Moisture Transport in Nonwoven Wicking Geotextiles: Roles of Wettability and Pore Structure

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Abstract. Over the past decade, wicking fibers have been introduced into geotechnical applications to improve the performance of granular materials, particularly in transportation embankments that are prone to moisture-related issues. Their main role is to drain capillary water from surrounding soils, which helps improve overall embankment performance. In this study, water retention tests and droplet contact angle measurements were used to examine the hydraulic behavior of a recently developed wicking geogrid composite, with a focus on distinguishing between wettability and wickability. The results show that while wettability is necessary for wicking, it alone does not ensure effective liquid transport, as pore-scale features such as porosity, pore size distribution, and pore connectivity play a key role. It was also observed that water retention behavior is primarily influenced by wettability and porosity and, therefore, cannot be used alone to assess wickability, as it does not capture key structural characteristics, such as pore connectivity. The contact angle results further support this interpretation by showing how wettability and pore structure work together to control liquid movement. Overall, the findings highlight the limitations of assessing the hydraulic response of nonwovens in geotechnical engineering and provide key insights for the reliable assessment and design of wicking geotextiles under field conditions.

1 Introduction

Conventional geotextiles provide effective drainage under fully saturated conditions but can act as barriers to capillary water migration under partially saturated conditions. This capillary barrier effect, which is well documented at the interface between two porous media with contrasting pore sizes and wettability, leads to the accumulation of moisture in the upstream soil and can adversely affect capillary drainage within the soil mass [1-3]. Geotextiles typically have larger pore sizes than surrounding embankment soils and are often made from hydrophobic polymeric materials. This combination of pore size and wettability contrast enhances the capillary barrier effect, leading to moisture accumulation in the adjacent soil.

To effectively drain capillary water from the body of embankments, wicking geotextiles were introduced approximately a decade ago to address the limitations of conventional geotextiles in capillary water drainage. Geotextiles are typically installed between soil layers with their edges exposed to air, allowing evaporation and drainage. This exposure creates a humidity gradient that, combined with the porous and continuous structure of wicking geotextiles, promotes in-plane moisture transport. In woven wicking geotextiles, the wicking fibers are usually made of nylon and contain microscopic channels that function as capillary tubes, promoting directional moisture transport. More recently, enhanced wettability has been achieved in nonwoven geotextiles by coating their fibers with hydrophilic hygroscopic chemicals. Due to the porous and interconnected structure of nonwoven geotextiles, this increase in fiber surface energy enables moisture transport in all directions.

The effectiveness of wicking geotextiles in reducing soil moisture content and, in turn, improving the performance of transportation embankments is well established in the literature. Ma, et al. [4] demonstrated a 5 percent reduction in moisture content, which led to a 30 percent increase in resilient modulus in a numerical simulation of embankments incorporating wicking fibers. Li, et al. [5] reported that the resilient modulus of a granular base can be doubled by reducing the moisture content from 6 to 3 percent. Jarjour, et al. [6] showed a 9 percent reduction in volumetric water content following heavy rainfall in a soil-wicking geotextile system compared to systems incorporating conventional fibers. This reduction can result in a substantial improvement in soil performance under traffic loading.

To compare the performance of wicking geotextiles and to evaluate their behavior under field conditions, it is essential to clearly distinguish between the concepts of wettability and wickability. Wettability is defined as the tendency of a solid vapor interface to be replaced by a solid liquid interface, whereas wickability refers to the spontaneous migration of liquid through a porous medium driven by capillary forces [7]. According to these definitions, wetting is a prerequisite for wicking, and the link between these two phenomena lies in the

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pore structure of the medium [8]. Consequently, in the absence of an adequate pore network, wicking cannot occur, highlighting the importance of pore structure in evaluating soil-geotextile interaction.

