The Hong Kong Polytechnic University
Institute of Textiles and Clothing

Development of Plant Structured Knitted Fabrics

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CERTIFICATE OF ORIGINALITY

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__________________________ (Signed)

CHEN QING (Name of student)

To My Parents and Husband

For Their Loves, Patience
and Support

Abstract

The water and moisture transport properties of textile fabrics are critical to clothing comfort. Clothing should assist the human body to maintain body temperature in a narrow range, and to keep the skin dry under different environmental conditions. Ideal fabrics should therefore prevent the accumulation of sweat on the skin surface by facilitating the transport of sweat away from the skin and evaporation of sweat to the outside environment.

Different approaches have been adopted in developing moisture management fabrics, viz. fabrics that facilitate the transport of liquid sweat from the inner surface to the outer surface. One approach is to make fibers to have non-circular cross-sections. When many of such fibers are spun together into yarns, micro-channels are created for wicking. Another way is to modify the molecular composition of fibers by grafting hydrophilic bond in molecule chain, thereby improving fiber hydrophilicity. Blending hydrophilic and hydrophobic fibers into a yarn or to form a composite core and sheath yarn is another way, which can offset the low drying rate of hydrophilic fibers and the poor water absorption of hydrophobic fibers so as to achieve better moisture absorption and release. Fabric structures can also be optimized to improve moisture management properties. For example, double-layered fabrics made of hydrophobic yarns in the inner layer and hydrophilic yarns in the outer layer help to transport sweat to the outer layer for evaporation and to keep the skin dry; hydrophilic and hydrophobic yarns may be knitted alternatively to form strips in a single-layered fabric. Fabric surfaces in

contact with the skin are raised to speed up the removal of liquid sweat. Besides, fabric surface may also be modified by chemical treatments to enhance hydrophility so as to improve water absorbency.

Recently, the biomimetics of a plants-shaped branching structure in fabrics has been proposed as a potential approach for enhancing the liquid water transport and moisture management properties of fabrics. Woven fabrics mimicking plants-shaped branching structure have been developed and demonstrated improved water absorption and moisture management. Nevertheless, knitted fabrics mimicking plants-shaped branching structure (plant structured knitted fabrics) have yet to be developed. This study therefore aims to explore this novel concept through creative design of knitting structures. In comparison with woven fabrics, plant structured knitted fabrics will have a potential application for sportswear and leisure wear for inherent stretchability as knitted fabrics and enhanced moisture management properties.

It was envisaged that the plants-shaped branching network in plants can be emulated in knitting by grouping several yarns together to form multi-yarned loops at the back side of the fabric (mimicking the stem of a plants), splitting yarns into individual ones to form single-yarned loops at the top layer (mimicking the branching).

With circular knitting technique, the above idea however could not be exactly

implemented, since it is not possible to split yarns in multi-yarn loops at the back side into individual ones, and to directly run to the top side to form single-yarned loops due to the inherent working principle of circular weft knitting. A weft plating knitting structure close to the above idea was therefore developed, in which two yarns were bundled together at the back side to act as main stems, with one yarn running to the top side to form loops. Tuck stitches were also used in circular knitting so as to emulate more branching effects. With Raschel warp knitting techniques, the above idea can be fully implemented.

The developed plant structured knitted fabrics were evaluated in terms of initial water absorption rate by the transplanar water transport tester, in terms of water content retained at the back and the top side of fabrics by the moisture management tester, in terms of air resistance by KES-F8-AP1 and in terms of vapor permeability in accordance with BS 7209.

It was found that both plant structured circular weft knitted and warp knitted fabrics had significantly higher initial water absorption rate and one-way transport property than their corresponding conventional structured knitted fabrics. In other words, the plants-shaped branching network can significantly improve liquid water transport. Additionally, the air resistance values of plant structured knitted fabrics were considerably lower than for those of corresponding control fabrics. The results confirmed that plant structured knitted fabrics can significantly improve liquid water transport and ultimately the comfort properties of fabrics.

The enhanced water transport properties of plant structured knitted fabrics could be the combined effects of following possible factors: (a) the yarns at the top side are individual, and therefore more area is exposed to air, it is easier for water in yarns at the top layer to evaporate; (b) the evaporation at the top layer creates the "cohesion-tension mechanism" to pull liquid water underneath; (c) the running of yarns from the bottom layer to the top layer creates a continuous water channel; (d) pores at the bottom layer are larger than those at the top layer, creating a net directional capillary force to drive liquid water from the bottom layer to the top layer; (e) the branching network reduces flow resistance from the bottom layer to the top layer.

List of Publications from the Study

Referred Journal papers

1. Chen, Q., Fan, J., Sarkar, M., and Jiang, G. Biomimetics of Plant Structure in Knitted Fabrics to Improve the Liquid Water Transport Properties, Textile Research Journal, Vol. 80(6): 568-576. 2010
2. Chen, Q., Fan, J., Sarkar, M., and Bal, K. Plant Based Biomimetic Branching Structures in Knitted Fabrics for Improved Comfort Related Properties, Textile Research Journal, Vol. 81(10): 1039-1048. 2011
3. Chen, Q., Fan, J., Sarkar, M., Biomimetics of Branching Structure in Warp Knitted Fabrics to Improve Water Transport Properties for Comfort (submitted to Textile Research Journal)

Conference Papers

1. Chen, Q., Fan, J., Sarkar, M., and Jiang, G. An Investigation of Water Transport properties of Rib Based Knitted Fabrics, The 86th Textile Institute World Conference, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong. 2008
2. Chen, Q., Fan, J., and Sarkar, M. Experimental Studies on Liquid Water Transport of Plant Structured Knitted Fabric, The Fiber Society's Fall 2009 Technical Conference and Annual Meeting, Athens, Georgia, USA. 2009
3. Chen, Q., Fan, J., and Sarkar, M. An Investigation of Water Transport Properties of Warp Knitted Fabrics in Plant-based Structures, The Fiber Society’s Spring

2011 Technical Conference and Annual Meeting, The Hong Kong Polytechnic University, Hong Kong. 2011

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1. Introduction

1.1 Background

Sweating serves a means of thermoregulation by creating a cooling effect through the absorption of the latent heat of evaporation of water. Hence, in hot weather, as the environmental temperature approaches the body temperature, or when the individual's muscles heat up due to exertion, it may become impossible for the body to lose heat by dry heat transfer, since dry heat flows from hotter regions to cooler ones. When the environmental temperature rises above 37℃, heat may even flow from the environment toward the body. Under such conditions, the body must call upon evaporative cooling so as to maintain heat balance.

The body experiences evaporative cooling by means of two processes: insensible perspiration and sweating. Insensible perspiration is the continual drying out of the skin as moisture moves from the skin surface into the environment. Insensible perspiration is not dependent on physical activities. Sensible perspiration is commonly known as sweating.

In general, sweating is largely caused by a rise in core temperature, but is affected by the increase in the skin temperature. Sweating reduces the core temperature, whereas the evaporation of sweat decreases the surface temperature. It is critical to remove sweat from the skin to retain a normal body temperature and increase the comfort.

The water and moisture transport properties of fabrics are essential to clothing comfort. Some studies have revealed that the water and moisture transfer rate of the clothing materials is an important factor affecting the thermoregulatory responses of the human body (Zhang, 2001; Park, 2006). Ideally, fabric which offers good comfort to the body should maintain a uniform body temperature under different temperature environments and prevent the accumulation of sweat on the skin surface by allowing the respired body water to pass to the outside environment when activity level increases.

A large number of studies have been conducted on the development of moisture management fabrics. Generally, they improved or achieved moisture management properties in five ways. Approaches include:

1. Changing fiber cross-sections to enhance wicking capacity.
2. Grafting hydrophilic bonds in molecule chain to improve the hydrophilicity of fibers.
3. Spinning hydrophilic and hydrophobic fibers into blended yarns.
4. Placing hydrophilic and hydrophobic yarns into two surfaces of fabrics.
5. Changing surface hydrophilicity properties by chemical treatment.

To facilitate the absorption of the perspiration of wearers, garments can be made of a textile fabric consisting of natural fibers, such as cotton, silk or linen, or by a blend of natural and synthetic fibers. Such garments, though they can absorb perspiration from the skin, can not quickly disperse moisture away from the skin. Once this kind of garment absorbs perspiration, a period of time is required to evaporate moisture, thus the wearers will feel cold and clammy.

Hence, to overcome this disadvantage, hydrophilic synthetic fiber has been widely used in sportswear for fast moisture absorption and evaporation rate. Such fibers are often made in irregular cross sections to enhance wicking. Also, hydrophilic and hydrophobic blended yarns at the optimized blending ratio were invented to absorb water and maintain comfortable touch with the skin. In terms of fabric structure, many researchers apply two layers or spacer structure by using different fiber and yarn fineness in different layers. Laminated fabric may impede movement because it is very hard, and it also affects the sense of comfort. It is also worth noting that chemical treatment is another way to modify fabric absorption properties, but poor washing stability is a drawback. Another common approach is to modify fabric properties by coating or lamination by using various polymers.

Recently, plant structured fabrics have been developed by mimicking the branching structure of natural plants. Plants have exceptional water transport properties, and the amount of water transpired by plants is much greater than evaporation from an uncovered water surface. In plants, water is raised through osmosis, capillary action and the cohesion-tension mechanism (Stern, 2000&2003). In addition, the plants-shaped (branching) network creates a minimum resistance to fluid flow between a point (or source) and volume (or area) (Bejan, 2000). It is therefore envisaged to mimic the plant structure in textile fabrics to improve their liquid water transport properties.

Fan et al. (2007) first reported on plant structured woven fabrics. Subsequently, some novel woven structures (Sarkar et al., 2009a & 2009b), which emulate the branching structure of plants, were invented by Fan and his co-workers. These novel fabrics exhibited faster liquid water transport and better moisture management properties than that of fabrics with conventional structures.

A review of literature revealed that no research has been done to simulate the plant branching network in knitted fabrics though a number of moisture management knitted fabrics have been developed using different methods and commercialized.

1.2 The objectives of the project

In view of the above, the present project set out to extend the concept of mimicking plant structured branching networks into knitted fabrics. Unlike previously developed plant structured woven fabrics, plant structured knitted fabrics have an advantage for use in sportswear for the inherent extensibility of knitted structure.

The goal of this research was

1. To apply this new concept to produce innovative products, involving the emulation of branching networks in the planar direction of knitted fabric. Prototypes were fabricated using the available knitting technology (circular or warp knitting). Since branching networks have low water transport resistance and high water evaporation rate, plant structured fabrics will improve water transport in the planar direction of fabrics to remove sweat on the body to the outside, leading to enhanced comfort, especially in summer or sporting environments.

2. To study the effect of knitting structure on water transport and analyze the possible mechanism of liquid water transport in knitted fabrics. The liquid water transport properties, water vapor permeability and air resistance of the developed fabrics were therefore tested to objectively evaluate the developed fabrics. The possible mechanism of liquid water transport in novel plant structured knitted fabrics were also studied.

1.3 Project significance

The liquid water transport and moisture management properties of textile materials are very important to the comfort of clothing and there is a great deal of research involved in the improvement of comfort of fabrics and clothing. Thousands of new products have been developed based on these research results. The fabric structures are as important as other factors in the improvement of clothing comfort. However, literature on the effect of fabric structures upon clothing comfort is lacking; only a limited number of studies have been directed towards the effect of construction on liquid water absorption and moisture transport properties.

This project should improve our understanding of the effect of knitting structure on liquid water transport and moisture management properties. The plant structured knitted fabrics to be developed can be applied in sportswear, underwear, footwear, mattress, etc for its improved liquid water transport and moisture management properties.

1.4 Methodology

Since the purpose of this study was to develop plant structured knitted fabrics, knitting approach was adopted, focusing on circular and warp knitting techniques. We aim to achieve the grouping of two or more yarns to form one multi-yarned loop at the inner side and separating them into single yarn to form two or more individual single-yarned loops at the outer side of fabrics.

Two liquid water transport tests, namely Transplanar Water Transport Test (TWTT) and Moisture Management Test (MMT), were used to test fabric liquid water transport properties. Air resistance and water vapor permeability were also measured as additional parameters related to the comfort in evaluating the performance of the developed fabrics.

The significances of differences in terms of measured properties between controls and the developed plant structure fabrics were analyzed statistically using SPSS 16.0.

1.5 The overview of thesis

The chapters of this thesis are organized as follows:

Chapter 1 Introduction: the current chapter. This chapter introduces the rationale, objectives, methodologies and significances of this study. Besides, the outline of this thesis is also given.

Chapter 2 Literature Review: this reviews the achievements, and presents limitations and gaps of earlier work in the relevant disciplinary areas, so as to present the general understanding of background. This determines knowledge gaps and identifies research objectives and significances.

Chapter 3 Methodology: this describes the methodologies adopted in detail. This study demonstrates the findings in terms of the initial water absorption rate, one-way water transport, water vapor permeability and air resistance of plant structured knitted fabrics and conventional structured fabrics.

Chapter 4 Development of weft plating structures to emulate the branching network of plants: weft plating knitting technique is developed to fulfill the project aims. The results are reported and compared with conventional structured fabrics.

Chapter 5 Development of weft tucking structures to emulate the branching network of plants: weft plating tucking stitch is used to achieve plant knitting structures. Also, the results are reported and compared with conventional structured fabrics.

Chapter 6 Development of warp knitting structures to emulate the branching network of plants: warp knitting is utilized to mimic plant branch networks. The results are reported and compared with conventional structured fabrics.

Chapter 7 Mechanisms of liquid water transport through knitted fabrics with branching network: this chapter investigates a possible mechanism of water absorption in plant structure knitted fabric.

Chapter 8 Conclusions: this presents general conclusions, limitations and suggestions for future work.

2. Literature review

2.1 Introduction

From Chapter 1, it is clear that the research and development of plant structured knitted fabrics involves the knowledge of liquid water transport theory and techniques for fabricating such fabrics.

In the present chapter, I will therefore examine the literature relevant to the stated objectives. In so doing, a theoretical foundation will be provided. I will first draw upon the literature dealing with liquid water transport, including wetting and wicking in fibrous materials. Then the development of moisture management fabrics will be focused on, specifically those related to knitted fabrics. Thereafter past work in biomimetic textiles including the woven plant structured fabrics will be reviewed. Finally the past literature and highlight research gaps relevant to the primary aims of this study will be summarized.

2.2 Wetting and wicking in fibrous materials

Liquid transport in fabrics occurs in a wide variety of situations, including the initial contact of a dry fabric with liquid, liquid flow through a fully saturated medium, and the removal of liquid from a fabric. The moisture transfer in fabrics includes wetting and wicking (Kissa, 1996).

In the process of liquid movement in a fibrous medium, firstly liquid must wet fiber surface, this is termed wetting; secondly liquid can be transported by means of capillary action, this is termed wicking (Patnaik et al., 2006). During sweating, the transport of liquid water is very important for wearer comfort.

2.2.1 Wetting

Wetting is a complex process. It is further complicated by the structure of fibrous assembly e.g. yarns, woven/nonwoven/knitted structures, and pre-forms for composites (Patnaik et al., 2006).

There is a distinction between two terms: ‘wetting’ and ‘wettability’. The wetting of a solid surface is the condition resulting from its contact with a specified liquid. Wettability is the potential of a surface to interact with liquids with specified characteristics (Miller, 1977). It is the initial behavior of a fabric, yarn, or fiber when brought into contact with a liquid (Harnett & Mehta, 1984). Wetting involves two terms: surface tension and contact angle of materials.

2.2.1.1 Surface tension

Surface tension and surface energy are the interaction between the forces of cohesion and the forces of adhesion which determines whether wetting or not, as well as decides the spreading of a liquid over a surface of solid.

The Young-Dupre equation (Adam, 1964; Adamson and Ling, 1964; Miller and Young, 1975; Miller, 1977) is commonly used to express forces in equilibrium, viz.

$$\gamma_{SV} - \gamma_{SL} = \cos\theta * \gamma_{LV} \qquad (2\text{-}1)$$

where γ_{SV} is the solid-vapor surface tension, γ_{SL} is the liquid-solid surface tension, γ_{LV} is the liquid-vapor surface tension, and θ is contact angle between the liquid drop and the surface of solid to be wetted.

2.2.1.2 Contact Angle

Contact angle serves as a convenient means for visualizing and describing the geometry of solid–liquid contact (shown in Figure 2-1). Contact angle is the angle between the liquid–vapor (air) interface and the solid–liquid interface (Miller & Young, 1975; Miller, 1977; Saville, 1999).

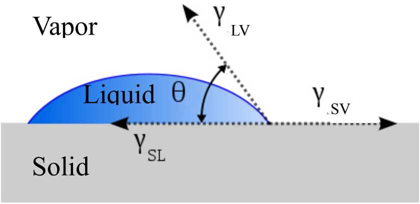


Figure 2-1 Contact angle

The theoretical description involves: the liquid phase of the droplet (L), the solid phase of the substrate (S), and the gas/vapor phase of the ambient (V).

$$\cos\theta = \frac{\gamma_{SV} - \gamma_{SL}}{\gamma_{LV}} \qquad (2\text{-}2)$$

Where θ is the equilibrium contact angle, this means that although the difference between the liquid-solid and solid-air surface tension ($\gamma_{SV} - \gamma_{SL}$) is difficult to measure directly, it can be inferred from the easily measured contact angle, if the liquid-air surface tension (γ_{LV}) is known.

