravimetric water content and total suction using the following equation:

$$\theta=\theta_r+(\theta_s-\theta_r)/\ [1+(\alpha\psi)^n]^{1-1/n} \quad (1)$$

where,

θ = gravimetric water content at a given suction
θ_s = saturated gravimetric water content
θ_r = residual gravimetric water content
ψ = suction or matric potential (MPa)
α = inverse of the air-entry suction, related to the pore size distribution
n = parameter related to the pore size distribution and rate of water loss

3 Results and Discussions

The soil water retention curves (SWRC's) were plotted for all the specimens; Figure 2 presents the SWRC plots for untreated soil specimens and those treated and cured for 7 days, and Table 1 lists the fitted van Gunechten parameters for the corresponding experimental data. The curves showed a notable variation between the untreated and treated soil specimens. The saturated gravimetric water content (θ_s) increased with treatment, showing the highest for BP only-treated soil samples attributing to xanthan's hydrophilic nature, which enhanced water retention. This behaviour stems from xanthan's chemical composition, as it contains -OOH and -OH functional groups with negative charges. These groups interact with slightly positively charged soil particles, generating capillary forces that improve water retention, particularly in the low suction range [23]. However, in fungi-BP treated soils, a marginal reduction in θ_s was observed when compared to biopolymer treated soil. This could be attributed to the partial consumption of biopolymer by fungi as a nutrient source during its growth, resulting in reduced presence of hydrogel within the soil matrix, thereby slightly decreasing its water retention capacity at lower suction ranges. For the untreated sand, a θ_s of 10% was obtained reflecting the practical moisture retention limit due to its coarse texture and high permeability, which prevents full saturation under test conditions.

The parameter α is associated with air entry properties. A higher air entry value (AEV) corresponds to a lower α value, indicating greater resistance to air penetration [24]. In this study, the decrease in α parameter following biopolymer (BP) treatment or fungi-BP treatment, suggested that the treated soil required higher pressure (suctions) for the air to enter the soil pores compared to the untreated soil. It signifies that the soil can retain water under higher suction without allowing air to penetrate, indicating a dense or finer-textured soil with small pore sizes. For fungi-BP-treated soils, a greater decrease in α was noted indicating the additional compactness, resulting from mycelial pore-filling with extracellular polymeric substances (EPS) and hyphae networks. A notably lower value of α was found for PE+BP treated soils possibly due to the better growth of *Pleurotus eryngi* fungi hyphae at 7 days of treatment.

The residual gravimetric water content (θ_r), representing the soil's minimum water retention, was similar across specimens but appeared slightly higher for untreated samples, likely a fitting artifact common in coarse soils. Treated samples exhibited a more gradual desaturation curve and reached residual water content at significantly higher suction values, especially in fungi-biopolymer-treated soil (Fig. 2). This shift can be attributed to altered soil pore structure and particle bonding, as the biopolymer hydrogel and fungi hyphae within the soil particles enhance interparticle cohesion, making water removal more difficult. Additionally, stabilisation reduces pore sizes and permeability, leading to a denser microstructure that retains moisture more effectively, requiring greater suction to extract the remaining moisture. This ultimately enhances the soil's strength and treatment durability, allowing it to resist moisture loss more effectively, improving its long-term performance in applications such as road construction and foundation stabilisation.

A notable decrease in the n value was observed, reflecting a lower rate of desaturation in fungi-biopolymer-modified soil. This behaviour is attributed to the formation of hydrogels by xanthan gum, which traps water in the soil matrix, hindering rapid drainage and slowing down desaturation. In addition, the filamentous fungi can produce proteins called hydrophobins, which make fungi capable of inducing hydrophobicity to the previously hydrophilic surfaces [25]. Salifu et al. [11] showed that not all the pores within a fungal treated specimen become hydrophobic. But still the pores available for water expulsion may be reduced as the water will not be passing through the hydrophobic pores. Furthermore, the fungal mycelia may create an interconnected network along with hydrogels within the pores, further impeding rapid water movement.

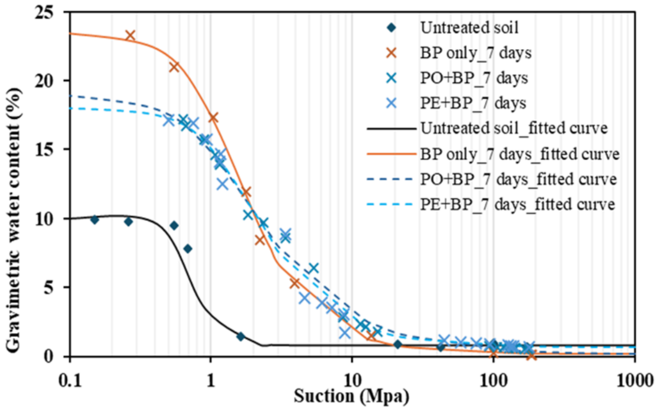

Fig. 2. Water retention characteristics of untreated, BP alone treated, and fungi-BP treated soil

Table 1. Fitted van Genuchten parameters for all the different specimens tested.

	n	θ_r	θ_s	α
Untreated soil	5.267	0.008	0.100	1.400
BP only treated soil	2.250	0.002	0.235	0.867
PO+BP treated soil	1.863	0.001	0.190	0.838
PE+BP treated soil	2.160	0.006	0.181	0.663

To understand the alterations happening in detail, high resolution image of the untreated and fungi-biopolymer treated soil were taken using Teslong MS100 portable digital microscope (Fig. 3a and 3b). The nearly rounded sand particles can be seen from the image of untreated soil. The action of biopolymer and fungal mycelium can be seen together in Fig 3b; biopolymer hydrogel coating the particles and forming connection bridges between two soil particles, and fungi mycelium creating a web like network interlinking different soil particles. The fungi mycelia and hydrogel within the pore spaces of soil alters the hydraulic behaviour causing a shift in SWRC when compared to the untreated soil.

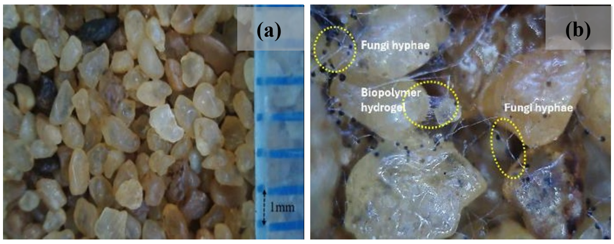

Fig. 3. Microscopic images of (a) untreated soil (b) fungi (PO)-

4 Conclusions

The results of this study demonstrate that biopolymer (BP) and fungi-BP treatments significantly influence the soil water retention behaviour, which has important practical implications for enhancing soil performance in geotechnical and geoenvironmental applications. At residual conditions, the amended samples exhibit higher suction than the unamended soil, indicating stronger moisture retention. The combined effect of enhanced water retention (higher θ_s), increased air-entry value (lower α), and slower desaturation (lower n) indicates that fungi-BP treatments can further delay desaturation, which can help mitigate desiccation cracking and enhance long-term performance of soil making it ideal for applications like slope stabilisation, road subgrade improvement, and agricultural fields where increased water retention is beneficial. The study thus provides exciting insights into the potential of fungi-biopolymer treatment as a sustainable soil stabilisation technique.

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