Liquid contact angle with a material, which is a direct consequence of wetting, is widely used to characterize the wetting regime between a liquid and a solid surface. When a wetting regime exists between a liquid and a porous medium, fluid absorption occurs within the pore network, and analyses of time-dependent droplet spreading and imbibition during droplet contact angle tests on porous materials are commonly used to compare the wettability and wickability of fibrous porous media [9, 10]. Sarah, et al. [11] examined the time-dependent behavior of a liquid droplet during contact angle measurements and identified capillary pressure and viscous resistance as the driving and resisting forces, respectively. Zaman, et al. [12] conducted droplet contact angle tests on woven wicking and nonwicking geotextiles and reported a rapid reduction in contact angle on wicking fibers due to droplet penetration into the fiber structure. In contrast, the water droplet remained on the surface of nonwicking geotextiles due to their hydrophobic nature. Similarly, Liu, et al. [13] performed droplet analyses on nonwoven wicking and nonwoven nonwicking geotextiles and demonstrated a significantly higher droplet imbibition rate compared to woven wicking fibers.

A clear distinction between wicking and wetting has not been consistently established in the geotechnical engineering literature, and the performance of wicking fibers is often evaluated using the water retention curve. This curve represents the amount of water retained by a porous medium under varying suction levels. The water retention curve and commonly used mathematical models, such as those proposed by Brooks, et al. [14], Fredlund, et al. [15], Van Genuchten [16], were originally developed for soils. These models have also been adopted to estimate the moisture transport rate at different suction levels based on the retention curve [17].

Previous studies have applied the water retention curve and associated fitting models to characterize the hydraulic behavior of geotextiles. More recently, the water retention curve has been used to highlight the higher capacity of wicking geotextiles to retain water within their porous structure, and the fitted models have been employed to estimate hydraulic conductivity over a range of suction levels. In a comparison between woven wicking and nonwicking geotextiles, Lin, et al. [18] interpreted the higher water retention capacity observed in wicking fibers as evidence of enhanced wettability relative to the nonwicking woven sample. Similarly, Jarjour, et al. [19] adapted this methodology to demonstrate improved wettability in a wicking nonwoven geotextile compared with its nonwicking counterpart. That study further attributed the higher air entry value of the wicking nonwoven geotextile to its increased water retention capacity, which was associated with a stronger wetting regime. Although this approach to interpreting geotextile water retention curves for assessing wetting behavior and wicking rate is appropriate when comparing samples with similar pore structures, it may lead to misleading conclusions in other cases. This is because water retention is governed by the combined effects of wettability and porosity. In addition, other pore-scale characteristics, such as pore connectivity, are not captured by the water retention curve, which can lead to inaccurate interpretations of wickability.

This study investigates the wettability and wickability of a nonwoven wicking geotextile and compares its behavior with that of a nonwoven nonwicking reference material. Contact angle tests and water retention curve measurements were conducted to distinguish between wetting and wicking mechanisms. The water retention test results demonstrate the limitations of interpreting wettability and wickability based solely on retention capacity. Contact angle experiments were performed using both water and mineral oil as test liquids to clarify the limitations of retention-based metrics and to supplement the data used to evaluate wetting and wicking behavior in nonwoven materials. In addition, comparison of the contact angle test results highlights the combined influence of wettability and pore structure on wicking rate. Overall, this study addresses existing gaps in geotechnical engineering by providing deeper insight into the interpretation of experimental methods used to evaluate the unsaturated hydraulic behavior of nonwoven wicking geotextiles and their effectiveness under field conditions.

2 Material

This study focuses on the hydraulic behavior of a continuous filament needle-punched nonwoven wicking geotextile, for which only limited investigations have been reported in the literature, mainly on earlier versions of the material [6, 13, 19, 20]. In general, nonwoven wicking geotextiles are relatively recent developments, and their hydraulic behavior and field performance remain under active investigation.