If γ_{SV} is larger than γ_{SL} , then cos θ is positive, and contact angle θ must be between 0 ° and 90° . If γ_{SV} is smaller than γ_{SL} , then contact angle must be between 90° and 180° . With increasing wettability, contact angle decreases and cos θ increases.

2.2.2 Wicking

Water transport in fabrics includes both the diffusion of water vapor and wicking of liquid water processes. At a low water content level, water vapor diffusion is a major mechanism, and it is mainly related to fiber hygroscopicity and fabric porosity. At a high water content level, wicking is a dominant mechanism; it is the spontaneous transport of liquid driven into porous system by capillary forces.

2.2.2.1 Capillary action and capillary pressure

Capillary action is the ability of a narrow tube to spontaneously draw liquid water upwards against the force of gravity (Bear, 1972; Adler and Walsh, 1984). It occurs because of inter-molecular attractive forces between liquid and solid surrounding surfaces; if the diameter of tubes is sufficiently small, the combination of surface tension and forces of adhesion between liquid and container act to lift liquid.

The transport of liquid water into a fibrous assembly, or into textile fabric, can be caused by the external forces like capillary forces. It causes the pressure difference across the liquid - vapor interface which results in capillary pressure for liquid water transport. The capillary pressure occurring in capillary tube (shown in Figure 2-2) is related to the surface tension of liquid-vapor, contact angle and the radius of the capillaries, viz.

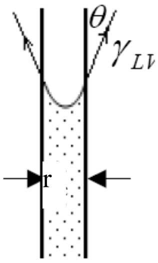


Figure 2-2 Capillary tube

$$P = \frac{2\gamma_{\mathrm{LV}} \cos\theta}{r} \qquad (2\text{-}3)$$

where P is the capillary pressure developed in a capillary tube of radius r, γ_{LV} is the liquid-vapor surface tension, θ is contact angle at the solid-liquid-air interface, and r is the radius of the capillary tube.

The gravitational force limits the height of wicking when a tube is kept vertical until the weight of liquid balances the capillary force (Adamson, 1967; Batchelor, 1967). The equilibrium height may be determined by

$$h = \frac{2\gamma_{\mathrm{LV}} \cos\theta}{rg\rho} \qquad (2\text{-}3)$$

where γ_{LV} is liquid-air surface tension, θ is contact angle, ρ is density of liquid, g is acceleration due to gravity, and r is the radius of a tube.

2.2.2.2 Vertical wicking and transverse wicking in textile assembly

The theoretical description of capillary flow into a fibrous assembly is usually considered as consisting of a number of parallel capillaries. Two types of wicking are: longitudinal wicking and transverse wicking (Ramachandran & Kesavaraja, 2004). The longitudinal wicking distance travelled along a capillary by a liquid in time t is given by

$$h = \left(\frac{rt\gamma_{\mathrm{LV}} \cos\theta}{2\eta} \right)^{0.5} \qquad (2\text{-}4)$$

where γ_{LV} is the liquid-air surface tension, θ is contact angle, η is viscosity of angle, r is the radius of tube, and t is time.

Transverse wicking is important as it removes liquid sweat from the skin during perspiration. This wicking behavior is important for clothing during strenuous body activities. Good transverse wicking is especially desirable for sportswear. The measurement of this wicking is much more difficult than that of the longitudinal wicking, as distance involved in this wicking is very small and the time taken to transverse in the thickness of fabric is very short.

According to the capillary action equation, if the contact angle (0° $<\theta<$90°) or the capillary radius become smaller, capillary pressure become greater. Fabrics or fibers have the pores of different size, and they are interconnected so that water is not transported uniformly along the straight line of capillary tubes. Moreover, this equation assumes that water is continuously supplied, whereas the volume of water is limited in actual practice. If a finite volume of water is supplied to fabrics, the contact angle hysteresis and the dynamic nature of contact angle should be considered for water transport. After water is initially absorbed by fabrics, it moves from the large capillary into the small capillary. The net pressure between capillaries for water transport is obtained:

$$\Delta P = P_A - P_R = \frac{2\gamma_{\mathrm{LV}}\cos\theta_A}{r_A} - \frac{2\gamma_{\mathrm{LV}}\cos\theta_R}{r_R} \qquad (2\text{-}5)$$

where γ_{LV} is the liquid-air surface tension, θ is contact angle at the liquid-solid-air interface, r is the radius of capillary, R is large capillary, and A is small capillary.

If there is no contact angle hysteresis ($\theta_A = \theta_R$), all of water will move into the small capillary because P_A is greater than P_R. However, if there is a contact angle hysteresis, as water moves into the small capillary A, for example, θ_R is smaller than the θ_A, the net capillary pressure determines water flow. If the net capillary pressure approaches zero, water transport will stop. The above equations provide the theoretical explanation for water transport in fabrics, but they are based on ideal capillaries.

The fiber shape and arrangement which determine capillary size and continuity influence liquid water transport. The surface property like roughness also influences the rate of water transport. Therefore, fiber crimp, fiber denier, and yarn size are dominant factors for water transport. Due to the interconnected pores of different sizes, the fibrous structure has a significant influence on water transport through fabrics. Fabric structure which determines the capillary size and the distribution of water within fabrics imparts the amount of water absorbed by fabrics. The external factors such as pressure and the amount of water initially held in fabrics also had a great influence on the transfer of wicking properties.

This section has reviewed the main theories of liquid water transport, including wetting and wicking in fibrous material. The next section examines the past developments of textiles with moisture management function.

2.3 Textiles with moisture management properties

Moisture management fabrics (MMF) can be defined as “the controlled movement of water vapor and liquid water (perspiration) from the surface of the skin to the atmosphere through the fabric” (Cotton Incorporated, 2002).

Many moisture management fabrics have so far been developed, thanks to the advancement in textile manufacturing technologies. The moisture management function may be achieved through physical or chemical modifications of fibers, yarns and fabrics.

2.3.1 Moisture management fibers

Many synthetic fiber products are marketed for providing moisture management function. For example, Coolmax®, Coolplus®, Moira TG 900® (Saneco, 2009; Moira® , 2009), Topcool® (Modified PET, 2009), SecoTec®, CoolTech®,Coolcel®®, Aerocool®, Technofine®, Hygra®, Coolmax®, EasTlon®, Icool®, SofiDry, Texcare®, Lenpur®, Coolnice®, and Cool Dry®.

Constant efforts have been made by synthetic fiber manufacturers to impart moisture and water absorbing properties to synthetic fibers. Roughly classified, these efforts have been directed toward two methods: making polymer itself water-affinitive (incorporating hydrophilic co-monomer into the hydrophobic polymer); rendering fiber surface water-affinitive through a post-spinning treatment (creating special irregular cross-sections).

2.3.1.1 Spinning treatment of synthetic filaments

Cross-sectional approach

There could be cross-shaped, H-shaped, Y-shaped, W-shaped, I-shaped or five-star cross sections, or honeycomb paths, which create channels for the removal of liquid sweat from body, making wearer feel cooler and more comfortable. Figure 2-3 shows the five star cross section of MOIRA TG 900® fiber (Saneco, 2009; Moira®, 2009).

Figure 2-3 The five-star cross section of MOIRA TG 900®

To replicate some of the advantageous properties of natural fiber such as wool and cotton, polyester filaments with a unique hexachannel cross-section were produced (Aneja, 2000b). Figure 2-4 shows the unique hexachannel cross-sections.

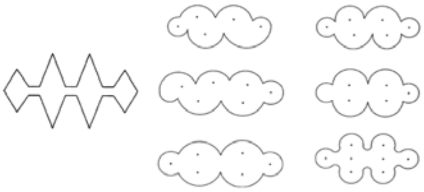


Figure 2-4 Hexachannel cross-section

The liquid water transport properties can be improved by longitudinally-grooved fibers with scalloped-oval cross-section (Aneja, 2000a), as can be seen from Figure 2-5.

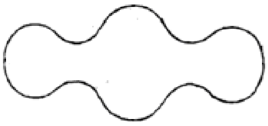


Figure 2-5 Scalloped-oval cross-section

Doi et al. (2002) reported a synthetic fiber with excellent moisture-absorbing/releasing properties. The cross-sectional shape of fiber can vary, for example, circular, triangular, L-shaped, T-shaped, Y-shaped, W-shaped, flat-shaped, dog-bone shaped, hollow or indefinite.

Lancaster (2005a & 2005b) invented a profiled polymer filament with an open hollow cross-sectional shape along the longitudinal axis of filament (see Figure 2-6). The cross-section was dimensioned to prevent the filament from interlocking with other filament of the same cross-section. Fabrics constructed of the filaments showed an advantage in the wicking of water over identically constructed fabrics made of filaments having circular cross section.

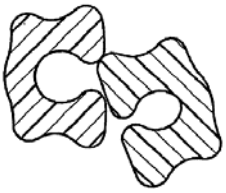


Figure 2-6 Profiled polymer filament

Hietpas et al. (2007) invented a scalloped oval cross-section shape in a ratio a: b of 2:1 to 5:1 shown in Figure 2-7 (“a” is a fiber cross-section major axis length; “b” is a fiber cross-section minor axis length).

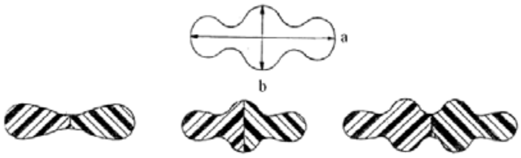


Figure 2-7 Scalloped oval bicomponent fibers

Split-type micro-fibers

Fabrics, treated to have split-type micro-fibers, contain numerous capillaries, and hence can absorb sweat and transport moisture rapidly. Lee et al. (2004) developed such a high absorptive synthetic fiber. Fabrics made of this fiber were exposed to an alkaline solution in combination with thermal and mechanical treatment. Split type micro-fiber fabrics can be formed by separating bi-component filaments.

Core-sheath fiber

Umino et al. (2004) developed a moisture management synthetic fiber with two components: one component capable of absorbing and non-absorbing moisture was a modified polyalkylene oxide and another was a fiber-forming polymer. This fiber had the structure of a core-sheath type. First compound was located in a core portion, and second compound is as a sheath.

2.3.1.2 Synthetic fibers incorporating hydrophilic co-monomers

Because of the inherent, hydrophobic nature of many synthetic fibers, such as polyester, polypropylene etc, fabrics formed entirely from these synthetic fibers exhibit poor moisture absorption properties. Hydrophilic co-monomers have been incorporated into polyethyleneterephthalate to provide hydrophilicity, but at the expense of other fiber properties.

Graft polymerization of hydrophilic vinyl monomers onto hydrophobic substrates is a permanent treatment. The treatment of polyester materials with reducing agents such as lithium borohydride or various oxidizing agents, although it is fairly effective, imparts a relatively high cost to finished materials. Both acid and base treatments of polyester materials have been described, but the improvement in hydrophilicity is offset by a significant loss in fabric strength due to the hydrolysis of linkages.

Delcron® Hydrotec fiber (Hydrotec fiber, 2009) is another example of such approach. This is an engineered hydrophilic synthetic performance fiber. It is designed to provide bonding sites to attract water molecules. Thus fibers absorb moisture from the skin and transport it to fabric surface where evaporation occurs at a faster rate.

To sum up, researchers utilized the modification of cross-section, fineness or graft branch to achieve the improved hydrophilic properties of synthetic fiber. Next subsection reviews moisture management products developed through yarn modification.

2.3.2 Moisture management yarns

Several approaches are known for processing hydrophilic fabric, e.g. cotton, into fast drying type. The drying rate of cotton fabrics with reduced thickness turns to be equal to that of polyester fabrics. Other solutions employed the use of the blend of cotton and synthetic material, e.g., cotton/polyester, cotton/nylon, or cotton/ polypropylene. Moreover, core-sheath yarn, textured or crimped yarn are moisture management yarn from the point view of changing yarn structure. In addition, composite yarns have also been developed for making moisture management fabrics. These novel yarns yield fabrics that quickly absorb perspiration from a wearer’s skin and release that moisture, resulting in the surprising levels of wearer comfort and wearer preference.

2.3.2.1 Core- sheath yarns

Okada (1986) produced a textile fabric utilizing cored yarns. The core yarn comprised thread wadding in a bundle of inner hydrophilic fibers, and a thread sheath in the outer hydrophobic fibers arranged on the exterior of thread wadding. The outer fibers had high moisture permeability and low water retention, and the inner fibers were encompassed by the outer fibers at a predetermined thickness, which permitted expansion upon the absorption of water or moisture vapor.

Based on the previous research on core-sheath yarn, Peters and Fay (2003) produced a gradual transition between different fibers in core-sheath yarn which also comprised hydrophilic fibers embedded at the yarn center within a matrix of hydrophobic fibers. The transition began at the center of composite yarns where hydrophilic fibers were concentrated and progressed to the outermost layer where hydrophobic fibers predominated. The fibers produced by these researchers are shown in Figures 2-8 and 2-9.

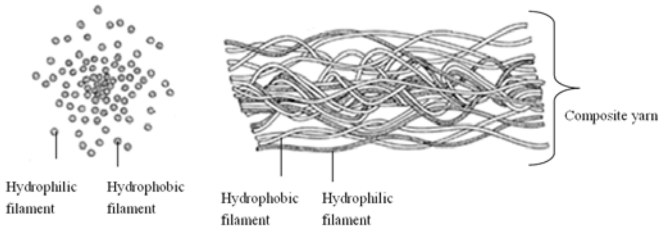


Figure 2-8 Hydrophobic/hydrophilic fiber distribution within the composite yarn of a cross-section view

Figure 2-9 The composite yarn plied with one or two multifilament hydrophobic yarns

2.3.2.2 Crimping textured yarns

Using crimping method such as false twist method, stuffing crimping method, and jet stuffing by hot jet of heated fluid, synthetic fiber with absorbing and non-absorbing component can absorb water and transport water through voids between yarns (Umino et al., 2004). Besides, the polyamide series fiber had higher boiling water shrinkage than polyester fiber in this yarn. After heat treatment in dyeing process, loops and voids formed by mainly polyester monofilaments were forced to appear on the surface of polyamide fiber. Therefore the entangled and mixed yarn can provide high water absorption capacity.

2.3.2.2 Blended yarns

To reduce the water absorption of hydrophilic fibers or offset the water absorption of hydrophobic fibers in a material, blending them together is a normal approach to produce yarn with improved water absorption and drying rate.

Blending yarn with different material

Katz and Del (1999) blended 85 to 90 % hydrophobic fiber in weight and 10 to 15 % hydrophilic fiber in weight into a yarn. Fabrics with these yarns, which exhibited a combination of properties strongly, were preferred by wearers, as compared even to fabrics made of yarns containing only 5% more, or 5% less, of hydrophilic fiber.

Cotton blended yarn composed untreated and water- repellent treated cotton fiber (Cotton Incorporated, 2002). This yarn can reduce the absorbent capacity of cotton fiber and maintain wicking properties.

Hietpas et al. (2007) provided a spun yarn comprising cotton and polyester bi-component staple fiber with a scalloped oval cross-section shape to improve the liquid water absorption properties of this yarn.

Blended yarns with different denier

Aneja (1999 and 2000) produced a copolyester filament by mixing the different denier of longitudinally-grooved fibers with scalloped-oval cross section. Wicking rates and drying rates for fabrics of mixtures increased, according to the invention in contrast to the fabric of yarns of single denier fiber.

2.3.3 Moisture management fabrics

There have been many developments in moisture management fabrics through different techniques including weaving, knitting, nonwoven, laminating and bonding. Since this study is about knitted fabrics, this review focuses on knitted structures with moisture management function. Single-layered, double-layered, spacer and multi-layered moisture management fabrics are covered in this sub-section.

2.3.3.1 Circular weft knitted fabrics

2.3.3.1.1 Single-layered circular weft knitting structure

In general, most single layer moisture management fabrics were produced with moisture management filament or yarn knitted into conventional structure, such as plain weft knitting structure or basic tricot warp knitting structure.

In addition, some modifications of single-layered knitting structures have been invented. Miller and Cravotta (2004 & 2006) developed a fabric which was formed from the filamentary yarns and spun yarns of similar synthetic materials having the same denier. Alternative courses were knitted between a filamentary yarn and a spun yarn. One course consisting of only one filamentary yarn was followed by one course consisting of only one spun yarn. The combination of different yarn could enhance the liquid transport in fabrics. Figure 2-10 gives a fabric knitted with different yarns.

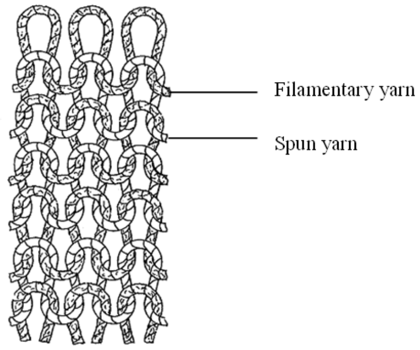
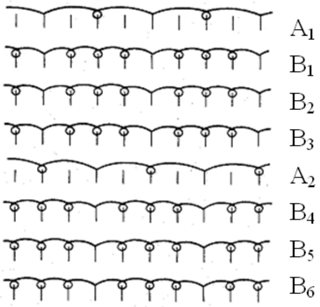


Figure 2-10 The knitted fabric comprised alternating courses of filamentary and spun yarns

Lubos and Ludmila (2004) invented a moisture management fabric by creating alternating stripes made of hydrophobic and hydrophilic yarns in a plain single jersey knitting structure. This fabric could facilitate the water spreading in single layered fabrics.

