Technical Review of Development and Applications from Wicking Fabric to Wicking Geotextile

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ABSTRACT

Moisture-wicking fabrics first appeared in the market more than 20 years ago and have been mostly used for the clothing industry to improve comfort by soaking sweat when they are worn on human body. Extensive research has been conducted in this industry to improve properties and behavior of wicking fabrics. In recent years, wicking fabrics have been increasingly used as wicking geotextiles to remove moisture from soils to mitigate frost heave, poor drainage, and soil expansion problems. This paper provides a comprehensive literature review of the development of wicking fabrics in the clothing industry and the applications of this technology as wicking geotextiles in geotechnical engineering. The review first discusses the basics of wicking fibers including types of polymers, geometries of fibers, fiber-water surface interaction, water transportation in fibers, water evaporation from fibers, fiber-water-soil interaction, and their influence factors, and then summarizes recent research and advances in the use of wicking geotextiles to solve moisture-related problems in geotechnical engineering, especially for roadways.

INTRODUCTION

Removal of water (i.e. drainage) in an efficient and timely manner is necessary to improve the long-term performance of roadways. While traditional geotextiles made of synthetic permeable textile materials (e.g. polyester, polyamide, polypropylene, and polyethylene) have excellent water absorption, transportation, and evaporation abilities during gravitational drainage, they are not effective in unsaturated soil conditions due to its fiber properties and pore structure. Both the traditional woven and non-woven geotextile fibers are unable to produce enough capillary force that allows them to absorb and transfer moisture from soil particles under a certain saturation limit. Hence, moisture that comes from precipitation, freeze-thaw, and capillary rise of the groundwater remains within base/subbase courses and subgrade, weakens soils, and induces distresses of roadways over time.

In recent years, geotechnical engineers and researchers have paid attention to removing moisture from unsaturated road sections with the help of geotextiles. To do this, one type of geotextile namely "wicking geotextile" was introduced to the market by providing an improved lateral drainage ability. Wicking geotextile includes special fibers that have four deep groves (4DG) channels to produce high capillary force to absorb and wick water out of road sections. Recent studies on the wicking geotextile have proved its effectiveness to remove moisture from unsaturated soil and hence, increase the overall roadway performance. Various laboratory experiments and field monitoring have taken place to date to quantify the behavior and working mechanisms of the wicking geotextile.

While the wick geotextile is a relatively new addition to the geotechnical community, this concept has been well known to the garment industry since the late 1950s, mostly for manufacturing performance apparels (e.g. athletic, comfort, and cooling) that can transfer and evaporate body moisture (e.g. sweat) to the environment at a faster rate. Textile engineers and researchers have conducted many investigations on the properties and size/shape of pore structures of fibrous materials. Their studies indicated that wicking fibers can effectively absorb and transfer liquid. However, liquid quantity and transfer mostly depend on the fiber type, pore structure, internal surface, chemical treatment, and liquid property.

This paper discusses the advancements of wicking fabrics in the textile industry and their evolution into a wicking geotextile in chronological order considering various issues. This summary work will provide the information useful to study the development and efficacy of the wicking geotextile especially for drainage purposes in geotechnical engineering applications.

DEVELOPMENT OF WICKING FABRIC IN TEXTILE INDUSTRY

Methods to Evaluate Wicking Ability. A typical fabric has warp and weft directions based on the manufacture process. Wicking ability in two directions may be different. Harnett and Mehta (1984) described four different laboratory tests to evaluate wicking ability of knitted fabrics in different directions: (1) strip test, (2) plate test, (3) spot test, and (4) siphon test. They found the vertical strip test (also known as the column test) is appropriate for tracking movement of water while the horizontal plate test is suitable for simulating a sweating skin surface (Fig. 1). To evaluate wetting and wicking of fabrics, Ghali et al. (1994) measured capillary pressure and permeability of cotton and polypropylene fabrics at different saturation levels using the column test and the siphon test, respectively.