The Wicking Geotextile (WG) examined in this study is a component of the WickGrid™ geocomposite, which is manufactured by heat bonding a biaxial polypropylene geogrid to the wicking geotextile to provide mechanical reinforcement in addition to moisture management. Since the primary objective of this research is to investigate the hydraulic behavior of the fibers, only the geotextile component is considered and tested, as shown in Fig. 1. For comparison, a nonwicking nonwoven geotextile (NG) with a comparable structure was used, produced using a similar manufacturing process but without the application of a hydrophilic coating. Table 1 summarizes the properties of the geotextile samples. As shown in the table, the nonwicking geotextile exhibits higher moisture content than the wicking geotextile under fully saturated conditions, which is attributed to its higher porosity.

Table 1. Summary of geotextile properties.

Property	Unit	*WG*	*NG*
Permittivity	*l/s*	1.54	1.64
AOS*	*μm*	75	75
Unit mass	g/m^2	249	242
Thickness	*mm*	1.57	1.94
Water Content (ω**)	-	6.2	8.9

* Apparent Opening Size

** ω is the gravimetric water content (GWC)



a) b)

Fig. 1. Visual comparison of the tested samples: (a) nonwicking geotextile and (b) wicking geotextile.

3 Experimental campaign

As discussed previously, this research implements contact angle testing to complement water retention curve measurements and provide a better understanding of water transport in nonwovens. Water retention testing is the traditional approach used in geotechnical engineering to evaluate moisture transport in porous geomaterials. In addition, the evolution of water droplets on fibrous porous structures, commonly used in textile research, was analyzed to assess wicking behavior. Together, these methods are used to evaluate the hydraulic performance of nonwoven wicking geotextiles.

3.1 Water retention testing procedure

In this research, the retention capacity of the geotextile samples was determined at suction values ranging from 0.1 to 15 psi using a pressure cell constructed according to the pressure chamber test procedure [21]. In this method, the specimen is placed in contact with a saturated ceramic porous disk, which prevents air passage while allowing moisture transport. The water within the disk pores blocks airflow and enables the disk to function as a membrane up to a specified pressure, while still permitting water to pass through. The air pressure difference across the porous disk corresponds to the applied suction, and since the geotextile is in direct contact with the disk, its suction is considered to be equal.

After positioning the saturated sample on the porous disk, air pressure is applied to the pressure cell containing the specimen. Since the opposite side of the disk is exposed to atmospheric pressure, the applied chamber pressure is equal to the imposed suction level. The chamber pressure was regulated using an electronic air pressure controller with an accuracy of 0.1 percent of the operating range, enabling water retention curve measurements over the full suction range within a single experimental setup. The applied suction is maintained for 24 hours to allow moisture equilibrium to be reached, after which the sample is weighed to determine its moisture content. The procedure is repeated at different suction values, and the moisture content is determined by weighing the sample after equilibrium at each suction level.

Empirical relationships such as the Van Genuchten model [16] can be applied to fit a continuous curve to the experimental data, allowing the moisture content to be estimated over the full range of suction values. This approach has also been shown to be applicable to geotextiles [22]. The resulting curve can be used to determine the Air Entry Value (AEV), defined as the suction level at which water begins to drain from the largest pores of the porous medium. A high air entry value has also been used as an indicator of the hydrophilic property of wicking fibers in the literature [19]. Accordingly, the experimental data in this study were fitted using a modified form of the Van Genuchten equation, as presented in Equation 1.

$$\omega_i = \omega_r + \frac{\omega_s - \omega_r}{[1+(\alpha\,\psi_i)^q]^p} \quad (1)$$

Where ω_s denotes the saturated water content, ω_r represents the residual water content, α is a fitting parameter corresponding to the AEV, q is a fitting parameter related to the rate of desaturation, and $p = 1 - 1/q$.

3.2 Contact angle characterization procedure

The contact angle of a liquid on a surface is a quantitative measure of the wettability regime between the liquid and the solid surface and arises from the equilibrium among solid-liquid, solid-vapor, and liquid-vapor interfacial tensions. The contact angle can be determined using different testing approaches, including the droplet method and the immersed method. In this study, the droplet contact angle test is employed to evaluate the hydraulic behavior of nonwoven geotextiles.