Toda (1988) utilized the combination of fiber fineness and single jersey knitting structure to control the size of the inter-fiber space. The feature in this structure was that inter-fiber space in a yarn comprising a surface layer was smaller than that in a yarn composing a back layer. Figure 2-11 shows the detailed notation of single jersey structure.



Yarns B_1 to B_6 were in the outer surface layer, floating yarns $A_1$and A_2 were in the back layer. B_1 to B_6 were polyester false-twist textured yarns of 150 total denier composed of 48 filament, and A_1 and A_2 were polyester false-twist textured yarns of 300 total denier composed of 96 filament.

Figure 2-11 Single jersey structure

2.3.3.1.2 Double- layered circular weft knitted fabrics

Many smart double-layered knitted fabrics have been developed in such a way that their inner face close to the skin has optimal wicking and sensory properties, whereas the outer face of the fabric has optimal moisture dissipation behavior. In addition to high rates of wicking and drying, first-layer knits added air to the roster of features. Traditional knits such as pique, honeycomb of ribbed raise textures trap a certain amount of air between the body and knits. By reducing the contact points between the skin and the garment, air can circulate freely and let the body breathe (Shishoo, 2005).

To obtain different layers using different material, the plating technique of circular knitting was employed based on basic single-jersey or double-jersey structures; double-jersey structures were modified to obtain different surfaces; spacer structure was another general solution to place hydrophilic and hydrophobic material in two surfaces.

Plating circular weft knitted fabrics

Basically, plating technique was comprehensively employed to produce different layers with different materials. Further, some researchers also refined the fineness of fiber or yarn in corresponding layers. With other auxiliary knitting technique, it can offer vertical and horizontal channels in fabrics.

Toda (1988) utilized plating knitting structure in a two-layered structure. The feature of those fabrics in this structure was that the inter-fiber space in a yarn comprising a surface layer was smaller than that in a yarn composing a back layer, because the finer yarn was used in surface layer and coarser yarn was used in the back layer. This could enhance the capillary pressure from inner side to outer side. Figure 2-12 shows the detailed notation of weft knitting.

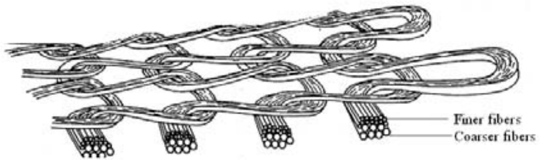


Figure 2-12 The fabric formed by plating method

Rock et al. (2001) reported an anti-microbial enhanced knit fabric. Also, by plating knitting construction, hydrophilic synthetic inner layer and outer layers were formed. The outer layer was blended with treated synthetic fibers with anti-microbial properties. The outer layer was water-absorbent and the inner layer had permanent wicking properties; both layers were integrated and yet had distinct properties due to the two different yarns (Foshee, 2008).

Chesebro (1992) used a plating construction in the partial section of sock to control characteristics. The body yarn was knitted in successive courses in whole sock. A hydrophobic yarn was knitted in plating relationship with the body yarn at the sole section, and hydrophilic yarn was plaited in the instep section where moisture generated by the foot was wicked and transported from the sole to the instep to be evaporated.

In much research of Lumb and Rock, they restricted the weight or fineness of different material of two layers with the aim to optimize water liquid transport properties. Lumb and Rock (1994) applied either a rendered hydrophilic polyester or nylon material as a first layer; at least 25% by weight of total fabric; a moisture absorbent material such as cotton was used in the second fabric layer (see Figure 2-13).

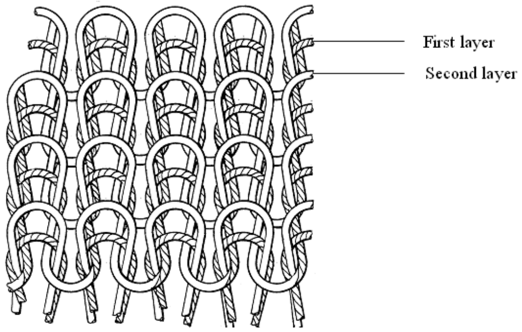


Figure 2-13 A plating construction

In a plated fabric, hydrophilic fiber was located in the inner layer; an outer layer comprised at least 5% by weight of a super absorbent material (Rock and Lumb, 1994). A hydrophilic and microporous barrier layer was deposited on the outer layer. It was claimed the advantage of a barrier layer was that the weight of liquid retained by the absorbent layer was slowly and continually reduced by evaporation without allowing liquid through the barrier layer to wet the outer garments.

Based on their previous work, Rock et al. (1996) optimized and restricted that the fiber's fineness of the inner and outer layer was in a ratio of between 1:1 and 1.45:1. In addition, the yarn's fineness of the inner and outer fabric layer was between about 1:1.10 and 1:5.0. Further, the surface of the inner fabric layer was lightly sanded, brushed or napped in order to slightly raise the fabric surface with softness. Each layer was rendered substantially hydrophilic by chemical treatment.

Rock et al. (2007) also improved thermal insulation of plaited double-knit fabrics. They modified the fiber denier range of the inner layer between 0.7 and 6.0 denier, and that of the outer layer between 0.3 and 2.5 denier. Meanwhile, yarn denier range also was modified between 50 and 150 denier for the inner layer, and between about 100 and 300 denier for the outer layer respectively.

Apart from the formation of two different layers, using knitting a plating construction can provide vertical and horizontal channels in the inner fabric layer with rendered hydrophilic polyester or nylon (Rock & Haryslak, 2002&2005). A moisture absorbent material was placed in the outer layer. Vertical channels were formed by using tipped and tipless sinkers, high and low sinkers; horizontal channels can be created by removing the loop yarn from one or more feeds, or using a shrinkable yarn which could create channels after processing with wet or heat. The inner layer was raised to improve the soft feeling and conduction was enhanced.

Modification of double-jersey circular weft knitted fabrics

Based on conventional simple double- jersey structure, typical pique and honeycomb are induced. Actually, through the diverse combinations of knitting notations, the numerous modifications of double-jersey structure can be generated. The most of these structures with moisture management properties have similar principle in which hydrophilic and hydrophobic yarns can be arranged in different layers.

In the work of Kuznetz (1985), composite fabrics were produced to permit air ventilation by the opening knit mesh construction of double weave or double knitting techniques. Figure 2-14 illustrates schematically the composite fabric and its functions. The inner layer contained hydrophobic synthetic fibers with extremely low moisture content. The outer layer has hydrophilic characteristic and is composed of fibers such as cotton or wool, or synthetic fibers which are highly absorbent.

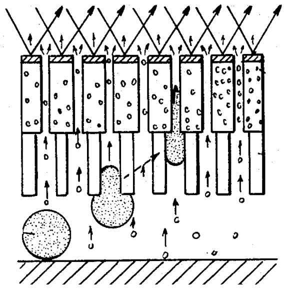


Figure 2-14 schematically illustrates the composite fabric and how it functions

Figures 2-15, 2-16 and 2-17 show the detailed notation of weft knitting developed by Toda (1988). In Figure 2-16, Feeder Nos. 1,3,5,7,9 and 11 for forming a back layer, and Nos. 2,4,6,8,10 and 12 for forming a surface layer. In Figure 2-17, Non-textured polyester multi-filaments were fed to the first and third feeders so as to constitute a face layer. On the other hand, false-twist textured polyester yarns were fed to the second and fourth feeders so as to constitute a back layer.

The purpose was to utilize fiber fineness, knitting structure, or yarn type order to control the size of the inter-fiber space of each layer in a multi-layered structure. The feature of those fabrics in structure was that the inter-fiber space in a yarn comprising a surface layer was smaller than that in a yarn composing a back layer.

Figure 2-15 Circular knitting notation

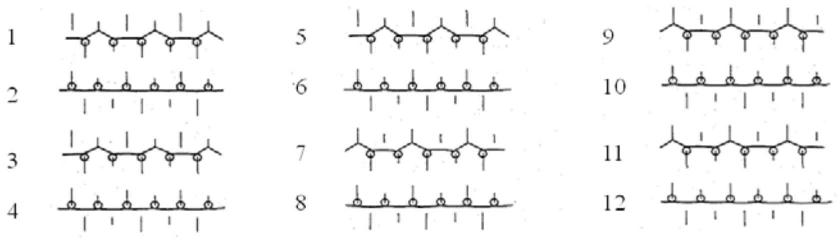


Figure 2-16 Circular knitting notation

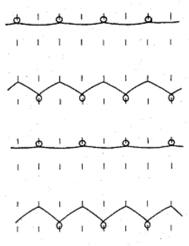


Figure 2-17 The knitting notation of double-faced fabric

Strauss and Rankin's (1991) work utilized Swiss or French pique with exposed cotton yarn on one side and a combination of cotton and core spun yarn on the other side. This core spun yarn had a resilient continuous filament yarn covered by a cotton fiber.

To quickly wick perspiration and other body fluids away from the body surface of the user, the hydrophilic fibers of a relatively high denier (not higher than 6D) were placed in the inner layer (Yeh, 1997). On the other hand, to pull perspiration and other body fluids from the inner fabric layer, the fibers of a relatively low denier (not higher than 3D) were arranged in the outer layer.

Riegger (2000) bonded three layers by weft knitting. The middle layer bonded the inner and outer layers together, while the inner layer and outer layer remained independent of each other and retained their respective functions. A pattern also can apply to either or both the inner and outer layer by tucking the middle layer between the inner and outer layers.

Yeh (2002) knitted a rendered hydrophilic inner fabric layer with relative high denier fibers; and a rendered hydrophilic outer fabric layer with relatively lower denier fibers, which was processed by peach sueding finish. Relative lower denier fibers could pull perspiration and body fluids from the inner layer to the outer layer. The two layers were formed integrally and concurrently by knitting. Figure 2-18 shows the fabric of this invention.

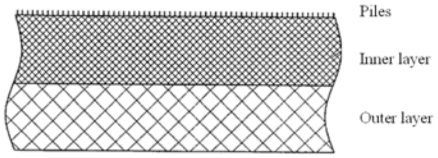


Figure 2-18 Inner, outer layers and piles

Kasdan and Kornblum (2002) developed an irregular pique construction of a double knit. Two feeds used microfiber yarns and the other two used regular non-microfiber yarns. Knitting notation is given in Figure 2-19. The fabric contained at least 40 weight percent microfiber yarn (from 50 to 100 denier with 80 to 120 filaments more) and conventional non-microfiber yarn (from 50 to 100 denier with 25 to 50 filaments), which was worn against an individual's body for maximum moisture absorption with microfilament knit on the face to provide maximum siphon to remove moisture from a wearer's body.

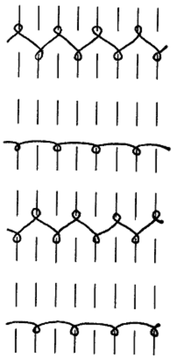


Figure 2-19 An irregular pique construction of a double knit

Of Lee's (2002) fabric, voids in the inner layer were generated by a divided PET/nylon-conjugated fiber after subjecting a double layer fabric to a weight loss finishing process. The outer layer contained ordinary polyethylene terephthalate (PET) filament. The fabric was characterized by external moisture discharge and absorption at a high velocity.

An invention of Yeh (2003) contained the first fibers and the second fibers. The first fibers had either circular cross-sections or multiply indentations along the longitudinal side of fibers. The second fibers had multiply indentations along the longitudinal side of fibers. The capillary action of the first fibers was induced by the inter-fiber spaces or the indentation spaces, while the capillary action of the second fibers was forced by the combination of both inter-fiber and indentations spaces. Since the capillary action of the second fibers was greater than that of the first fibers, the moisture absorbed by the first fibers can be easily transferred to the second fiber. Figure 2-20 illustrates fabric developed by this research.

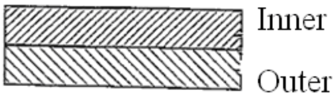


Figure 2-20 Fabric construction

Li et al. (2002 & 2004) invented a composite layer which had an upper surface of small exposed areas of hydrophilic material covering a total area about 25% of the overall area of upper surface. An inner layer, normally positioned adjacent to the body of a user, was predominately a hydrophobic textile material such as polypropylene. In contrast, the outer layer was predominately a hydrophilic material. Figure 2-21 shows knitting instructions they invented.

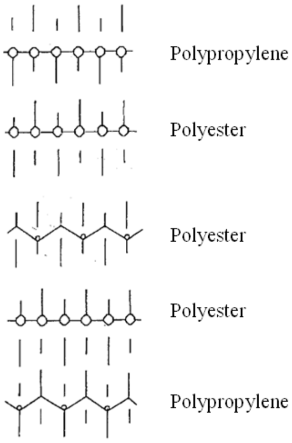


Figure 2-21 Knitting instructions for forming the composite material

Ackroyd and Lai (2009) created a peached surface knitting materials. The transport enhancing material was located in the inner side, while the evaporation impeding material was spaced away from body. Peaching process was employed to create a capillary web system in the inner side.

Circular spacer structure

Pernick (1998) used spacer yarns to wick moisture from hydrophobic layer to hydrophilic layer. Spacer yarns were knitted into respective knit fabric layers. Hydrophilic layer was coated on its outer side. Many knitting notations used by them are presented in Figure 2-22.

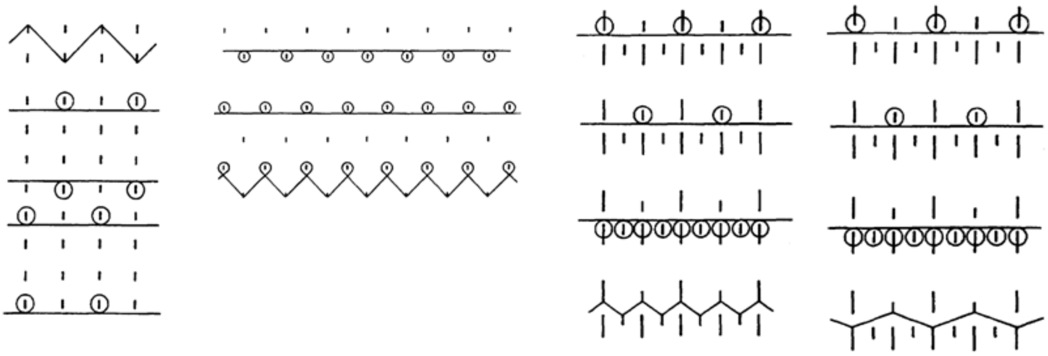


Figure 2-22 Knitting notation

2.3.3.2 Warp knitted fabrics

Substantial products were produced by using Tricot, Raschel warp knitting techniques. The fundamental principles of producing warp knitted moisture management fabrics are also similar with circular weft knitting. Hydrophobic yarns and hydrophilic yarns are respectively arranged in corresponding guide bars. This could provide the inner layer functioning as wicking substrates, and the outer layer functioning as water absorption substrates.

Tricot warp knitted fabrics

Toda (1988) made a single tricot fabric on a 28 gauge tricot warp knitting machine. With the aim to control the size of the inter-fiber space of each layer, 75 D non-textured polyester with 36 filaments, 50 D false-twist textured polyester with 24 filaments and 50D non-textured polyester with 48 filaments were respectively arranged in the front, middle and back guide bars. As a result, the inter-fiber space in a yarn comprising a face layer was smaller than that in a yarn composing a back layer. Figure 2-23 shows the detailed notation of warp knitting.

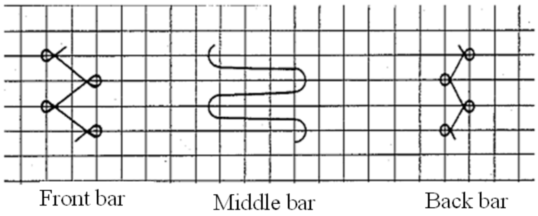


Figure 2-23 A single tricot knitting construction with raising treatment at the back surface of fabric

DeMott et al. (2004) invented a chemically treated polyester micro-denier warp knit fabric at three-bar construction. Multifilament synthetic pile yarns on the technical back were raised or broken to produce a plush surface and monofilament synthetic ground yarns appeared in technical face.

McMurray (2005&2008) placed hydrophilic yarns in the outer layer and micro-denier hydrophobic yarns in the inner layer of tricot warp knitted fabrics. In order to obtain the high performance of moisture transport, wicking finishing was also additionally applied.

Raschel warp knitted fabrics

Byles (1991) developed a Raschel warp knitted fabric, which had a relatively thick, dense liquid retaining absorbent pile layer, a non-absorbent napped layer and an intermediate ground yarn structure(see Figure 2-24). The hydrophobic layer was aimed to wick liquid to hydrophilic layer while resisting return flow leakage.