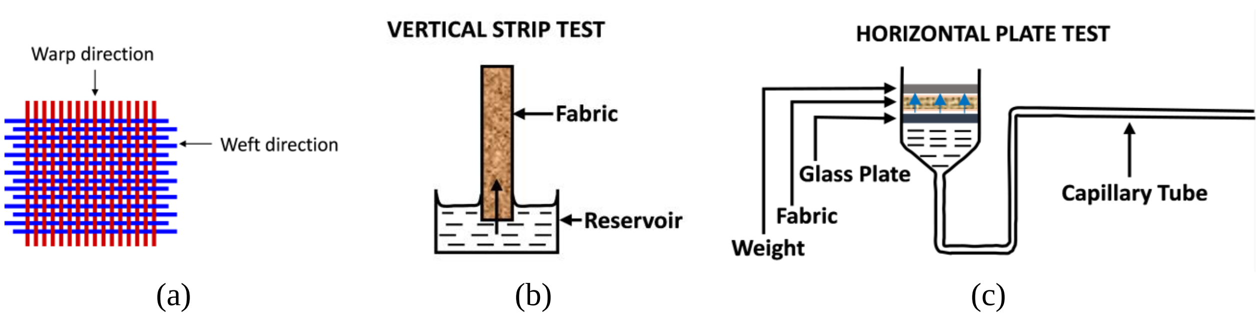

Figure 1. Laboratory tests to measure wickability in different directions: (a) fiber directions, (b) parallel to the fabric plane, and (c) perpendicular to the fabric plane (modified from Harnett and Mehta, 1984).

Ansari and Kish (2000) used an electrical resistance technique to measure the travel distance of water in the fabric which showed a good agreement with Lucas-Washburn's capillary flow theory. Ansari et al. (2007) and Mazloumpour et al. (2011) adopted inductive sensors to trace the electromagnetic field of water in the fabric to measure the distance traveled by water (i.e. liquid wicking). Instead, Parada et al. (2017) used a neutron radiography technique to measure the travel distance of water.

Rossi et al. (2011) adopted the X-ray tomography to examine the wickability perpendicular to the fabric plane of denier gradient fabrics (i.e. denser fabrics) under low- and high-pressure conditions. Zhuang et al. (2002) used the image analysis method to measure the travel distance of a liquid in the fabric, which was validated with manual observation. Mhetre and Parachuru (2010) used a similar approach to measure the liquid travel distance on a wide range of cotton and polyester fabrics.

Wicking Rate of Fabric. Adler and Walsh (1984) investigated a wide range of fabrics and proposed a critical moisture concept that a minimum amount of water existing in the capillary pores of yarns and fibers is required to start wicking of water in the fabric. Hsieh (1995) concluded that the geometrical configuration of the fibrous material controls the liquid travel distance. Then, Rajagopalan et al. (2001) concluded that the liquid travel distance can be increased by reducing the void area between filaments. Nyoni and Brook (2006) reported that the penetration and retention of liquid in the fabric depend on the pore size, shape, and orientation. Fangueiro et al. (2010) found the fabric made with viscose Outlast yarns (hydrophilic fibers) performs best for wicking in both the vertical and horizontal directions. In their study, Yanılmaz and Kalaoğlu (2012) concluded that the greater wicking height happens in fabrics having smaller capillary pores between yarns. In addition, Chatterjee and Singh (2014) concluded that macro-capillaries control short-term wicking while microcapillaries control long-term wicking in the fabric.

The literature from the textile industry reveals that simple strip and plate tests are widely used to measure in-plane and cross-plane liquid transport respectively. Table 1 summarizes the fabric properties from the literature, while Fig. 2 shows the comparisons between different fabrics for vertical wicking heights considering the gravity effect. In general, cotton has the highest wicking height, followed by polyester, and then polypropylene even though there are some variations from different studies.

Table 1. Pertinent information of the fabrics in Fig. 2

Literature	Fabric Type	Fabric Description
Zhong et al., 2001	Polypropylene	Yarn count (tex) = 13.4, diameter of yarn (mm) = 0.32, fineness of filament (dtex) = 0.6, no. of filaments in a yarn = 224, diameter of filaments (mm) = 0.0092
Ansari et al., 2007	Cotton	Yarn count = 10, density of yarn (per cm) = 18.1
Fangueiro et al., 2010	Polypropylene-viscose	Fabric mass (g/m^2) = 132.48, wales density (per cm) = 13.9, courses density (per cm) = 18.1, fiber thickness (mm) = 1.38
Mazloumpour et al., 2011	Cotton	Yarn count = 10, density of yarn (per cm) = 18.1
Das et al., 2011	Polyester	Fiber denier = 4.72, no. of filaments in a yarn = 32 yarn denier = 151, yarn radius (mm) = 0.0072
Chatterjee and Singh, 2014	Polyester staple yarn	Fabric thickness (mm) = 0.54, ends per inch (EPI) = 48, pick per inch (PPI) = 50
Saricam and Kalaoglu, 2014	Polyester	Weft density (per cm) = 18, fabric mass (g/m^2) = 180.4, fabric thickness (mm) = 0.45
Xu et al., 2016	Polyester	Fabric mass (g/m^2) = 130
Wang et al., 2021	Cotton	Mean fineness (dtex) = 1.4, ends per inch (EPI) = 170, pick per inch (PPI) = 93

*tex=mass in grams per 1,000 meters of yarn; *dtex=mass in grams for every 10,000 meters of fiber or filament.