The intrinsic contact angle represents the inherent strength of the wetting regime between a liquid and an ideal solid surface. However, its measurement is particularly challenging for porous materials, since the test requires a smooth and solid surface [23]. In addition, when a wetting regime exists, liquid absorption into the pore structure leads to a time-dependent contact angle rather than a single equilibrium value. Nevertheless, analysis of liquid droplet imbibition during droplet contact angle testing provides valuable insight into the wicking behavior of fibrous porous media.

Fig. 2 illustrates the goniometer setup used in this study to record the contact angle and its variation with time. The experimental system consists of a high-speed camera and a computer-controlled syringe pump for dispensing liquid droplets of prescribed volume. Shadowgraphic videos were captured and analyzed on a frame-by-frame basis using a double-sided elliptical fitting method in the image processing software to determine the contact angle and droplet volume at each time step [24]. Fig. 3 presents a schematic definition of the contact angle (θ) for a liquid droplet resting on a surface in a nonwetting regime.

The contact angles of water and mineral oil were measured in this study. These liquids were selected to represent a wide range of viscosity and polarity, as shown in Table 2. This multi-liquid approach, applied to both wicking and nonwicking materials, enables distinction between wettability and wickability.

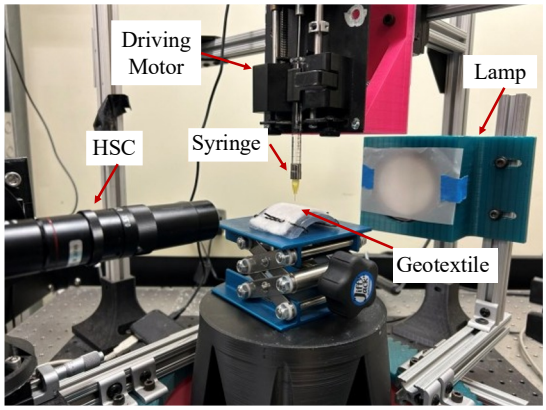


Fig. 2. Goniometer setup for contact angle measurements.

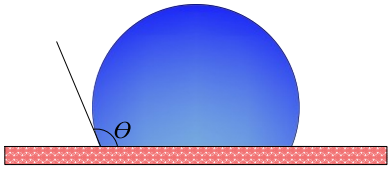


Fig. 3. Definition of the contact angle (θ) for a liquid droplet (schematic of the droplet in a non-wetting regime).

Table 2. Properties of the test liquids.

Properties	Test liquid	
	Water	***Mineral oil***
Density (*g/ml*)	1	0.85
Surface tension (*N/m*)	0.072	0.03
Kinematic viscosity (*cSt*)	1	65
Polarity (-)	Polar	Non-polar

4 Results and discussion

The use of the water retention curve to infer wickability and higher wettability of wicking geotextiles relative to conventional counterparts is widespread in the geosynthetics literature [18, 19, 25]. However, the geotechnical engineering literature does not clearly differentiate between the concepts of wettability and wickability and does not adequately consider the role of pore structure properties. This limitation arises because the water retention curve was originally developed for soils, which consist of discrete particles with pore structures that are broadly similar in form and connectivity and are therefore not treated as independent variables. In contrast, for geotextiles, and particularly for nonwoven materials, pore structure is a variable that depends on several factors, including fiber diameter, water flow path length, porosity, pore geometry and connectivity, and pore size distribution [26].

In textile research, wettability and wickability are well-established concepts, and pore structure has been identified as the key factor linking these two phenomena [9, 26-28]. In this context, the contact angle test has been widely used to assess the wickability of fibrous materials [9-11, 29-33]. More recently, Zaman, et al. [12] and Liu, et al. [13] applied the water droplet contact angle measurements to demonstrate the hydrophilic response of wicking geotextiles.

In the present study, the water retention capacity of a wicking geotextile is compared with that of its nonwicking counterpart to improve the interpretation of wettability and to clarify the role of pore structure in governing wickability. In addition, droplet contact angle tests are conducted on both materials to evaluate wettability and wickability from a complementary perspective.