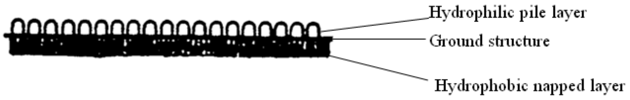


Figure 2-24 A multi-layer moisture management fabric

Warp knitting spacer

Rock and Lohmueller (1998) produced an integrated three-dimensional spacer fabric for bed pads. The fabric included a first fabric layer with fibers rendered hydrophilic, a second fabric layer with hygroscopic fibers, and a resilient yarn interconnection the two layers. Figure 2-25 presents the 3D structure of this kind of fabrics. Particularly, the back hydrophilic layer was obtained by chemical treatment or utilizing modified fibers. Especially the back layer surface was sanded, brushed or napped and comprised a raised surface fabric. Pile yarn, which interconnected the two layers, maybe a monofilament or hydrophilic multifilament yarn.

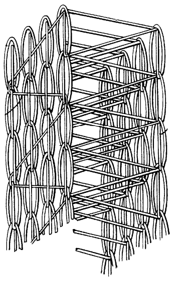


Figure 2-25 3D structure

Miskie (2006&2008) produced a three-dimensional spacer fabric, which had a first hydrophilic layer with fine mesh adapted nearby the skin, a hydrophilic second layer with relatively open mesh, and an intermediate spacer layer interconnecting the first and second layers. It is believed the fine mesh at the inner layer could absorb water effectively, and open mesh could speed up water evaporation.

Shirasaki and Kaneko (2007) developed a three-dimensional warp knitted fabric in which breathability and cushioning property especially were well suited for a motor vehicle seat in a manner that a feeling of stickiness and steaminess when sweating was eliminated. The front face had a smaller number of loops, while the back face had a larger number of loops. The connecting yarns stitched these two ground structures together.

A three dimensional fabric for footwear and apparel was developed by Etchells et al. (2005&2007). One surface was water repellent and includes pores of a predetermined size to allow moisture to pass through. The fabric contained a moisture absorbing agent which functioned to capture and hold moisture. Another surface was dense knitted to absorb moisture from the inner side. Fabrics were accomplished by treating a knitted spacer with a water repellent or water absorbent treatment. Figure 2-26 is the demonstration of footwear fabric.

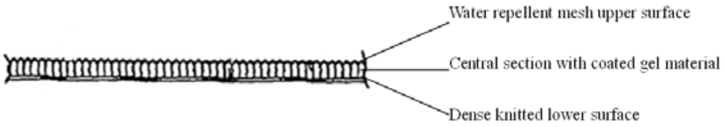


Figure 2-26 Footwear fabric

2.3.3.3 Multi-layered moisture management fabrics

Numerous multi-layered moisture management fabrics have been developed by integrating several single-layered fabrics together as an entire material. Bonding, laminating, coating and stitching are common approaches employed.

By the use of a bonding agent or fusion bonding techniques, Okada (1985) made a sweat absorbent material for outer wears (see Figure 2-27). This fabric contained a water absorbent layer and a water permeable layer which had low moisture absorbency and high moisture permeability.

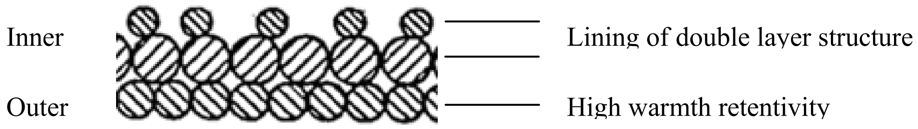


Figure 2-27 Cross-section of a sweat absorbent material for outer wears

Considerable multi-layered fabrics were developed with the purpose to absorb a large amount of water, applied for baby diapers, adult incontinence articles and in particular to sanitary napkins. Due to more fabric layers within this type of fabrics, fabric weight and thickness were higher. That could lead to the high capacity for absorption.

Meyer et al. (1989) developed an absorbent component for a disposable diaper. It contained a liquid permeable hydrophobic top layer, a liquid permeable transport layer and an absorbent hydrophilic body. The top layer had an effective average pore size. A liquid permeable transport layer was less hydrophilic than the absorbent body and had an effective average pore size smaller than the pore size of the top layer.

Moretz and Brier (1993a & 1994a) developed a fabric with the capacity of absorbing a relatively large amount of fluid, like urine, and not wick efficiently and quickly a relatively small amount of fluid, like drops of perspiration, away from the skin (Figure 2-28). A relatively thick inner first layer which was moisture permeable hydrophobic with raising nap for being positioned next to the skin; a second layer which was relatively thin intermediate hydrophilic fabric layer positioned adjacent hydrophobic fabric layer; and a third layer, relatively thick outer hydrophilic fabric layer.

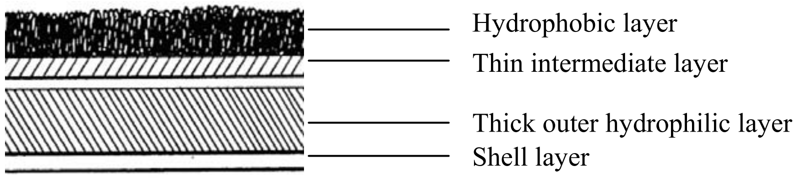


Figure 2-28 Cross-sectional view

Mehawej (2003a & 2003b) developed an absorbent diaper including a composite core made of superabsorbent polymer and a high loft nonwoven web impregnated with the superabsorbent polymer.

Cooper (2005) applied conventional laminating or thermobonding techniques to bond a multi-layer protective fabric. Of the outer layer, an inside hydrophobic layer and an outside layer were knitted together by hydrophobic monofilament yarns. The middle layer was a porous, cushioning material while the inner layer was a cushioning, abrasion-resistant material.

Nishimoto et al. (2002) a employed wet or dry lamination method to produce a moisture-permeable waterproof fabric, which included a base fabric, a moisture-permeable resin layer with a non-porous urethane resin film, and a surface protective resin. The surface protective resin contained a hydrophilic urethane resin as a main component, and organic fine particles excellent in moisture-absorbing and releasing property.

Liner materials were introduced into multi-layered fabrics. Baychar (2001) attached each liner by lamination, mechanical bonding or a combination of them. The inner liner contained foam material layers, breathable membranes, waterproof films and the outer fabric layer. A moisture transfer system was incorporated into in-line skate as either a removable liner for a shell boot or a liner for a softboot. Stefan et al. (2005) also applied the lining as a back layer, using point laminating or the stitch to integrate three layers together.

Rearick and Andersen (2002) present cellulosic substrates comprising an inside and an outside with a reduced absorbent capacity of wicking liquid and an absorbent capacity higher than the inside. An absorbent core made on a continuous air-laid machine was introduced into an absorbent article (Gross et al., 2003). This absorbent core had a discrete wicking layer made with compressible fibers. The low density of a fibrous layer led to effective wicking, located nearby the moisture impervious outer cover.

A stretchable multi-layered material was developed by Fahrenkrug et al. (1989). It included a liquid-previous bodyside layer, liquid-impervious outer layer, an absorbent layer, and a stretchable layer by bonding them (see Figure 2-29).

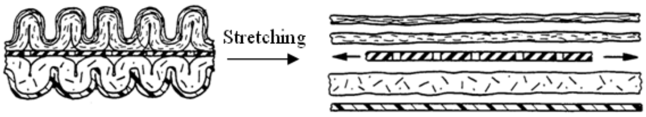


Figure 2-29 Before and after stretching

A polygonal-shaped quilting stitch was employed to stitch two independent layers of a double layer sweater by Murphy (1998) (see Figure 2-30). The hydrophobic outer layer comprised of a blend of wool and acrylic yarn and the hydrophilic inner layer comprised of a synthetic wicking enhanced yarn, such as polyester or acrylic.

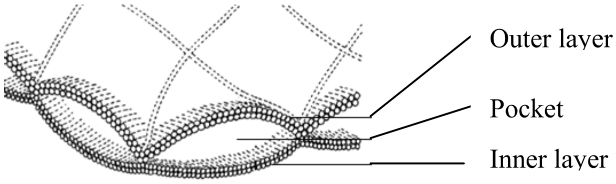


Figure 2-29 A double layer sweater

Apart from the bonding, laminating and stitching techniques, coating was another solution employed in the formation of multi-layered materials. Rock (2008) coated a bound of hydrogel on the outer surface of a plated single jersey or double knit construction by a circular knit or warp knit. Hydrogel exhibited expansion or contraction in response to change in relative humidity or exposure to liquid sweat. As a result, air movement and liquid management in response to different conditions can be adjusted.

In view of the above, fabric structure is an important aspect which previous researchers employed to achieve the aim of moisture management fabric. Generally, moisture management fabrics can be formed as long as two different materials can be separated into the inner layer and outer layer. In this manner, different materials resulted in respective hydrophilic or hydrophobic properties in two layers.

The 2.3 section reviews the products which were developed in previous years. Because there are much research conducted to investigate the effects of parameter of fiber, yarn structure etc. on the moisture management properties of materials. Their work is very essential to provide theoretical basis for developing optimal moisture management fabrics. Therefore, the 2.4 section covers the research on moisture management properties of textiles from four aspects, such as fiber and filament, yarn, fabric and multilayer system.

2.4 Fiber, yarn and fabric parameters affecting the moisture management properties of textiles

Multi-dimensional moisture transfer in textiles is commonly known as moisture management property. Moisture management in clothing fabric typically refers to the transport of both moisture vapor and liquid away from the body of clothing wearer. Many researchers consider the moisture management property of fabrics to be a major contributing factor to its perceived comfort. For instance, during intense physical exercise an individual's perspiration rate increases dramatically over normal perspiration rate. Excreted perspiration in the form of liquid and vapor is absorbed by the inner surface next to the skin. At the outer surface moisture is evaporated into the surrounding environment and/or is accumulated on the outer surface of fabrics. Fabrics possessing desirable moisture management properties impart a dry feeling to the wearer and are extremely desirable for casual wear, sportswear, or personal protective clothing.

The moisture management properties of fabrics are related to several factors: fiber type, fiber dimension, yarn structure, yarn component, fabric structure, fabric thickness, fabric porosity, and hydrophilic or hydrophobic properties material etc. A considerable number of investigations have been carried out to examine the relationship between water transport and fiber properties, fabric/fibrous structural parameters, and construction of clothing systems.

Fabric wicking behavior was dependent on the structure of constituent yarns, their orientation in fabrics, fabric structure, pretension, and force applied (Nyoni & Brook, 2010). The following four sub-sections aim to summarize previous work from the aspect of fiber, yarn, and fabric structure as well as fabric combination in a multi-layered garment system.

2.4.1 Fiber parameters

2.4.1.1 Fiber fineness

Hsieh and Thompson (1996) showed micro-denier PET fabric had higher water retention than regular PET fabric due to more pores. Wettability was improved by micro-denier PET fabric which possessed smaller contact angle. Zhang et al. (1999) investigated that the fineness of polypropylene fiber affected wicking ability, and fine fiber was beneficial for water transport.

Kim et al. (2003) suggested that excellent water absorbency can be achieved by spitting nylon/polyester (N/P) microfibers to yield fine and aligned capillary columns between fibers, and to create larger surface areas. Considering changes in areal density, Kim et al. concluded that water absorption for microfibers occurred not because of hydrophilicity, in the case of cotton, but because of capillary pressure.

Ali (2008) found that PAM nano-fibers showed a huge increase in surface area. The electro-spun PAM/PAN hybrid nano-fibroses fabric absorbed 1077-1290 its original weight. The ratio of absorbed weight and original weight of this fabric ranged from 3.6 to 4.3 times more than commercialized PAM granular.

Das et al. (2008) adopted a vertical wicking tester to measure the vertical movement of liquid along fibers against gravity. Compared with standard denier fabrics, micro-denier filament fabrics increased the wicking properties through fabrics because of a reduction in fiber diameter, but air permeability and water vapor permeability were reduced.

2.4.1.2 Fiber shape

Cotton fibers, with their flat, lima-bean-shaped cross section and ribbon like appearance, would produce very irregular capillaries within yarn that could inhibit fluid flow (Das, 2007).

The wearing comfort and performance of garments made using multi-porous water absorbent acrylic fibers were measured (Kenji, 1984). The results of this acrylic fiber were compared with those of cotton, wool and regular acrylic fibers, multi-porous water absorbent acrylic fibers easily diffuse water and dry.

Zhang et al. (2006) claimed noncircular fibers (see Figure 2-31) had a convergence in the low radius value range compared to the other three (triangle, square, round). Sfen has 33 capillaries, Swon has 27, and Scri has 19. It was acquired the sequence of wicking height ability shown as Sfen > Swon > Scri > triangle >square > round. Shapes of Sfen and Scri had much better integrative capillary effect for hydrophobic polyester bundle. Concave polygon shape was advantageous for surface driven flow in fiber bundle because of grooves.

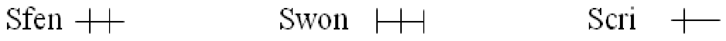


Figure 2-30 Noncircular fibers

Loua et al. (2007) found that the increasing percentages of polyester-textured filaments with Y-cross section in warp knitted fabric facilitated water absorption height and water diffusion area. Polyester-textured filaments with Y-cross section possessed hygroscopicity and permeability.

Das et al. (2008) changed fiber shape factors (in order: circular; triangular; trilobal; micro-denier), an increase on wicking rate was obtained when fiber surface area was increased. By contrast, water vapor permeability of fabrics was reduced.

2.4.2 Yarn parameters

Yarn parameter is classified as material type and blended ratio, yarn formation process and void between fibers. The material of yarn can change moisture management properties of yarn from inherent aspects. Yarn formation process determines fiber orientation, arrangement of yarn and void between fibers. External tension on wetting yarns also imparts moisture absorbing/releasing ability.

2.4.2.1 Component type and blending ratio of blended yarn

Das (2007) proposed that under wetting circumstances, the component material of yarn can drastically change the structure of yarn and entire wicking properties of fabrics. Yarns spun with natural fibers had very irregular capillaries due to various factors such a fiber roughness, cross-sectional shape, and length.

Su et al. (2007) spun composite yarns using profiled polyester fibers and natural cotton fibers at different blend ratios. The results revealed that diffusion rate and drying rate increased with decreasing cotton content but absorption can be improved with the addition of cotton fiber. For core and cover yarns, the addition of profiled polyester filaments can enhance their performance in moisture absorption and release. They concluded that the optimum ratio of core and cover yarns of profiled polyester filament / profiled polyester staple /cotton at 42/46/12 and 42/35/23 did not only provide a better touch sense but also efficient moisture absorption and release.

However, Yoo and Barker (2005b) tested moisture evaporation through saturated fabric samples using a gravimetric absorption test. The results showed that blending Nomex® fiber with hydrophilic FR rayon fiber, while producing measurable and significant differences in fabric level laboratory tests, did not necessarily translate into perceptible differences in moisture-related comfort response to these garments.

2.4.2.2. Yarn formation, void between filaments or fibers and twist

Yarn formation determines yarn twist, yarn tension and void between fibers or filaments. These factors affect water absorption speed and water retention. The space among filaments and the increase in the number of filaments depended on the methods of yarn formation (Ansari & Kish, 2000). In yarns with natural fibers arranged in a relatively disorderly manner, capillary continuity was poor, and this causes changes in water transport rate over the length of yarns (Das et al., 2007). The heterogeneity of pore size, shape and orientation (Bogaty et al., 1953; Hollies et al., 1956 &1957; Hoffman, 1952; Rebenfeld & Miller, 1995) impacted the penetration of liquid into yarns and hence its liquid retention properties as exhibited by textured continuous filament yarns.

Karahan and Eren (2006) investigated terry fabrics made of different cotton yarns. The type of yarns had the most significant effect on their static water absorption properties. Two-ply ring- spun yarn showed a higher water absorption value than two-ply open-end yarn and single-ply ring-spun yarn. In their further study (Karahan and Eren, 2006), 29.5 tex ring-carded yarn had a quicker water absorption than 29.5×2 tex ring-carded yarn and 29.5×2 tex open-end yarn. Furthermore, it can reach saturation earlier than the other two yarn types. 29.5×2 tex open-end yarn had lowest water absorption rates.

Kane et al. (2007) studied the influence of cotton yarn type (ring and compact yarn) on comfort properties. The single jersey fabrics made of compact yarn shows better higher water absorbency, more air permeability than ring yarns.

Das et al. (2007) proposed the compact spinning can incorporate edge fibers into yarn due to the elimination of spinning triangle. The liquid movement in the smaller pore of yarns was greater because of high pressure and in this case, liquid retention in the smaller pore size was less than that of larger pore. The spreading of liquid was rapid in small pores which were uniformly distributed and inter connect.

Das et al. (2007) developed EliTe® compact yarns using compact spinning. It was observed that thermal resistivity values of the fabrics developed from EliTe® compact yarns were lower than fabrics made from normal yarns, indicating they were cooler fabrics compared to normal fabrics. In addition, it shows slightly higher values of moisture vapor transmission rate and wicking properties as compared to fabrics made from normal yarns.

Peters and Fay (2003) argued that area within the yarn cross-section was critically important to superior moisture management performance of composite yarns. An increase in the area of the inter-face between hydrophobic and hydrophilic components did not increase the total amount of moisture, but did enhance the kinetics of absorption. Hence, moisture transfers become more rapid and effective in moisture management fabrics.

Yarn twist was also an important parameter and studied by many researchers. Ansari and Kish (2000) found that wicking performance was significantly impacted by twist. More twists generally decrease wicking with a sudden rise in wicking performance at higher twist levels because of spiral wicking. However, the direction of twist inserted had no significant effect on the wicking performance of yarns.