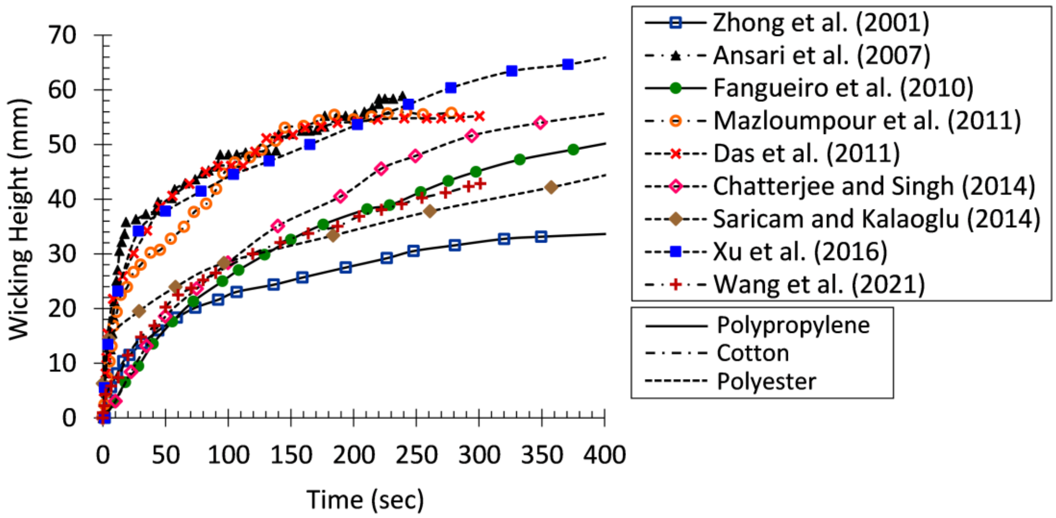

Figure 2. Comparison of vertical wicking heights for different fabrics in the literature.

Moisture Evaporation from Fabric. Awano et al. (1987) concluded that the fabric with larger inter-fiber spacing (i.e. capillary pores in the fabric) promotes water evaporation from the fabric. However, larger pore spacing may reduce the speed of water transport due to the lower capillary pressure. Wang et al. (2009) studied the honeycomb-structured micro-porous polyester fabric and concluded that the water vapor transmission (WVT) property of the fabric defined below can be improved by treating the fabric with a hydrophilic additive:

$$WVT(g/24h.m^2) = \frac{24\Delta m}{St} \tag{1}$$

where Δm = assembled weight reduced after one hour (g); t = test time (hr); A = measurement area of the fabric sample (m^2).

Likewise, Mazloumpour et al. (2011) found from the laboratory experiments that the water wicking height and the water vapor permeability (WVP) index as defined below decrease with the increase of the weft yarn density of the fabric:

$$WVP\ (g/day.m^2) = \frac{24M}{At} \tag{2}$$

where M = reducing weight of water vapor among the sample with time (g); t = time (hr); and A = test area of the fabric (m^2).

Ansari and Kish (2000) and Saricam and Kalaoglu (2014) reported similar conclusions. This phenomenon happens due to the reduction of capillary spaces between weft yarns by increasing the weft yarn density. Figure 3 shows the comparison between the experimental results from Wang et al. (2009) and Mazloumpour et al. (2011) with the fabric properties given in Table 2. At the same weft density, polyester fabric transmits more water vapor than cotton fabric.

Furthermore, Fangueiro et al. (2010) and Saricam and Kalaoglu (2014) studied the water evaporation rate (WER) on a wide range of fabrics. The comparison between WERs of different fabrics is shown in Fig. 4 with the fabric information provided in Table 3. Polyester fabric has the fastest WER as compared to polypropylene-viscose and slack interlocked fabrics.