4.1 Water retention response of the geotextiles

Fig. 4 presents the experimental data and the fitted water retention curves for both the wicking and nonwicking geotextile samples. Each sample was tested five times, and the average gravimetric moisture content was calculated at each corresponding suction level. Gravimetric moisture content is defined as the ratio of the mass of the saturating liquid to the mass of the dry sample.

First, the fully saturated samples showed a gravimetric water content of 6.2 and 8.9 for WG and NG, respectively, as reported in Table 1, while the recorded moisture content under near saturated conditions in Fig. 4 is 3.3 and 3.8 for the WG and NG samples, which are significantly lower than the values reported in the table. This difference is attributed to the overburden pressure applied to the geotextile sample during water retention measurements, which is necessary to ensure proper contact with the porous disk. This observation indicates the high sensitivity of nonwoven materials to changes in pore structure and their associated hydraulic properties.

Also, as shown in the figure, under saturated and near-saturated conditions ($\psi < 2.5$ kPa), the nonwicking geotextile exhibits higher retention capacity than the wicking geotextile. This behavior is attributed to the more porous structure of the nonwicking sample compared to the wicking geotextile and is consistent with the well-known higher hydraulic conductivity of porous media with higher porosity under near-saturated

conditions. However, beyond the air entry value, a sharp reduction in retention capacity is observed for the nonwicking geotextile, whereas the wicking geotextile exhibits a more gradual decrease in moisture content with increasing suction. This slower rate of moisture reduction is attributed to the higher wettability of the wicking fibers. As a result, at suction values greater than 2.5 kPa, the wicking geotextile retains more water, indicating that fiber wettability becomes the dominant factor governing water retention under partially saturated conditions. This higher moisture content at high suction levels represents the water film surrounding the filaments of wicking geotextiles, which facilitates capillary water transport. This behavior explains the ability of wicking geotextiles to transport moisture in partially saturated conditions. The air entry values were determined to be 1.80 kPa and 1.24 kPa for the nonwicking and wicking geotextiles, respectively. Comparison of these values indicates that air entry value alone is not a reliable indicator for drawing conclusions regarding the wettability of geotextiles, as it can also be influenced by the porosity of the medium.

Based on the above discussion, the water retention capacity of geotextiles is governed by the combined effects of wettability and porosity, which cannot be distinguished or evaluated independently. Consequently, drawing conclusions regarding wettability solely from water retention capacity is not appropriate. It is further recognized that the hydraulic conductivity of porous media at varying suction levels is often estimated to be proportional to their water retention capacity [16]. However, important pore-scale variables, such as pore connectivity and pore size distribution, are not accounted for in the water retention curve. As a result, estimating the wicking rate solely from the water retention curve can lead to unreliable results.

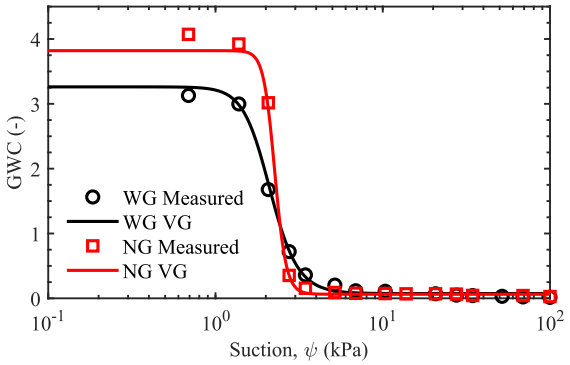


Fig. 4. Curve-fitted geotextile water retention data

4.2 Contact angle test results for geotextile samples

The experimental campaign was initiated by placing 8-µL liquid droplets on the surface of dry geotextile samples. On the nonwicking geotextile, the water droplet remained stable on the surface without noticeable change, exhibiting a contact angle in the range of 127 to 132 degrees. According to the classification proposed by Kutilek, et al. [34], wetting behavior can be divided into complete wetting ($\theta = 0$), incomplete wetting ($0 < \theta < 90°$), and non-wetting ($\theta \geq 90°$).