Das and Ishtiaque (2004) compared plain-woven fabrics with normal, twist-less and hollow viscose yarn in weft. Fabric with twist-less viscose yarn in weft had a highest weft wise wickability, followed by fabric with hollow viscose yarn and normal viscose yarn. Fabric with hollow viscose yarn exhibited highest water absorbency, whereas fabric with twist-less yarn in weft has lowest value.

The results of Hollies et al. (1956), Kamath et al. (1994) and Ansari and Kish (2000) indicates that for a particular yarn, at low twist level, wicking increased until an optimum twist level was attained above which wicking started to decrease. However, twist direction had an insignificant effect on the wicking performance of yarn (Nyoni & Brook, 2010).

With exception of the above, fiber swelling was another factor which influenced water absorption speed and water retention (Das et al., 2007; Zhang et al., 2007). Due to fiber swelling, changes in fiber when wetting can significantly affect liquid movement and retention behaviors. Fiber's swelling not only increased liquid retention in fibers at the expense of capillary liquid capacity in inter-fiber pores, but also complicates pore structure. This swelling of fibers can cause bottle necking or the closing of capillaries, which in turn caused flow in those capillaries to be slow or even stop. It was well known that this type of response to moisture was prevalent in yarns made of cellulosic fibers.

2.4.2.3 Extension of yarns

Wicking performance was significantly impacted by yarn tension (Ansari and Kish, 2000). Nyoni and Brook (2010) investigated the effects of short interval dynamic loading and unloading on yarn and fabric wicking performance. The conventional extension recovery method on a modified Instron tensile tester was employed to evaluate wicking properties at different cyclic load ranges (see Figure 2-32). The results indicated that straining forces generated between the filaments of yarns resulted in spasmodic pumping of liquid. Fabric wicking behavior was dependent on the structure of constituent yarns, their orientation in fabrics, fabric structure, pretension and force applied.

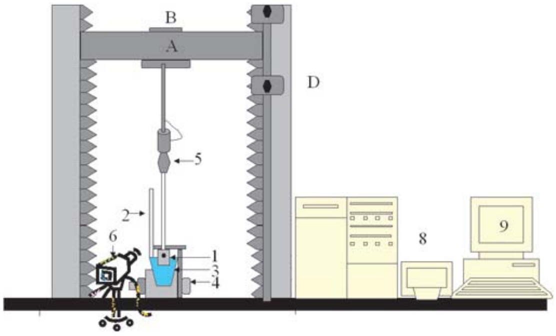


Figure 2-31 A modified Instron tensile tester

2.4.3 Fabric parameters

Regarding previous research on fabric parameters, pore size, pore distribution, thickness, density, material fabric, fabric structure have been investigated to explore the moisture management properties of fabrics.

2.4.3.1 Pore size or porosity of fabrics

Hsieh (1995) examined the effect of pore contribution on liquid transport and retention in 100% cotton and polyester fabrics. The distance of liquid movement can be facilitated by reducing pore size. Optimal liquid spreading or total liquid retention can be achieved by controlling pore sizes and distribution. The findings proved that small, uniformly distributed and interconnected pores facilitated fast spread of liquid in fibrous materials, whereas a large number of such pores or a high total pore volume can achieve a high degree of liquid retention.

Crow and Osczevski (1998) found that pore size and total pore volumes determined the amount of water wicked from one layer to another layer when wicking occurred in a multi-layered assembly. Kim et al. (2003) suggested that the increased numbers of pores can retain a great deal of fluid related to changes in maximum water absorption in agree with the findings of Hsieh (1995). The capacity of a fibrous material to retain liquid was not only determined by its pore sizes but also its overall porosity.

Hong and Kim (2007) investigated comfort related to vertical wicking behaviors in cotton and polyester blended knit fabrics widely used for summer clothing. The higher the capillary pressure, the higher the vertical wicking. In highly porous knit fabrics, vertical wicking mechanism was complex as the effect of gravitation force was significant. Higher surface wetting tension led to higher capillary rise over a long wicking period.

Das et al. (2007) stated that fabrics with higher porosity generating higher wicking rate facilitated the transfer of perspiration across the transverse of fabrics. Better wicking ability created faster liquid water transfer speed and more uniform moisture spreading on fabric surface.

However, Hsieh and Thompson (1996) showed pore size distribution and pore connectivities can be limiting factors in the liquid retention of hydrolyzed PET fabrics with modified wetting properties and porosity.

2.4.3.2 Thickness, density of fabrics

The thickness of fabrics is a key and controlling variable when it comes to moisture management - the thicker the fabric, the more moisture it holds. Most synthetic fabrics, like those made from micro fiber polyester, were considerably thinner than cotton fabrics.

Crow and Osczevski (1998) observed that the amount of water absorbed by fabrics was strongly correlated with a fabric’s thickness. Zhang et al. (1999) claimed that the increases of fabric weight and thickness resulted in higher water absorption rate due to high-wicking pore volume in knitted fabrics in their research range. The moisture-absorption capacity of a fabric depended on fabric thickness and bulk density (Yoo & Barker, 2005a).

Prahsarn et al. (2005) investigated that the thickness of polyester knit fabrics predominately influenced upright cup and sweating hot plate measurements. The most important factors determining moisture vapor transmission were fabric thickness and porosity related to fiber, yarn and fabric variables.

Laing et al. (2007) examined that whether wool knit fabrics worn next to the skin had differences in responses to water vapor and water. Laing et al. cited that water vapor transmission depended on fabric thickness (and air permeability) but not fiber type although fiber type did affect liquid absorption rate. Moreover, the researchers reported a thicker fabric needed a longer transient period to reach a steady state of water vapor diffusion.

Therefore, using a thin knit structure with unobstructed inter yarn pores was important in achieving optimum moisture vapor dissipation (Prahsarn et al., 2005). Similarly, the drying rate of cotton fabrics with reduced thickness turned to be equal to that of polyester fabrics (Cotton Incorporated, 2002).

With regard to the density of fabric parameter, Karahan et al. (2006 & 2007) surveyed the static and dynamic water absorptions of woven terry fabrics. Static absorption testing showed that an increase in warp and weft densities reduced the percentage water absorption of terry fabrics, whereas an increase in pile length increased it. Warp density, weft density and pile height had only a small effect on the percentage of water absorption speed of terry fabrics, compared with yarn type. Hence, they recommended there was no need to consider these factors when designing terry fabrics. The increase of weft yarn density resulted in lower wicking rise of water (Mazloumpour et al., 2011).

Kim et al. (2003) suggested that fast liquid water absorption can be further enhanced by high density microfiber loops which were formed by chemical splitting. As a result of highly dense microfiber loops, a great deal of fluid related to maximum water absorption can be absorbed.

Kane et al. (2007) studied the influence of structural cell stitch length (SCSL) on comfort properties. With increased SCSL, air permeability, water absorbency and the area covered by water spreading increased. As a result of larger number of loops, fabric density was greater. Therefore, at a certain time higher density of fabric can lead to higher resistance to the absorption of water, and decrease the absorption and spreading of water.

Regarding two-layered knitted fabrics with hydrophobic filament in the inner layer, a properly reduced stitch density in the inner layer could promote water transfer throughout fabrics (Long, 1999). In addition, the looser the fabric construction, the better the water-holding ability (Zhang et al., 1999).

2.4.3.3 Material type of fabrics

Material type is one of important factor to determine water-holding ability (Zhang et al., 1999). Higher moisture regain causes better water-holding ability. Synthetic fabric leaves the wearer warm and dry, since it does not pick up moisture (Crow & Osczevski, 1998).

In order to decrease wetting time and absorption rate compared with pure wool fabric, pure wool was knitted with polyester because the polyester fiber created more liquid water transfer channels with a wicking force (Zhou et al., 2007).

Considerable research focuses on the type of material located in two different layers which could provide moisture management properties. Zhang et al. (1999) explained the reason why hydrophilic fiber should be placed at the outer side and hydrophobic fiber placed at the inner side. When people perspire at the starting period, hydrophilic fiber can absorb water and keep the skin dry. However, when hydrophilic layer was saturated, still-air spaces were blocked; the thermal insulting value will decrease rapidly. As a result, human body feels wet and cold.

By wicking effect, hydrophobic material at the inner side could transport water through the space between fibers and yams to the outer layer. The hydrophilic outer with good water absorption ability had a larger wet area leading to a rapid evaporation.

Long (1999) demonstrated that liquid water transport depended very much upon the differential water absorption property of materials in the two layers. More water can be transferred from the inner to the outer layer by capillary action in the better water absorption of the outer-layer yarn and the worse inner-layer yarn.

Compared fabrics with the same knit back yarn and different knit face yarns, fabrics containing polyester trilobal flat yarn combined with different functional fibers at the back side transferred moisture more easily than polypropylene knitted at the face side (Zhang et al., 1999).

Fangueiro et al. (2010) studied the effect of material of the face and the back sides on wicking ability, focusing on different plated knitted functional fabrics. Fabrics with viscose Outlast® at the back side, no matter what material at the face side in this study, presented highest water absorption and horizontal wicking, following by Coolmax® PBT, Dry-release®, and elastane. Because Viscose Outlast® was a hydrophilic fiber with irregular cross-sectional shapes. Coolmax® also presented irregular cross-sectional shapes. These two yarns can form more capillaries than the others.

Li and Hu (2007& 2009) proposed that better moisture management properties can be achieved by controlling the proportion of hydrophobic areas or points on the inner surface at 40% and 70%; and the outer surface had a high proportion of hydrophilic area which should exceed 50% of total area for optimum moisture management.

2.4.3.4 Structure of fabrics

Some knitting or weaving constructions and fiber assembly are compared to reveal which structure is more effective for transporting moisture.

Kane et al. (2007) studied the influence of four knit structures (single jersey, single pique, double pique, and honeycomb) on comfort properties. Of the four knitted structures, double pique fabric was found to have larger water spreading area than the others due to more openness of the structure. The combination order of knit-tuck stitches played an important role in dimensional and comfort properties. In addition, double pique showed better performance for summer outer wear; whereas single jersey fabric showed better performance for summer inner wear.

Hasan et al. (2008) presented the influence of the type of weave (plain weave; warp rib weave; twill weave) on topography and wettability of fabrics. The spreading rate decreased with increasing waviness for the plain weave, whereas it increased in the case of the twill weave. These researchers suggested that fabric wettability could be adjusted (in certain limits) by the variation of density and interlacing. The findings showed that water penetration strongly depended on air permeability for plain topography but not twill.

In order to achieve anisotropic flow properties, Coskuntuna et al. (2007) developed two types of fibrous structures. In one of the structures, a parallel arrangement of continuous filament yarns in the middle layer of a three-layer structure was designed to transport liquid in one specific in-plane direction with minimum wicking in any other direction. The top and bottom `layers consisted of low areal density nonwoven fabrics. Structures with larger pores in the middle layer promoted wicking. Another structure was designed to maximize liquid transport through the thickness of a fabric with minimum wicking in the surface plane. It contained flocked fibers in the middle layer oriented parallel to the direction of flow.

Besides, non-woven structure was compared with woven structure by Mukhopadhyay et al. (2006). They measured water retentivity and implications of retentive structures in civil applications. It was found that generally non-woven structures were more retentive than woven under the different test conditions of humidity and temperature of test.

Recently, the biomimetics of a plants-shaped branching structure in fabrics were considered as a potential approach for enhancing the liquid water transport and moisture management properties of fabrics, as the plants-shaped network provided minimum resistance to fluid flow (Fan et al., 2007). Woven fabrics mimicking the plants-shaped branching structure have been developed and demonstrated improved water absorption and moisture management (Sarkar et al., 2009a & 2009b). It is shown in Figure 2-33.

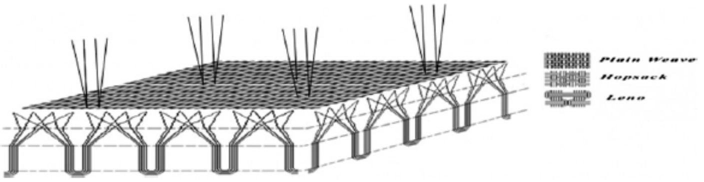


Figure 2-32 An example of plant structured woven fabrics

2.4.4 Parameters of multi-layered systems

Since daily wearing condition involves several garments, the investigation of water transport between these layers also was carried out, including the contact between these layers, the fabric surface of each layer, the fabric selection of inner layer, water distribution in this multi-layered system, as well as external pressure on whole system.

Zhuang et al. (2002) investigated liquid transfer behavior and liquid interaction among different fabrics in clothing systems. The moisture management of liquid as well as of vaporous sweat was affected different combinations of materials. It was found that the performance of individual fabric and the contact way among them largely determined the quantity of liquid transferred. Figure 2-34 presents the two measurements of water transport in clothing system.

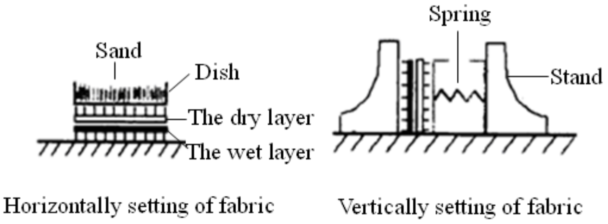


Figure 2-33 The two measurements of the water transport

When the smooth face of dry layer contacted the face of wet fleece fabric, more water can be transferred than when there was a contact between face dry fabric and back wet fleece fabric. When the first layer was integrated double-sided aquator fabrics, more liquid was transferred from wet layer than the case for other fabrics.

The effect of introducing a fleece fabric into the clothing system was determined by the type of first layer fabric. If the inner fabric was a polyester eyelet knit fabric, a fleece fabric decreased the amount of liquid transfer. However, when the inner fabric was an aquator fabric, less water was transported. The raised side of dry fleece fabrics contacted either side of a wet fleece fabric layer, there was no significant transfer wicking between them.

Cao et al. (2006) believed an essential consideration in the development of a liquid cooling garment (LCG) was the design of an inner fabric layer. Of 18 fabrics with different materials and structures, a knitted polyester fabric with spandex was selected as a candidate for the inner fabric layer of a liquid cooling garment. Not only wicking and water distribution properties were better than others, but also knitted fabrics can reduce air gap between fabric and the skin due to its better stretch property for creating a tighter fitting garment.

Keiser et al. (2008) noted that both the material properties and properties of the neighboring layers or even of whole combination determined the moisture content contained in a single layer. The innermost three layers of a clothing system consisting of five and six layers can accumulates over 75 % of moisture. It was important to note that the distribution of moisture depended on the interaction of the moisture transport properties of different layers. The neighboring layer of underwear turned out to be dominant for moisture distribution in multilayer protective clothing.

An initially higher external pressure caused an early start to wicking (Zhuang et al., 2002). The researcher found that there was an optimum external pressure values, and that the greater quantity of initial water in the wet fabric, the greater transfer to the dry.

2.5 Biomimetics and textiles

2.5.1 Biomimetics

The imitation of living systems, ‘biomimetics’, is the abstraction of good designs from nature. Biomimetics is a novel approach to developing designs and products or to solving human problems by taking inspiration from nature. Biomimetic refers to human-made processes, substances, devices, or systems that imitate nature.

The structure and functions of natural biological materials are precise and well defined. The imitation of living systems, ‘biomimetics’, could make it possible in future to replicate the molecular design and morphology of natural biological materials since their structure and functions are related. Much R&D work is going on in the field of biomimetic chemistry and fabric formation. There are more interests for a formal imitation (patterns, texture) rather than drawing inspiration from functions nature performs.

2.5.2 Marketed textiles inspired from biomimetics

Biomimicy could provide special properties to textile with performance enhancement in terms of material construction and their appropriate placement on the body. For instance, water and soil-repellent fabric is produced by imitating the surface of a lotus leaf. Water rolls like mercury from lotus leaf, whose surface is microscopically rough and covered with a wax-like substance with low surface tension. When water is dropped on to the structure of a lotus leaf, air is trapped in the dents and forms a boundary with water. It is the basis of Schoeller’s water-repellent and easy-care NanoSphere finish inspired by lotus leaf concept.

Moreover, shark skin has been mimicked for competition swimwear by Speedo®. The spider’s fiber is stronger and more resilient than anything in the market today.

Mimicking material used by spiders to create webs could provide a way to manufacture fiber without using high heat, high pressure, or toxic chemicals.

2.5.3 Water transport mechanisms in plants

Plants have exceptional water transport properties, and the amount of water transported by plants is much greater than the evaporation from an uncovered water surface. Thus, the imitation of plant structure in textile fabrics was proposed to achieve the superior property of water transport so as to remove sweats from surface of human body. The mechanism of this transpiration is osmosis capillary action and cohesion-tension mechanism. Furthermore, plants structured networks are essential to water transport in plants. Plants-shaped networks in plants have a minimum resistance to fluid flow between a point (or source) and volume (or area).

First of all, how does water travel through the roots from 3 to 6 meters or more beneath the surface and then up the trunk to the topmost leaves of a plants that can be more than 90 meters tall?