Table 2. Pertinent information of the fabrics in Fig. 3

Literature	Fabric Type	Fabric Description	Controlled Environment
Wang et al., 2009	Polyester	Warp yarn (tex) = 16.7 Weft yarn (tex) = 30 Fabric mass (g/m^2) = 235.2 Thickness (mm) = 0.36	Temperature = 38°C Relative Humidity = 90%
Mazloumpour et al., 2011	Cotton	Yarn count = 10 Yarn density (per cm) = 18.1	Temperature = 28-30°C Relative Humidity = 38-40%

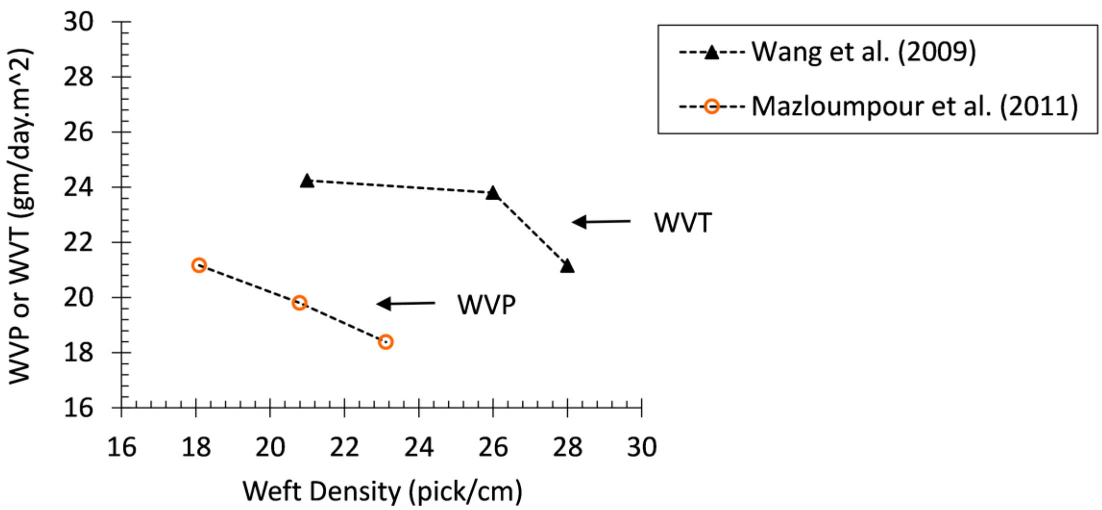

Figure 3. Dependency of water vapor transmission rate on weft density of fabric.

Table 3. Pertinent information of the fabrics in Fig. 4

Literature	Fabric Type	Fabric Description	Controlled Environment
Fangueiro et al., 2010	Polypropylene -Viscose	Fabric mass (g/m^2) = 132.48 Wales density (per cm) = 13.9 Courses density (per cm) = 18.1 Fiber thickness (mm) = 1.38	Temperature = 20±2°C Relative Humidity = 65±3%
Yanılmaz and Kalaoğlu, 2012	Slack Interlocked	Thickness (mm) = 2.45 Fabric mass (g/m^2) = 429.1 Pore size (mm) = 0.51	Temperature = 20±2°C Relative Humidity = 65±5%
Saricam and Kalaoglu, 2014	Polyester	Weft density (per cm) = 18 Fabric mass (g/m^2) = 180.4 Fabric thickness (mm) = 0.45	Temperature = 20±2°C Relative Humidity = 65±5%

EVALUATION OF WICKING GEOTEXTILE FROM WICKING FABRIC

In the last decade, several laboratory and field tests have been conducted to evaluate the drainage mechanisms and performance of the wicking geotextile.

Mechanism of Water-Wicking Geotextile Interaction in Soil. Lin et al. (2017) and Guo et al. (2017) discussed the working mechanism of the wicking geotextile to remove water when it is placed inside typical road sections. Due to the high capillary pressure of the wicking fibers, the wicking geotextile absorbs moisture that comes from capillary rise of the ground water table, surface infiltration of rainfall, and thawing of frost boils. Then, the moisture is transferred to the portion of the wicking geotextile which is exposed to the environment due to the difference in Relative Humidity (RH) between buried and exposed portions. The moisture evaporates from the exposed portion of the geotextile to the environment. Figure 5 shows the mechanism of water-wicking geotextile interaction in soil.