It should be noted that, in this test, the droplet was placed on a porous medium and was therefore in contact with both the fibers and the air in the pores. As a result, additional factors such as surface pore density and surface roughness influence the measured contact angle [33]. Nevertheless, since no droplet imbibition was observed and the droplet remained on the surface throughout the test duration, the only reasonable conclusion is that the intrinsic contact angle of the nonwicking geotextile is greater than 90°.

For the wicking geotextile, the water droplet was highly unstable due to the strong wetting interaction between water and the wicking fibers, along with the low viscosity of water, which reduces flow resistance and accelerates droplet imbibition. This wetting regime was sufficiently strong that the droplet was absorbed so rapidly that it could not be reliably recorded by the high-speed camera. In addition, the very rapid dynamics of the absorption process introduced significant uncertainty in the measurements, making water contact angle measurements on the WG unreliable. Similar behavior for nonwoven wicking geotextiles has also been reported by Liu, et al. [13].

To overcome the inability to measure the contact angle using water droplets, the test was performed using mineral oil as the wetting liquid. Mineral oil is a nonpolar liquid with lower surface tension that exhibits strong wetting behavior on both wicking and nonwicking geotextiles. In addition, the higher viscosity of mineral oil (65 cSt) provides increased viscous resistance and slows down the imbibition process. Fig. 5 and Fig. 6 present the variation of contact angle and normalized imbibed volume with time for 8-µL droplets. Interestingly, the absorption rate, which can be interpreted as the wicking rate, was approximately three times higher for the nonwicking geotextile than for the wicking geotextile. To interpret this observation, the Lucas Washburn equation, presented in Equation 2, can be considered. This equation is widely used in textile research to approximate wicking behavior and provides a useful framework for understanding the influence of pore structure and wettability on liquid transport [8].

$$\frac{dL}{dt} = \frac{r\gamma \cos\theta}{4\eta L} \tag{2}$$

where L denotes the wicking length, γ represents the surface tension at the liquid vapor interface, η indicates the viscosity of the liquid, θ is the intrinsic contact angle between the solid and the liquid, and r refers to the capillary radius.

In this equation, capillary pressure acts as the driving force, while viscous resistance represents the resisting force. Formulating the balance between these driving and resisting mechanisms leads to Equation 2, in which the wicking rate, expressed as $dL.dt$, is proportional to the pore size. Therefore, it can be concluded that the higher porosity of nonwicking geotextiles results in lower viscous resistance. From a pore structure perspective, this explains the faster droplet dissipation

observed in the nonwicking sample, which exhibits higher porosity.

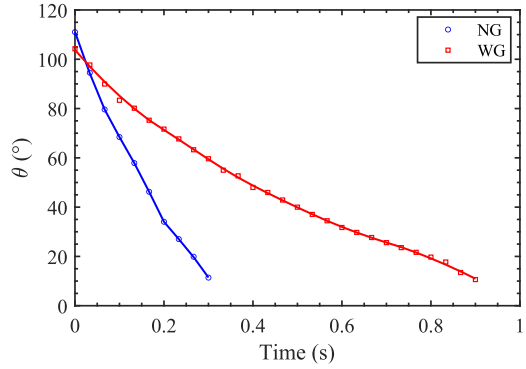


Fig. 5. Time-dependent variation of the contact angle of mineral oil droplets.

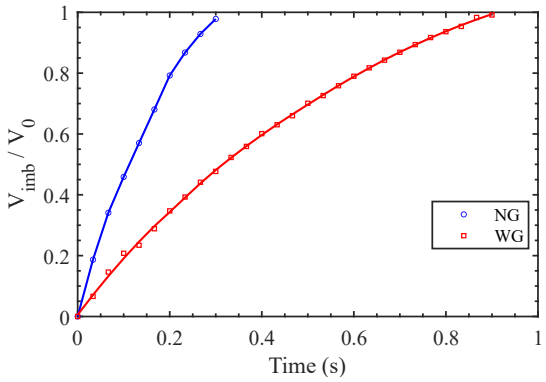


Fig. 6. Variation of the normalized imbibed volume of mineral oil droplets with time.