This has been a subject of much debate for the past 200 years. One of the earliest explanations for the rise of water in a living plant was given in 1682 by the English scientist Nehemiah Grew (Stern, 2000; Burris & Nehemiah, 1963). He suggested that cells surrounding the xylem vessels and tracheids performed a pumping action that propelled water along. This was questioned, however, when it was found that water will also rise in lengths of dead stems (Stern, 2000; Holbrook et al., 2002). Then after Malpighi (Stern, 2000; Marcello, 2009) suggested it, the belief that capillary action moved water became popular. Capillarity might produce enough force to raise water a meter or two, but the diameters of tubes were not small enough to raise it more than that.

The pioneer plant physiologist Hales (Stern, 2000; Stephen, 2009) discovered and measured root pressure as one means by which water moves through plants. But the force exerted by root pressure has been shown generally to be less than 30 grams per square centimeter. Hales identified a pulling force due to the evaporation of water from leaves and stems. This has led to cohesion-tension theory, the most satisfactory explanation for the rise of water in plants thus for far suggested. Although cohesion-tension theory has been widely accepted for about 100 years, it is currently being challenged. A new hypothesis, proposed by Martin Canny at Australian National University, suggested that living vascular tissue provides a tissue pressure in addition to pulling forces assumed in the cohesion-tension theory (Canny, 1998). This tissue pressure helped maintain the flow of water and repair any breaks that might occur in water columns. Recent work by Bejan (2000) has shown the plants-shaped network in plants has a minimum resistance to fluid flow between a point (or source) and volume (or area). The debate and research continue (Bejan, 2000, 2002, 2004).

The different water transport mechanisms are explained in greater details as follows

(Stern, 2000; Grahem et al., 2006; Rost et al., 2006; and Lack & Evans, 2001):

Cohesion-Tension Mechanism

The cohesion-tension theory believes there is a pulling force due to the evaporation of water from leaves and stems. Water molecules are electrically neutral, but they are asymmetrical in shape. This results in the molecules having very slight positive charges at one end and very slight negative charges at the other. Such molecules are said to be polar. When the negatively charged end of one water molecule comes close to the positively charged end of another water molecule, weak hydrogen bonds hold the molecules together. Hence, water molecules are cohesive; they stick together. They also are adhesive: they stick to hydrophilic molecules such as carbohydrates. Water molecules adhere to capillary walls (e.g. those of xylem tracheids and vessels) and cohere to each other, creating a certain amount of tension.

When water evaporates form the mesophyll cell in a leaf and diffuses out of the stomata pores (transpires), the cells involved develop a lower water potential than the adjacent cells. Because the adjacent cells then have a correspondingly higher water potential, replacement water moves into the first cells by osmosis. This continues across rows of mesophyll cells until a small vein is reached. Each small vein is connected to a larger vein, and the larger veins are connected to the xylem in the stem, and that, in turn, is connected to the xylem in the roots that receive water via osmosis from the soil. As transpiration takes place, it creates a “pull,” or tension, on water columns, drawing water from one molecule to another all the way through an entire span of xylem cells.

Capillary Action

Capillary action is generated by the adhesive force between the surface tension in the meniscus of water and the wall of a tube. It is well known that the height which water will rise in a narrow tube is inversely proportional to the diameter of a tube. It is also known that this rise occurs through the forces involved in the forming of a concave menisus (curved surface) at the top of a water column. Even though water can rise 1 meter or more in a very narrow tube, air must be present above the column for the forces to work, which is not generally the case in a plant; unless cavitations take place in the xylems, in which case capillary action helps water movement.

Minimum Flow Resistance of Branching Structure

The interconnected tubes of xylem extend throughout plants, from the roots up through the stem and branches to the tiny veinlets of leaves. The branching network and tapering of the xylem in plants minimize the resistance to fluid flow between a point and volume as proven by Bejan (2000, 2002 & 2004). This enhances the efficiency of water flow.

2.5.4 Woven plant structured fabrics

Woven textile fabrics emulating plant structures were reported in 2007 by Fan et al.

(Fan et al., 2007). Consequently, some novel weave structures, which emulated the branching structure of plants, were invented by Fan and co-workers. These fabrics with new structures possessed much faster liquid water transport and better moisture management properties. Garments made of such plant structured fabrics facilitated the transport of sweat faster away from the skin to the outer layer of fabrics, so making the wearer feeling drier and more comfortable.

Based on previous work, the present project aims to extend the biomimetics approach to knitted fabrics so as to enhance liquid transport and moisture management properties. It is believed that the plant structured knitted fabric will have a high potential for casual wear and sportswear application for its inherent stretchability as a knitted fabric and enhanced moisture management properties.

2.6 Summary

Historically, a considerable number of studies have been carried out to establish moisture management theory, develop moisture management fabrics and investigate how to optimize moisture management properties. Investigators have focused particularly on liquid water transfer properties through fiber, yarn and fabric structure perspectives. There have been a number of successful attempts to produce moisture management textile products. They are summarized as follows:

1) Fiber:

Different synthetic fibers are comprehensively used in sportswear or recreational performance apparel. The characteristic of these synthetic fibers is: irregular cross-section or hydrophilic chain linking in molecule.

Most textile fabrics made of synthetic fibers are, however, likely to result in the substantial entrapment of liquid moisture between the wearer's skin and undergarments, or between the undergarments of wearers and the outerwear. When moisture saturation takes place, the excess moisture wets the body of garment, and wearer begins to feel rather uncomfortable.

2) Yarn:

Blended yarns are developed to balance natural and synthetic fibers in one yarn. Though they can absorb perspiration from the area of the skin, it requires a period of time to evaporate moisture. Fabrics made from spun yarns of polyester with certain amount of cotton are very comfortable when dry; they become uncomfortable when wet due to the high moisture absorption of cotton. This is especially undesirable in cold weather when a person has perspired due to physical exertion.

3) Structure:

Placing hydrophilic and hydrophobic yarn on the face and back surfaces of fabrics, respectively, is considerably applied. But, moisture evaporation from the outside layer is less. The moisture absorbent material becomes saturated, and since there is little driving force to spread moisture outwards, evaporation is limited and the excess moisture backs up into the inner layer, wets wearers and leads to discomfort.

Therefore, there exists a need for a fabric that will provide increased comfort to wearers. More specifically, there is a need for a fabric which is capable of quickly absorbing perspiration from the skin of wearers, but which will also quickly release moisture so that moisture content in fabrics remains low.

Based on previous work, the present project aims to extend the biomimetics approach to knitted fabrics so as to enhance liquid transport and moisture management properties. It is believed that the plant structured knitted fabrics will have a high potential for casual wear and sportswear application for its inherent stretchability as a knitted fabric and enhanced moisture management properties.

2.7 Conclusions

This chapter has reviewed the research related to this study, including wetting and wicking theories, moisture management products and moisture management properties of textiles. The next chapter will describe the methodology used to formulate and test our hypothesis which plant structure have better water transport properties.

3. Methodology

3.1 Introduction

This chapter describes the research methodology, methods, and evaluations for this study. After a description of the design concept of plant structured fabrics, it provides knitting techniques adopted to fabricate plant structured fabrics. A rational for the selection of testing methods for the objective evaluation of developed samples are presented, as well as testing principles, procedures, instrumentations. Appropriate statistical methods are also chosen in order to analyze the effects of knitting structure and other factors.

3.2 The design concept of plant structured knitted fabrics

Is it possible to imitate natural branching networks in the transverse direction of knitted fabrics? The basic idea of this project is to emulate the plant structure in knitted fabrics so that it promotes liquid water transport from the back side of fabrics (normally worn next to the skin) to the face side (the surface exposed to the environment). Learning from plants, fabric structure should promote evaporation at the face side so as to create a “cohesion-tension mechanism” to pull liquid water underneath; there should be a continuous pathway of water transport from the inner layer to the outer layer. A branching network is also needed to minimize flow resistance.

The fundamental principle may be achieved as follows. Firstly, two or more yarns are grouped together at the back side of fabrics to form multi-yarned loops so as to simulate the stem of a plant. Secondly, these yarns are separated and individually run to the face side of fabrics to form single yarn loops; when fabrics are formed in this way; continuous pathways and a branching network are generated to minimize flow resistance. Since yarns at the face side are individual and hence more area is exposed to the air, there is enhanced evaporation at the face side which creates the "cohesion-tension mechanism" to pull liquid water underneath. Furthermore, the back side and face side may be raised to better imitate roots and leaves. Net capillary is also generated from the back side to the face side if there are a large number of smaller sized loops at the face side relative to the back side.

To meet the requirements of design concept and accomplish knitting tasks, weft circular and warp knitting techniques are adopted to produce plant structured knitted fabrics. Because knitted fabrics produced on these machines are suitable for sportswear and summer casual wear applications due to thinner thickness and better stretchability. The sub-section below introduces knitting techniques employed by this study.

3.3 Knitting techniques

Since the purpose of this study was to develop plant structured knitted fabrics, knitting techniques (both circular and warp knitting techniques) were used to accomplish the tasks.

Knitting as a method of converting yarn into fabric begins with the bending or curving of yarns into either weft or warp loops. These loops are then intermeshed with other loops in either a horizontal or vertical direction in terms of courses and wales (Spencer, 2001), corresponding to the two basic forms of knitting technology - weft and warp knitting. A course is termed as a predominantly horizontal row of needle loops (in an upright fabric as knitted) produced by adjacent needles during the same knitting cycle (Spencer, 2001). A wale is termed as a predominantly vertical column of intermeshed needle loops generally produced by the same needle knitting at successive knitting cycle (Spencer, 2001).

3.3.1 Circular weft knitting technique

Weft knitting may be described as the method of creating a fabric via the interlocking of loops in a widthwise direction, one or more yarn ends being fed one at a time to a multiplicity of knitting needles (Spencer, 2001).

Weft knitted fabrics may be approximately divided into single or double jersey in line with whether they are knitted with one or two sets of needles. Based on the design concept of plant structure, two sets of needle are required for drawing yarns from one side to another side. Therefore, the double jersey circular weft knitting machine was applied. Figures 3-1 and 3-2 show some conventional double jersey structures (Spencer, 2001)and circular knitting machine.

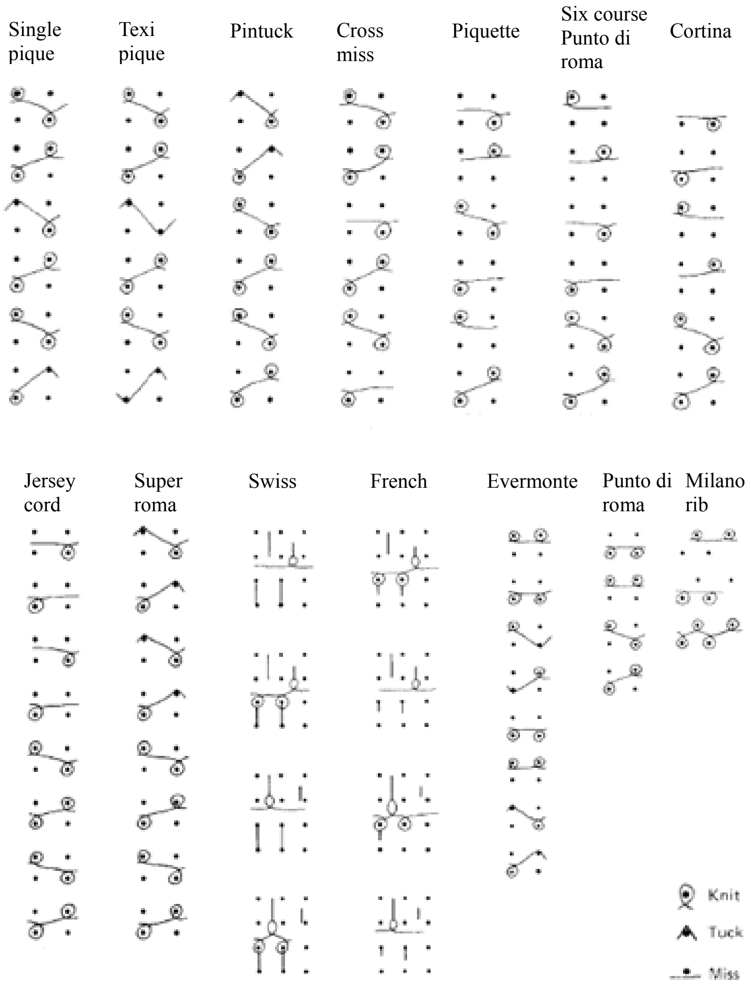


Figure 3-1 Double-jersey structures (Spencer, 2001)

Figure 3-2 Circular knitting machine

3.3.2 Warp knitting technique

Warp knitting may be described as the system of producing a fabric through the interlocking of loops in a lengthwise direction. In this manner, numerous separate ends of yarns are lapped individually around a lateral formation of each knitting needle (Spencer, 2001).

The two main types of warp knitted fabrics are tricot and Raschel. According to requirements of design concept, double - needle bar Raschel machine was selected to produce plant structured fabrics for drawing yarns from one side to another side. The front and back needle beds could knit two different fabric surfaces. Figures 3-3 and 3-4 demonstrate conventional sandwich Raschel knitting structure and machine.

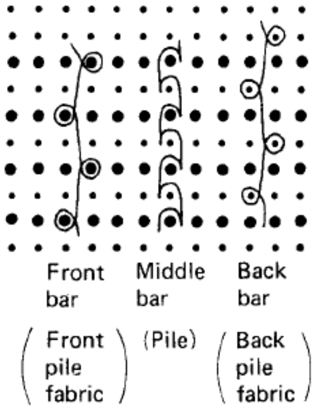


Figure 3-3 Conventional sandwich Raschel knitting structure

Figure 3-4 Rachel warp knitting machine

3.4 The objective evaluation of knitted fabrics

The moisture transport of fabrics had a significant influence on the microclimate between body surfaces and garments (Dai et al., 2008). As a consequence of quickly spreading sweat, the increase of the humidity was prevented; at the same time, by means of sweat evaporation, heat would be taken away and the skin surface cools down, in order to maintain a comfort microclimate under garments

(Shishoo, 2005). Hence, it was of importance to directly evaluate this performance related to wearing comfort.

With respect to the measurements of liquid water transport in textiles, AATCC vertical wicking test can provide the values of wicking height, wicking time, and wicking rate. Based on this typical vertical testing, a balance could be introduced to measure static and dynamic water absorptions (Mehmet, 2006 &2007). However, this method can not simulate the real wearing condition.

Many horizontal wicking experiments have been proposed to measure the transverse wicking behavior of textiles. A syphon test method was reported by Lennox-Kerr (1981, cited in Patnaik et al., 2006) and Phukon (1998). By means of siphon tube, the liquid level in the reservoir was adjusted to control surface contact between water and fabrics. Buras Jr et al. (1950, cited in Patnaik et al, 2006), Miller (1985), Gupta and whang(1999), Chattopadhyay and Chauhan (2004), Anand and Higgins (2004), and Laing (2007) manually adjusted either the height of tube or certain chambers to control hydrostatic head. A problem might exist that maintaining accuracy was difficult because sometimes water loss was caused by positive hydrostatic pressure not by fabric absorption in addition to manual errors. In some instruments, a load was placed on the top of fabrics to ensure contact with the sintered plate. This pressure on fabrics, as a consequence, can potentially change absorption characteristics.

Therefore, trans-planar water transport tester was employed to evaluate the efficiency of liquid water transport through the transverse direction of fabrics. This tester can measure initial water absorption rate which was an average rate of water absorption of fabrics in the first ten seconds. During the initial period of time, nearly 26% to 40% of water might be absorbed based on dynamic water absorption testing (Karahan et al., 2006 & 2007). The faster initial water absorption rate, the more water absorbed by fabrics at an initial time. As a result, fabrics could quickly remove sweat from the skin to create dry feeling of the skin. Besides, more water evaporated could accelerate the circulation process of water absorption and evaporation in continuous sweating condition. This instrument can simulate sweating condition by maintaining a constant water level. Absorbing water from the bottom side of fabrics eliminated gravity effect which exists in dropping water from the top side of fabrics. Thus, it was of crucial to conduct this measurement for water transport evaluation.

All fabrics were also tested by MMT test based on dropping test. This measurement was able to measure the difference of accumulative moisture content between the two surfaces. One-way transport capacity presented the capability of transporting water from the back to the face side. Negative values indicated there was no one-way transport, while positive values suggested there was one-way transport capacity with less water retained at the back side than the face side.

Air permeability was one of importance indicators related to comfort. Zhang et al. (2002) reported that physiological responses to heat were influenced by wind and the air permeability of clothing materials in 23℃. For instance, skin temperature, clothing microclimate temperature and relative humidity, clothing surface temperature, body mass loss, and salivary lactic acid concentration were significantly lower for clothing with higher air permeability in the environment with wind. In this study, air permeability was detected in terms of air resistance.

In addition, water vapor permeability also was measured. It was an important parameter for evaluating comfort characteristics of fabrics, as it represented the ability to transfer perspiration and maintain the appropriate humidity of microclimate under garments.

Prior to testing, the pre-finished fabric samples were conditioned at 20 ± 2℃ and 65 ± 2% R.H. for 24 hours. During testing, air velocity in the conditioned room was 0.2 m/s. The order of testing was randomized.