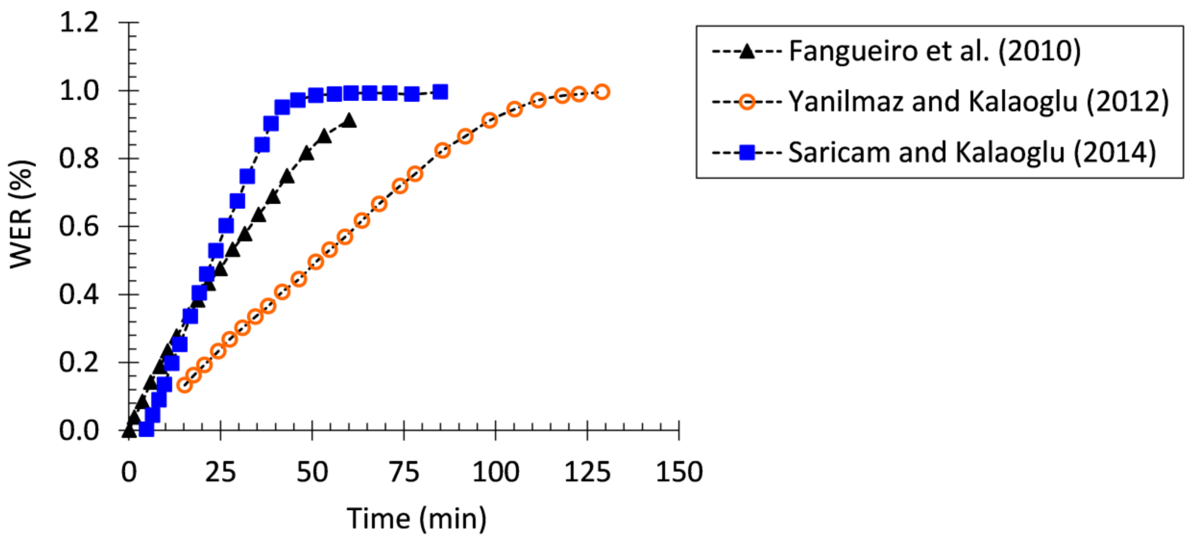

Figure 4. Water evaporation rate (WER) of fibers.

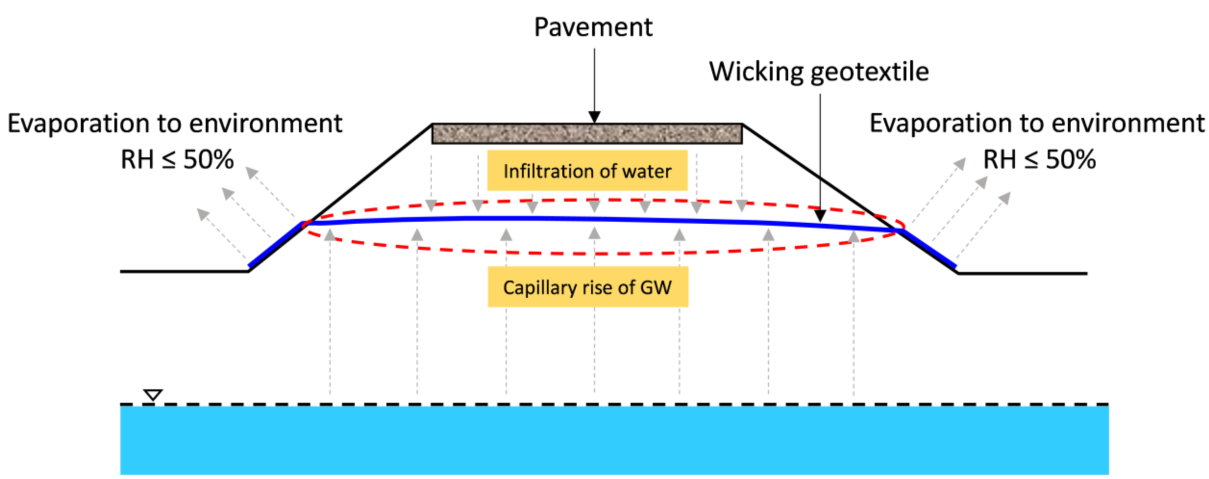

Figure 5. Mechanism of the water-wicking geotextile interaction in soil (Lin et al., 2017; Guo et al., 2017).

Laboratory Experiments. Effectiveness of the wicking geotextile to remove moisture from unsaturated soil conditions has been investigated in several studies with the help of small-scale laboratory setup. Azevedo and Zornberg (2013) used the wicking geotextile to remove water accumulated in capillary barriers that form between layers of two different sized porous materials by designing a small soil column test. At different temperatures and relative humidity values, Guo et al. (2017) evaluated the water removal rate of the wicking geotextile from water tanks in a controlled environment. Yuan (2017) concluded by performing repeated plate loading tests that the wicking geotextile increased the subgrade reaction modulus even under drainage conditions.

Wang et al. (2017) simulated a typical road section with artificial rainfall conditions where they observed that water reduction in the soil closer to the wicking geotextile was more than in the soil located farther from the wicking geotextile and they proposed an effective distance concept. Guo et al. (2019b) investigated the AB-3 aggregate with 10% fine particles in the soil column tests and they concluded that the wicking geotextile could effectively remove moisture from a zone ranging from 180 to 250 mm in the aggregate placed above the geotextile.