From a wetting perspective, which constitutes the second governing factor in wicking rate, the intrinsic contact angle must be considered. The geotextile filaments are composed of polyester, which is a nonpolar material. This nonpolar nature is compatible with mineral oil, which is also nonpolar, leading to a favorable wetting regime. In contrast, coating the filaments of the wicking geotextile with hydrophilic agents increases the polarity of the fiber surface, which weakens the wetting regime with mineral oil and increases the contact angle [35]. As a result, the wetting interaction between mineral oil and the nonwicking geotextile is stronger than that between mineral oil and the wicking geotextile due to the closer match in polarity. In essence, while the hydrophilic treatment applied to wicking geotextiles enhances wettability with water, it simultaneously reduces wettability with nonpolar liquids such as mineral oil.

Based on the above discussion, it can be concluded that wetting and wicking are two distinct yet closely related phenomena. This distinction is clearly illustrated by the use of mineral oil as the wetting liquid in the contact angle tests performed on both wicking and nonwicking geotextile samples. Although the nonwicking geotextile exhibits nonwetting behavior with water, it demonstrates a wetting regime when tested with mineral oil. This observation highlights the definition and role of wetting in the wicking process, particularly when pore fabric remains comparable between samples.

In addition, the Lucas Washburn equation explains the influence of pore size on wicking behavior and indicates that a higher fiber density, corresponding to lower porosity, can increase viscous resistance and consequently reduce the wicking rate. This effect was also confirmed by previous numerical modeling studies, which demonstrated that increased fiber density limits liquid droplet imbibition in nonwoven structures [9].

5 Conclusion

Nonwoven wicking geotextiles and wicking phenomena represent relatively recent developments in geotechnical engineering. Many studies in the geotechnical engineering literature have attempted to interpret wicking behavior primarily through the water retention curve. Wetting is defined as the tendency of a solid-vapor interface to be replaced by a solid-liquid interface. Although wetting is a necessary condition for wicking to occur, it is not sufficient on its own, as pore structure also plays a critical controlling role. For example, a porous medium may exhibit a strong wetting regime and high overall porosity, yet if the pore spaces are poorly connected, it can retain a significant amount of water while wicking does not occur.

The findings of this study demonstrate that water retention capacity cannot reliably be used to compare the wickability and wettability of geotextiles. Water retention capacity is governed by both wettability and porosity, which limits its applicability as a standalone indicator of wickability. In fact, other structural characteristics, such as the connectivity of pore spaces, are essential for moisture transport but are not explicitly captured in the water retention curve.

In contrast, wetting and wicking are clearly distinguished in the textile engineering literature, and this conceptual framework provides valuable insight into the hydraulic behavior of wicking geotextiles. In the present study, droplet contact angle tests were employed to emphasize this distinction, which is critical for evaluating the performance of wicking fibers. The strong wetting regime observed between mineral oil and the nonwicking geotextile, together with the nonwetting behavior of the same material in contact with water, highlights the fundamental role of wetting in the wicking process. Furthermore, the higher wicking rate of mineral oil observed in the nonwicking geotextile compared to the wicking geotextile is also attributed to the denser fiber arrangement of the wicking sample, which increases viscous resistance and limits liquid transport.

These insights are essential for assessing the performance and long-term behavior of wicking fibers under field conditions, where factors such as overburden pressure and pore space clogging may alter pore structure and significantly affect wicking efficiency, and should therefore be considered in design. Overall, the findings of this study highlight the limitations of relying solely on the water retention curve to compare the performance of wicking geotextiles and underscore the

need for complementary approaches that explicitly account for both wettability and pore structure.

6 Acknowledgement

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