3.4.1 Transplanar water transport test

Principle

Trans-planar water transport tester was developed to measure the absorption rate of fabrics under conditions simulating profuse sweating (Sarkar et al., 2007), a perforated metal plate with a constant water level being used to simulate the condition of sweating. The reduction in the amount of water due to the absorption by fabrics can be recorded by software. Figure 3-3 illustrates the schematic diagram of transplanar water transport tester. Figure 3-4 is the picture of transplanar water transport tester.

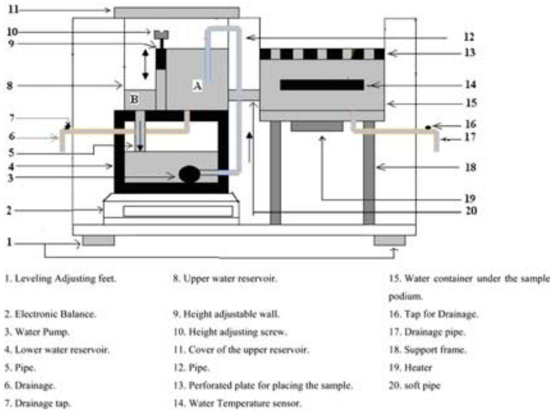


Figure 3-5 Schematic diagram of the transplanar water transport tester

Apparatus

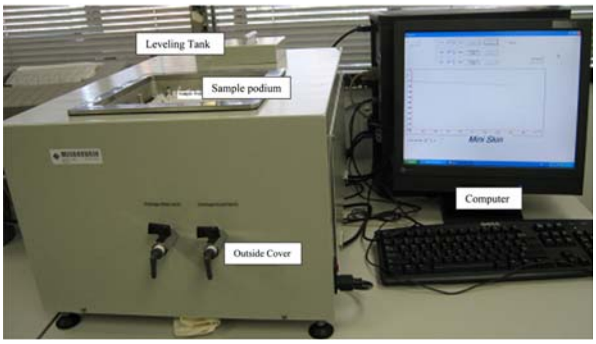


Figure 3-6 The picture of transplanar water transport tester

Procedure

For TWTT testing, a sample (18x18 cm^2) was attached to the bottom side of the template using double sided sticking tape. After warming the instrument up, the button was pressed to move the template down and the software starts to record water weight changes by the balance. During testing, the back sides (intended to be in contact with the skin) of fabric specimens were kept in contact with water surface. Water temperature was maintained at 20 ºC. The amount of water absorbed or transmitted through the fabric was measured in real time.

Calculation and Evaluation

Initial water absorption rate: it is the average amount of water absorption per second in the first ten seconds. Higher values indicate the faster speeds of fabric ability to absorb and transport water through transverse section in terms of efficiency of water transport properties.

$$\text{Initial water absorption rate(g/s)} = \frac{\text{water loss in instrument in 10 seconds}}{\text{wicking time(10s)}} \quad (3\text{-}1)$$

According to Sarkar et al. (2007), high initial absorption rates (from 2.09 to 2.54 g /s) can be found in knitted fabrics with water absorbent surface finish, cotton twill fabrics, multi-layer woven fabrics and commercial Dryfit® fabrics. On the other hand, fur fabrics, knitted fabrics with water repellent finish, cotton towel and polyester fabrics had relatively low initial absorption rates (from 0.04 to 0.40 g/s). Three individual tests for each fabric were conducted to calculate the average.

3.4.2 Moisture management test

Principle

The test was carried according to the procedures specified in AATCC-195. The MMT tester utilizes upper and lower concentric moisture sensors to measure changes in the contact electrical resistance of two surfaces of a fabric during wetting (Yao et al., 2006), this being related to the changes in the water content of fabrics. The fabric being tested is placed between two sensors. Figures 3-7 and 3-8 illustrate MMT tester.

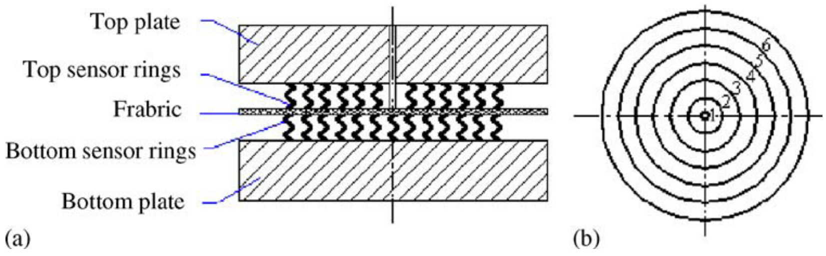


Figure 3-7 The principle of MMT tester

Apparatus

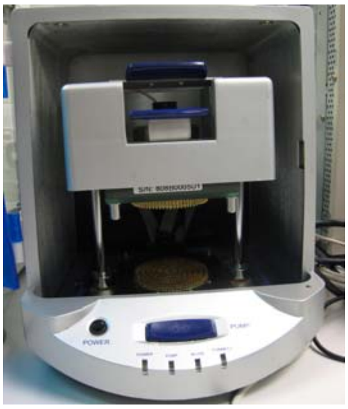


Figure 3-8 The picture of moisture management tester

Procedure

Specimen in 90× 90 mm squares was required. After placing fabrics between the two sensors, an amount of 0.2ml synthetic sweat (9% sodium chloride solution in water) was dropped onto the surface of fabrics. The one-way transport capacity was automatically calculated to represent the difference between the accumulative moisture content of two surfaces (viz. the face and the back) of fabrics. The measurement was repeated five times and the average value was calculated.

Calculation and Evaluation

The difference of accumulative moisture content between the two surfaces of a wet fabric was termed as accumulative one-way transport capacity, which reflected the one-way liquid transport capacity from the inner surface to the outer surface of fabrics. The average of three tests for each fabric was calculated. Table 3-1 shows the rake of one-way transport defined in literature.

Table 3-1 The grade range of evaluation

Grade	Range	One-way transport
1	<−50	No one-way transport
2	−50 to 100	Poor
3	100–200	Good
4	200–400	Very good
5	≥400	Excellent

3.4.3 Air resistance

Principle

Air resistance was measured using the air-permeability tester (KES-F8-AP1, Kato

Tech. Co.) developed by Kawabata (Instruction Manual, Kato Tech Co. Ltd). It can measure air pressure loss and calculate air resistance in unit kPa s/m when air flows through the transverse section of fabrics. The apparatus is shown by Figure 3-9.

Apparatus

Figure 3-9 The picture of air permeability tester

Procedure

The sample should be cut into square shape of 10 × 10 cm^2. During the testing, the constant rate of air flow (0.04 m/s) was generated by the piston motion/cylinder mechanism and passed through a specimen into atmosphere. The suction and discharge period of air were 5 seconds respectively and air pressure loss caused by air resistance of specimens was measured by a semiconductor differential-pressure gauge. The measurement was repeated five times for each fabric.

Calculation and Evaluation

The air resistance was directly indicated on a digital panel meter. The average of the five tests was taken for each fabric.

3.4.4 Water vapor permeability test

Principle

Water vapor permeability was measured according to BS 7209. A test specimen was sealed over the open mouth of a test dish which contained water, and the assembly was placed in a controlled atmosphere. Following a period to establish equilibrium of the water vapor pressure gradient across the sample, successive weighing of the assembled dish were made and the rate of water vapor permeation through the specimen was determined. The apparatus is shown by Figure 3-10.

Apparatus

Figure 3-10 The picture of water vapor permeability tester

Procedure

46 ml of water was placed in a dish with an internal diameter of 83mm. It was necessary to cut circular specimens with a diameter not less than the outer diameter

of dishes. Quick-drying adhesive cement was used for fixing test fabrics to the rim the test dishes. Adhesive-backed polymer tape with negligible water vapor transmission properties was used for sealing cover rings to test dishes. The assembly (dish, complete with specimen) was placed on a turntable, and initial weight was measured. After rotating the turntable for 24 hours, the assembly was reweighed. The water loss by evaporation was then used to calculate water vapor permeability.

Calculation and Evaluation

WVP (the water vapor permeability) in g/m^2/day is given by the equation:

$$WVP = \frac{24M}{At} \qquad (3\text{-}2)$$

Where M is the loss in the mass of assembly over the time period t (g), T is the time between successive weighing of the assembly (h), A is the area of the exposed test fabric (equal to the internal area of the test dish) (m^2). The average is obtained by testing three times for each fabric.

3.5 Data Analysis

The quantitative data of objective measurements was analyzed by SPSS version 16.0. One-way ANOVA was used to identify the significance of differences between fabric structures, while two-way ANOVA was used to identify the significance of differences between fabric structures, yarns, or their interactions. Any differences were considered to be significant if P value was equal to or less than 0.05.

3.6 Conclusions

In this chapter, I have explained the rationale for the approaches of sample development and evaluation. Circular weft knitting and warp knitting techniques were proposed to fabricate samples. TWTT and MMT were carried out to measure liquid water absorption and water distribution in fabrics, as well as air resistance and water vapor permeability for auxiliary assessments related to comfort. In doing so, I have aimed to lay the foundations for the research investigations to be described in the following chapters.

4. Development of weft plating structures to emulate the branching network of plants

4.1 Introduction

Weft plating technique was used to fabricate fabrics mimicking the branching network of plants. Since the working principles of a circular knitting machine do not allow for the formation of multi-yarned loops at the back side of fabrics and separately single-yarned loops at the face side, some compromises are necessary.

In this chapter, two structures were developed and compared to a simple rib structure. The first structure was presented as Experiment No.1, and it was based on 1×1 rib structure: two yarns were bundled together to make double-yarned loops at cylinder needles, with one running to dial needles to form single-yarned loops. The second structure, presented as Experiment No.2 used an identical plating technique as that in Experiment No.1, but had one yarn forming loops on both side of fabrics, creating a continuous conduit of water transport from the back side to the face side, and another yarn forming loops together with the first yarn at the back was formed by two yarns bundled together, simulating the coarse stem of plants. The difference between Experiments No.1 and No.2 is that, in Experiment No.2, half of needles on the dial worked in order to create less “stems” at the inner side and more “branches” at the outer side, better emulating the branching network which exists in plants. The detailed descriptions of experiments are given in the following sub-sections.

4.2 Experiment No.1

4.2.1 Sample preparation

In this experiment, 1×1 plating rib was designed to mimick branching networks. In this structure, as shown in Figure 4-1(B), two yarns were grouped together to form one stitch at the back side of the fabric to mimick a plant stem, and one of them would run to the face side of fabrics. The structure was compared with the basic 1×1 rib knitting structure as the control (shown in Figure 4-1(A)).

Three types of yarn were used to fabricate fabrics in these two structures (see Figure 4-1). Same needle depth was maintained to keep the loop length unchanged. The fabrics were produced on a 12E gauge machine. The six samples can be subdivided into three sets as presented in Table 4-1. The detailed descriptions are given below.

Set-I: Two different fabrics with Structures-A and B were produced in this set. As shown by Structure-B in Figure 4-1, sample No.1 was prepared using Yarn 1 containing two cotton 32Ne yarns (equals to 16Ne). For sample No. 2 with the Structure -B, yarn 1 and yarn 2 were single cotton 32Ne yarns.

Set-II: Samples Nos.3 and 4 were grouped in the Set-II. Sample No.3 was prepared using two cotton 20Ne yarns (equals to 10Ne) with the Structure-A. For sample No. 4 with the Structure-B, yarn 1 and yarn 2 were single cotton 20Ne yarns.

Set-III: In the last set, sample No.5 was prepared by combining 20Ne cotton and 150D Polyester yarn in Structure-A, sample No.6 was made of 20Ne cotton as Yarn 1 and 150D Polyester as Yarn 2.

To understand the effect of these two designs, design details are presented here. Although both designs had two layers, two layers were distinctly different in Structure-B. The difference between these two structures was that a separate yarn was used to be plaited at the bottom (inner layer in contact with the skin) layer for the Structure-B, which was not presented in Structure-A. For an example, for sample No.6, the polyester yarn was plaited into the bottom layer of the fabric (see details in Table 4-1).

(A) 1 × 1 rib

(B) 1 × 1 plating rib

Figure 4-1 Knitting notation

All gray fabrics were finished using scouring and bleaching process as follows. Water/fabric ratio is 50/1. Detailed ingredients were NaOH (3 g/L), stabilizer SIFA(0.5 g/L), detergent (0.5 g/L), sodium silicate (0.5 g/L) and H_2O_2 (12 ml/L).

Fabrics were processed at 100℃within 45min. After finishing, all dried fabrics were pressed properly and then taken for testing.

Table 4-1 Construction Details of Fabric

Sample No	Yarn (Yarn 1/ Yarn 2)	Structure	Mass (g/m^2)	Thickness (mm) ($0.5gf/cm^2$)	Density (loop/ cm^2)
Set I					
1	cotton 32Ne&cotton 32Ne	A	334.66	2.412	112.5
2	cotton 32Ne/ cotton 32Ne	B	258.24	2.061	110.5
Set II					
3	cotton 20Ne&cotton 20Ne	A	394.88	2.573	99
4	cotton 20Ne/ cotton 20Ne	B	370.38	2.391	101.6
Set III					
5	cotton 20Ne&polyeter150D	A	375.89	2.246	96
6	cotton 20Ne/polyeter150D	B	298.15	2.160	91.2

4.2.2 Results and discussion

The thickness and the mass of a knitted fabric depend on yarn count, and knitting structure. Comparing knitted samples prepared with different yarn count, it was observed that the fabrics produced with finer count had less mass and lower thickness for both knitting structures (see Table 4-1) as expected. From the structure point, samples in Structure-B were thinner and lighter than that of Structure-A knitted with the same yarns.

4.2.2.1 Transplanar water transport test

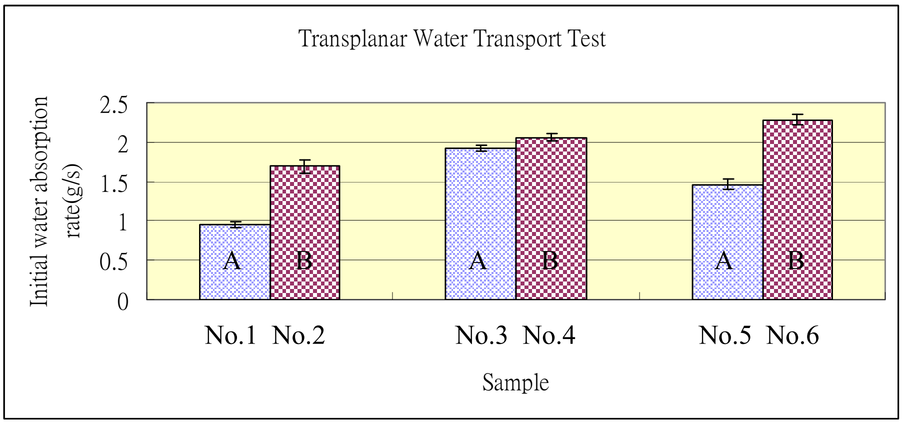


Figure 4-2 The results of transplanar water transport test

Initial water absorption rate is the average value of three specimens at the first ten seconds for each sample (see Figure 4-2). The one-way analysis of variance was tested to recognize differences between fabrics properly. If the probability (p) value was less than 0.05, it would lead to a conclusion that the difference was significant.

Between fabrics with the Structures-A and B (sample Nos.1, 3 and 5 against sample Nos.2, 4 and 6 respectively), significant (P value < 0.05) differences (28%, 6.7%, and 56%. respectively) were observed. This is probably due to the presence of one extra yarn in the inner layer of fabrics, which facilitates faster water absorption.

4.3 Experiment No.2

From Experiment No.1, we learned that when two yarns were grouped at the back side, the performance of water absorption was enhanced. In the following Experiment No.2, we designed that one yarn formed loops on both sides of fabrics, creating a continuous conduit of water transport from the back side to the face side, another yarn formed loops together with the first yarn at the back so that loops at the back were formed by two yarns bundled together, simulating the coarse stem of plants. On the face side, in addition to loops formed by the first yarn, the third yarn was introduced to form independent loops. As a consequence, the loop number at the face side was twice as many as that at the back side. More independent loops at the face side made the yarns more exposed, creating enhanced evaporation and simulating the “cohesion and tension effect” as existed in plants.

4.3.1 Sample preparation

Figure 4-3 (C), (D) and (E) shows a conventional 1x1 rib double jersey structure, a double jersey knitting structure constructed of different yarns for the face and back, and a double jersey knitting structure mimicking the branching network of plants. The structures shown in Figure 4-3 (C) and (D) are used for comparison purpose in the study.

In Structure-D, in the first feeder Yarn A is stitched on each dial needle to form loops at the back side; in the second feeder Yarn B is stitched on short cylinder needles and tucked on short dial needles to link the face and back side; and in the third feeder Yarn C is stitched on long cylinder needles and tucked on long dial needles to link the face and back side.

In Structure-E, in the first feeder Yarn B is stitched at both dial and cylinder needles, at the same time Yarn A is knitted on short dial needles; in the second feeder Yarn C is stitched on long cylinder needles. The yarn setting on machine in the first row is shown in Figure 4-4.