Lin et al. (2019) performed a series of interface shear tests with the AB-3 aggregate and the wicking geotextile to evaluate the strength properties. They found that the interface frictional angle decreased with the increase of moisture content. Lin et al. (2019) and Azevedo and Zornberg (2013) carried out laboratory tests to determine the Geotextile Water Characteristic Curves (GWCC) as shown in Fig. 6. Lin et al. (2019) found that the curves are different in cross-plane and in-plane directions.

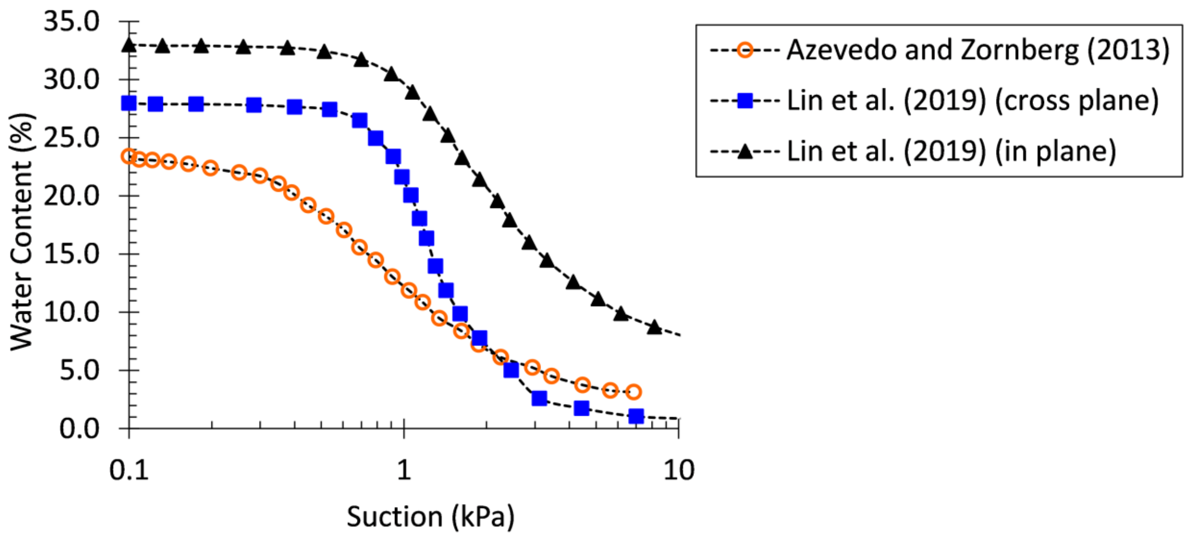

Figure 6. Soil-geotextile water characteristic curve.

Guo et al. (2019a) investigated the surface permanent deformations of test sections with or without a wicking geotextile by cyclic plate loading tests after seven days of the simulated rainfall event and demonstrated the benefits in reducing the surface permanent deformation. Hachem and Zornberg (2019) designed a test setup by placing the wicking geotextile at the interface of the base course and the subgrade with the presence of a constant water table located at the subgrade to examine the moisture removal ability of the wicking geotextile for capillary rise.

Field Test and Monitoring. Lin et al. (2017) investigated the long-term performance of the wicking geotextile to mitigate the frost boil problems in a roadway section in Alaska. They observed that the wicking geotextile was able to reduce the moisture content of the base course below its saturation level by removing water coming from thaw in spring. Bradley et al. (2017) investigated the mitigation of edge cracking in pavement shoulders using the wicking geotextile. They found fewer edge cracks in the test sections with the wicking geotextile than in the sections without the wicking geotextile. Zornberg et al. (2017) presented several case histories of road sections from Missouri, Idaho, Montana, California, and Texas to assess the lateral drainage capability of the wicking geotextile. Lin and Zhang (2018) introduced a bio-wicking system where they used grass on top of the wicking geotextile to enhance the moisture-reduction rate under unsaturated soil conditions. In another study, Lin and Zhang (2019) performed a scanning electron microscopy (SEM) analysis on wicking geotextile samples collected from the field test section. They concluded that the wicking geotextile was still functional after clogging with fine particles, mechanical damage, and aging. Biswas et al. (2021) studied the long-term reinforcement and drainage performance of the wicking geotextile from a field investigation. They placed the wicking geotextile between a base and a subgrade layer and found an effective wicking zone up to 305 mm below the geotextile layer.

CONCLUSIONS

Wicking fibers have been commonly used by the textile industry to manufacture functional performance fabrics to provide comfort to human body. On the other hand, the wicking geotextile uses wicking fibers to absorb and transfer water out of road sections where the wicking mechanism is more complicated than that for the fabrics used by the garment industry. To understand the wicking process of liquid in a fibrous assembly, different methods have been adopted in the textile industry to evaluate wicking behavior including simple laboratory tests to advanced scanning techniques. This paper discussed these methods, liquid evaporation, water transport, and pore structure shape. The second part of the paper focused on the wicking geotextile. The wicking geotextile may be categorized as the functional geotextile as it has outstanding ability to drain water out of soil to prolong roadway life. This paper summarized the test methods in several recent studies to effectively quantify the wicking ability of the wicking geotextile. The benefits of the wicking geotextile as compared with non-wicking geotextiles were compared and demonstrated. Both soil-column tests and field tests showed that the wicking geotextile has an influence zone to effective reduce moisture content of soil. However, the wicking fiber-soil-water interaction is still not well understood; therefore, further studies are required to quantify the benefit of the wicking geotextile in enhancing lateral drainage to soils for future design.

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REFERENCES

Adler, M. M., and Walsh, W. K. (1984). “Mechanisms of Transient Moisture Transport Between Fabrics”. *Text. Res. J.*, 54, 334–343.

Ansari, N., and Kish, M. H. (2000). “The Wicking of Water in Yarn as Measured by an Electrical Resistance Technique”. *J. Text. Inst.*, 91, 410–419.

Ansari, N., Nosraty, H., and Rahmani, H. (2007). “Measurement of capillary spaces of woven fabric by wicking determination of water into samples”. In: *Proceedings of the 9th Asian Textile Conference*. Taichung, Taiwan.

Awano, M., Shirai, M., and Ishikawa, K. (1987). “The attempt to evaluate the water absorption-evaporation behavior of textile fabrics”. *Seni Gakkaishi*, 43, 155–160.
Azevedo, M., and Zornberg, J. G. (2013). “Capillary barrier dissipation by new wicking geotextile”. In: *Advances in Unsaturated Soils Proceedings*. Taylor & Francis Group, London, 559–565.
Biswas, N., Puppala, A. J., Khan, M. A., Congress, S. S. C., Banerjee, A., and Chakraborty, S. (2021). “Evaluating the Performance of Wicking Geotextile in Providing Drainage for Flexible Pavements Built Over Expansive Soils”. *Transp. Res. Rec. J. Transp. Res. Board* 036119812110013.
Bradley, A., Thiam, P., Drummond, S., Murchison, P., and Laprade, R. (2017). “Incorporating a new wicking geotextile in northern, low volume highways to mitigate pavement edge cracking”. *Presented at the TAC 2017: Conference and Exhibition of the Transportation Association of Canada*.
Chatterjee, A., and Singh, P. (2014). “Studies on Wicking Behaviour of Polyester Fabric”. *J. Text.*, 1–11.
Das, B., Das, A., Kothari, V. K., and Fangueiro, R. (2011). “Mathematical model to predict vertical wicking behaviour. Part II: flow through woven fabric”. *J. Text. Inst.*, 102, 971–981.
Fangueiro, R., Filgueiras, A., Soutinho, F., and Xie, M. (2010). “Wicking Behavior and Drying Capability of Functional Knitted Fabrics”. *Text. Res. J.*, 80, 1522–1530.
Ghali, K., Jones, B., and Tracy, J. (1994). “Experimental Techniques for Measuring Parameters Describing Wetting and Wicking in Fabrics”. *Text. Res. J.*, 64, 106–111.
Guo, J., Han, J., and Zhang, X. (2019a). “Large-Scale Rainfall Simulation and Cyclic Plate Loading Test of Wicking Geotextile-Stabilized Base”. In: *Geo-Congress 2019. Presented at the Eighth International Conference on Case Histories in Geotechnical Engineering*, ASCE, Philadelphia, Pennsylvania, 824–832.
Guo, J., Han, J., Zhang, X., and Li, Z. (2019b). “Evaluation of moisture reduction in aggregate base by wicking geotextile using soil column tests”. *Geotext. Geomembr.*, 47, 306–314.
Guo, J., Wang, F., Zhang, X., and Han, J. (2017). “Quantifying Water Removal Rate of a Wicking Geotextile under Controlled Temperature and Relative Humidity”. *J. Mater. Civ. Eng.*, 29, 04016181.
Hachem, A. E., and Zornberg, J. G. (2019). “Enhanced Lateral Drainage Geotextile to Mitigate the Effects of Moisture Migration from a High-Water Table”. In: *Geo-Congress 2019. Presented at the Eighth International Conference on Case Histories in Geotechnical Engineering*, ASCE, Philadelphia, Pennsylvania, 227–234.
Harnett, P. R., and Mehta, P. N. (1984). “A Survey and Comparison of Laboratory Test Methods for Measuring Wicking”. *Text. Res. J.* 54, 471–478.
Hsieh, Y.-L. (1995). “Liquid Transport in Fabric Structures”. *Text. Res. J.* 65, 299–307.
Lin, C., Presler, W., Zhang, X., Jones, D., and Odgers, B. (2017). “Long-Term Performance of Wicking Fabric in Alaskan Pavements”. *J. Perform. Constr. Facil.* 31.
Lin, C., and Zhang, X. (2019). “SEM Analyses on the Long-Term Drainage Performance of a New Wicking Fabric”. In: *Geo-Congress 2019. Presented at the Eighth International Conference on Case Histories in Geotechnical Engineering*, ASCE, Philadelphia, Pennsylvania, 313–321.
Lin, C., and Zhang, X. (2018). “A bio-wicking system to dehydrate road embankment”. *J. Clean. Prod.* 196, 902–915.

Lin, C., Zhang, X., and Han, J. (2019). "Comprehensive Material Characterizations of Pavement Structure Installed with Wicking Fabrics". *J. Mater. Civ. Eng.* 31, 04018372.
Mazloumpour, M., Rahmani, F., Ansari, N., Nosrati, H., and Rezaei, A. H. (2011). "Study of wicking behavior of water on woven fabric using magnetic induction technique". *J. Text. Inst.* 102, 559–567.
Mhetre, S., and Parachuru, R. (2010). "The effect of fabric structure and yarn-to-yarn liquid migration on liquid transport in fabrics". *J. Text. Inst.* 101, 621–626.
Nyoni, A. B., and Brook, D. (2006). "Wicking mechanisms in yarns—the key to fabric wicking performance". *J. Text. Inst.* 97, 119–128.
Parada, M., Vontobel, P., Rossi, R. M., Derome, D., and Carmeliet, J. (2017). "Dynamic Wicking Process in Textiles". *Transp. Porous Media*, 119, 611–632.
Rajagopalan, D., Aneja, A. P., and Marchal, J. M. (2001). "Modeling Capillary Flow in Complex Geometries". *Text. Res. J.* 71, 813–821.
Rossi, R. M., Stämpfli, R., Psikuta, A., Rechsteiner, I., and Brühwiler, P. A. (2011). "Transplanar and in-plane wicking effects in sock materials under pressure". *Text. Res. J.* 81, 1549–1558.
Saricam, C., and Kalaoglu, F. (2014). "Investigation of the Wicking and Drying Behaviour of Polyester Woven Fabrics". *FIBRES Text. East. Eur.*, 22, 73–78.
Wang, F., Han, J., Zhang, X., and Guo, J. (2017). "Laboratory tests to evaluate effectiveness of wicking geotextile in soil moisture reduction". *Geotext. Geomembr.*, 45, 8–13.
Wang, F., Zhou, X., and Wang, S. (2009). "Development Processes and Property Measurements of Moisture Absorption and Quick Dry Fabrics". *Fibers Text. East. Eur.*, 17, 46–49.
Wang, Y., Qiao, Q., Ding, Z., and Sun, F. (2021). "Strain-dependent wicking behavior of cotton/lycra elastic woven fabric for sportswear". *E-Polym.*, 21, 263–271.
Xu, P., Ma, X., Zhao, X., and Fancey, K. S. (2016). "Experimental investigation on performance of fabrics for indirect evaporative cooling applications". *Build. Environ.*, 110, 104–114.
Yanılmaz, M., and Kalaoğlu, F. (2012). "Investigation of wicking, wetting and drying properties of acrylic knitted fabrics". *Text. Res. J.*, 82, 820–831.
Yuan, H. (2017). *Effectiveness of Wicking Geotextile in Mitigating Freeze-thaw Problems of Aggregate Bases with Fines*. University of Kansas.
Zhong, W., Ding, X., and Tang, Z. L. (2001). "Modeling and Analyzing Liquid Wetting in Fibrous Assemblies". *Text. Res. J.*, 71, 762–766.
Zhuang, Q., Harlock, S. C., and Brook, D. B. (2002). "Longitudinal Wicking of Weft Knitted Fabrics: Part I: The Development of an Automatic Wicking Test Method Using Image Analysis". *J. Text. Inst.* 93, 88–96.
Zornberg, J. G., Azevedo, M., Sikkema, M., and Odgers, B. (2017). "Geosynthetics with enhanced lateral drainage capabilities in roadway systems". *Transp. Geotech.*, 12,85–100.