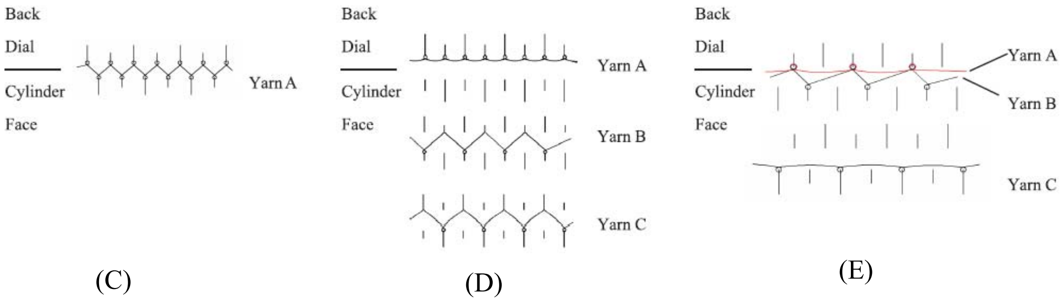


Figure 4-3 Knitting notation of (C), (D) and (E)

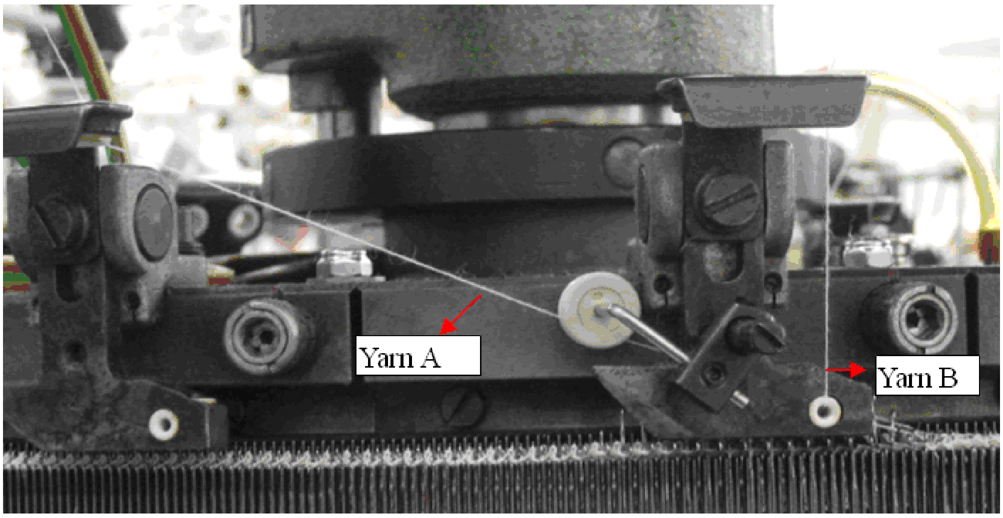
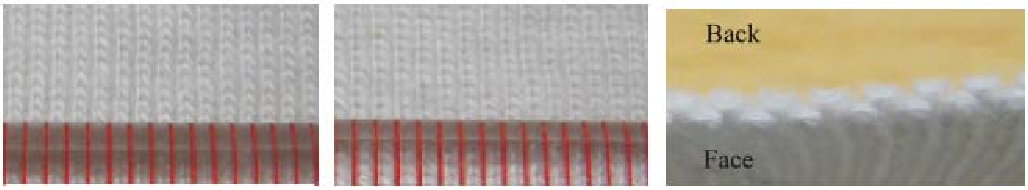


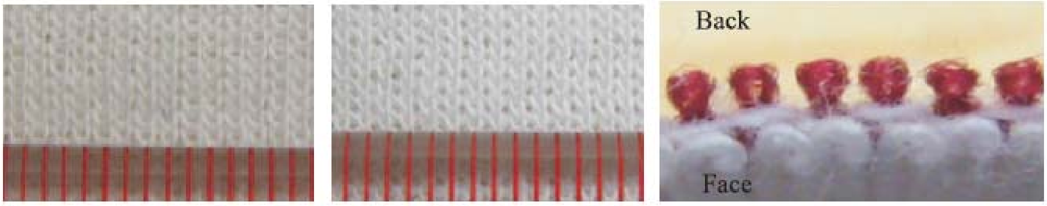
Figure 4-4 The yarn setting of the first feeder in Structure -E

In Structure-C, Yarn A appears on both the back and face sides of fabrics, so yarns in these two sides are the same. Both Structures-D and E can form distinct fabric layer when using different yarns. However, in Structure-E larger loops are formed at the back side and smaller loops at the face side, because Yarn A at the back side was only stitched on short dial needles, but Yarn B and Yarn C were stitched on every needle at the face side. Consequently, the walewise density of the back side and face side were the same, but the coursewise density of the back side was only half of that of the face side. The total density of loops in unit area at the back side was therefore only half of that at the face side.



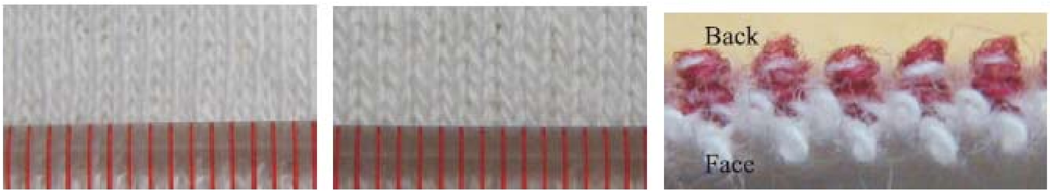
Face side Back side Cross-section

(C)



Face side Back side Cross-section

(D)



Face side Back side Cross-section

(E)

Figure 4-5 Face side, back side and cross-section of fabrics knitted in three structures

Figure 4-5 shows the face side, back side and cross section of fabrics knitted in three structures. The fabrics of Structures-C and D have the same loop number and size at the back and face side. The fabric of Structure -E has bigger loop size and less loop number at the back side, smaller loop size and more loop number at the face side, resulting greater inter-yarned space at the back and smaller inter-yarned space at the face, mimicking the tapering of water conduits (viz. xylem) in plants. Moreover, loops at the back side are formed by two yarns bundled together on every other needle, but loops at the face side are formed by single yarns on every needle, resulting in greater exposed yarn surface areas at the face than that at the back. The greater exposed yarn surface area promotes surface evaporation, whereas the bundling of two yarns at the back promotes liquid transport from the back to the face, creating a process similar to the "cohesion-tension mechanism" existed in plants.

We produced twenty two samples in three knitting structures illustrated in Figure 4-3 with different types of yarn combinations on a circular knitting machine. Table 4-2 lists the details of fabric samples. Samples Nos.7-12 were in Structure-C, among which sample Nos. 7-10 were knitted with two yarns fed together and sample Nos. 11 and 12 were knitted with a single yarn. Two yarns were fed together in sample Nos. 7-10 in order to compare them with samples in Structures-D and E made of the same two types of yarns. In Table 4-2, sample Nos. 13-20 and sample Nos. 21-28 were in Structures -D and E, respectively, made with eight yarn combinations. The finish procedure was identical as mentioned in Experiment No.1.

Table 4-2 Yarn type, mass, thickness and stitch density of the knitted fabrics

Sample No	Yarns	Mass (g/m^2)	Thickness (mm) ($0.5gf/cm^2$)	Density (loop/ cm^2) Face/back
Structure -C	Yarn A			
7	Cotton 32Ne & Cotton 32Ne (Two yarns fed together)	296.2	2.079	104/104
8	Cotton 32Ne & Cotton 40Ne (Two yarns fed together)	280.9	1.951	104/104
9	Cotton 32Ne & Polyester 100D (Two yarns fed together)	263.5	1.699	108/108
10	Cotton 32Ne & Polyester 150D (Two yarns fed together)	306.3	1.834	108/108
11	Cotton 32Ne (single yarn)	180.9	1.595	120/120
12	Cotton 20Ne (single yarn)	276.1	1.574	91/91
Structure -D	Yarn A / Yarn B/ Yarn C			
13	Cotton 32Ne/ Cotton 32Ne/ Cotton 32Ne	218.4	1.865	99/99
14	Cotton 40Ne/ Cotton 32Ne/ Cotton 32Ne	193.7	1.728	94.5/94.5
15	Polyester 100D/ Cotton 32Ne/ Cotton 32Ne	178.2	1.653	95/95
16	Polyester 150D/ Cotton 32Ne/ Cotton 32Ne	179.9	1.563	90/90
17	Cotton 20Ne/ Cotton 20Ne/ Cotton 20Ne	343.9	2.222	108/108
18	Cotton 32Ne/ Cotton 20Ne/ Cotton 20Ne	301.1	2.119	108/108
19	Polyester 100D/ Cotton 20Ne/ Cotton 20Ne	249.7	1.941	104.5/104.5
20	Polyester 150D/ Cotton 20Ne/ Cotton 20Ne	250.4	1.883	94.5/94.5
Structure -E	Yarn A / Yarn B/ Yarn C			
21	Cotton 32Ne/ Cotton 32Ne/ Cotton 32Ne	258.28	2.335	126/63
22	Cotton 40Ne/ Cotton 32Ne/ Cotton 32Ne	249.28	2.279	126/63
23	Polyester 100D/ Cotton 32Ne/ Cotton 32Ne	259.29	2.333	140/70
24	Polyester 150D/ Cotton 32Ne/ Cotton 32Ne	245.51	2.168	126/63
25	Cotton 20Ne/ Cotton 20Ne/ Cotton 20Ne	387.41	2.802	110/55
26	Cotton 32Ne/ Cotton 20Ne/ Cotton 20Ne	352.21	2.689	121/60.5
27	Polyester 100D/ Cotton 20Ne/ Cotton 20Ne	323.84	2.668	121/60.5
28	Polyester 150D/ Cotton 20Ne/ Cotton 20Ne	324.42	2.579	110/55

4.3.2 Results and discussion

4.3.2.1 The effect of knitting structure on initial water absorption rate

Table 4-3 Initial water absorption rates (g/s) measured by TWTT

Yarn	Sample No	Structure -C		Sample No	Structure -D		Sample No	Structure -E	
		mean	s.d.		mean	s.d.		mean	s.d.
Cotton 32Ne & Cotton 32Ne	7	2.02	0.173	13	2.04	0.068	21	2.27	0.123
Cotton 40Ne & Cotton 32Ne	8	1.94	0.090	14	2.01	0.042	22	2.25	0.071
Polyester 100D& Cotton 32Ne	9	1.99	0.046	15	1.90	0.122	23	2.19	0.045
Polyester 150D& Cotton 32Ne	10	1.83	0.104	16	1.81	0.015	24	2.05	0.131
Cotton 20Ne& Cotton 20Ne				17	1.94	0.031	25	2.22	0.154
Cotton 32Ne& cotton 20Ne				18	1.98	0.080	26	2.17	0.057
Polyester 100D& Cotton 20Ne				19	1.88	0.069	27	2.21	0.072
Polyester 150D& Cotton 20Ne				20	1.79	0.075	28	2.16	0.098
Cotton 32Ne Single	11	1.82	0.088						
Cotton 20Ne Single	12	1.76	0.089						

Table 4-4 The two-way ANOVA analysis of the initial water absorption rates (g/s)

Factor	Between Structures -C and -D		Between Structures -C and -E		Between Structures -D and -E	
	F	P	F	P	F	P
Structure	$F_{(1,16)}$=0.007	0.934	$F_{(1,16)}$=3.75	0.000	$F_{(1,32)}$=19.97	0.000
Yarn	$F_{(3,16)}$=8.909	0.010	$F_{(3,16)}$=0.49	0.050	$F_{(7,32)}$=4.409	0.002
Structure*Yarn	$F_{(3,16)}$=1.281	0.315	$F_{(3,16)}$=0.04	0.079	$F_{(7,32)}$=0.642	0.718

Note: When comparing Structure -C and -D, and comparing Structure -C and -E, sample Nos. 11 and 12 were excluded as they were knitted by single Cotton 32Ne and 20Ne yarns, respectively

Table 4-3 shows the results of initial water absorption rates measured by TWTT test. As can be seen, the initial water absorption rates of sample Nos. 11 and 12, which were made of single cotton yarns, were generally lower than those of fabric samples made of two or three yarn combinations, and fabric samples in Structure -E were about 10%-20% higher than those of corresponding fabric samples in the other two structures made of the same yarns.

The effects of fabric structure, yarn type and interaction on initial water absorption rate were further analyzed by two-way ANOVA to examine statistical significances. When comparing Structures-C and D and comparing Structures-C and E, the data for fabric samples made of four yarn combinations were analyzed by one-way ANOVA, since sample Nos. 11 and 12 were knitted by single Cotton 32Ne and 20Ne yarns in Structure-C. When comparing Structures-D and E, the data of fabric samples made of eight yarn combinations were analyzed by the one-way ANOVA. As can be seen from the results in Table 4-4, in terms of initial water absorption rates, the differences between Structures-C and D were not significant (P=0.934), but there were significant differences between Structure-E and Structure-C (P=0.000) or Structure -D (P=0.000).

Reasons for improved initial water absorption rates in Structure-E might be that there were two yarns grouped together at the back side (the side intended to be in contact to the skin) which can absorb water faster. The larger pore size at the back side and smaller pores at the face side also created a net capillary force in the direction from the back side to the face side, which also aided liquid water transport.

ANOVA analysis also showed that yarn types influenced initial water absorption rates significantly in all three structures (P=0.01, 0.05 and 0.002 respectively). Blended fabrics containing hydrophobic polyester yarns had a relatively lower water absorption rate compared with 100% cotton fabrics which were hydrophilic. Nevertheless, the interaction between structure and yarn types did not had significant effects on initial water absorption rate as shown by three two-way ANOVA tests (P=0.315, 0.079 and 0.718, respectively).

4.3.2.2 The effect of knitting structure on one-way transport capacity

Table 4-5 One-way transport capacity measured by MMT

Yarn	Sample No	Structure -C		Sample No	Structure -D		Sample No	Structure -E	
		mean	s.d.		mean	s.d.		mean	s.d.
Cotton 32Ne & Cotton 32Ne	7	66.15	5.24	13	61.93	14.08	21	104.29	4.239
Cotton 40Ne & Cotton 32Ne	8	79.84	6.27	14	68.28	3.782	22	107.13	16.34
Polyester 100D& Cotton 32Ne	9	79.86	26.71	15	297.11	24.62	23	485.66	36.45
Polyester 150D& Cotton 32Ne	10	-1.30	11.8	16	331.58	16.70	24	579.70	56.63
Cotton 20Ne& Cotton 20Ne				17	55.5	8.894	25	111.37	13.72
Cotton 32Ne& cotton 20Ne				18	62.635	21.91	26	132.96	31.67
Polyester 100D& Cotton 20Ne				19	191.92	29.01	27	286.35	13.43
Polyester 150D& Cotton 20Ne				20	165.59	2.916	28	304.20	23.57
Cotton 32Ne Single	11	50.09	10.98						
Cotton 20Ne Single	12	75.47	9.23						

Table 4-6 The two-way ANOVA analysis of one-way transport capacity measured by MMT

Factor	Between Structures -C and -D		Between Structures -C and -E		Between Structures -D and -E	
	F	P	F	P	F	P
Structure	$F_{(1,16)}$=426.99	0.000	$F_{(1,16)}$=508.22	0.000	$F_{(1,32)}$=246.67	0.000
Yarn	$F_{(3,16)}$=95.061	0.000	$F_{(3,16)}$=108.25	0.000	$F_{(7,32)}$=227.93	0.000
Structure*Yarn	$F_{(3,16)}$=17.994	0.000	$F_{(3,16)}$=157.99	0.000	$F_{(7,32)}$=15.125	0.000

Note: When comparing Structure -C and -D, and comparing Structure -C and -E, sample Nos. 11 and 12 were excluded as they were knitted by single Cotton 32Ne and 20Ne yarns, respectively

The results of one-way transport capacity are listed in Table 4-5. As can be seen, fabric samples in Structure-E had higher one-way transport capacity than fabric samples in the other two structures made of the same yarn types. Two-way ANOVA analyses were conducted to examine the significance of differences among these three structures. The results (listed in Table 4-6) shows, in terms of one-way transport capacity, there were significant differences between three structures, and the effects of yarn types and the interaction of structure and yarn types were also highly significant. The blended fabrics containing polyester in Structures-D and E had much higher one-way capacity than the corresponding 100% cotton fabrics. This might be because the hydrophobic yarns do not absorb water, so water retained in hydrophobic yarns at the back side would be less than that of hydrophilic yarns at the face side.

The improved one-way transport capacity of Structure-E may be due to the fact that there was less number of stitches and larger stitch size at the back side of fabrics, resulting in less water retained at the back side or more water transported to the face side. Therefore, the differences of accumulative moisture content between the two surfaces of fabrics were greater. According to the grading of one way transport properties (Yao, 2006), fabrics in Structure-E made of different fibers had good to excellent one way transport capacity.

4.3.2.3 The effect of knitting structure on air resistance

Table 4-7 Air resistance (kPa s/m) measured by air-permeability tester (KES-F8-AP1)

Yarn	Sample No	Structure -C		Sample No	Structure -D		Sample No	Structure -E	
		mean	s.d.		mean	s.d.		mean	s.d
Cotton 32Ne & Cotton 32Ne	7	0.197	0.012	13	0.095	0.004	21	0.078	0.005
Cotton 40Ne & Cotton 32Ne	8	0.152	0.009	14	0.085	0.004	22	0.074	0.004
Polyester 100D& Cotton 32Ne	9	0.136	0.006	15	0.104	0.005	23	0.091	0.005
Polyester 150D& Cotton 32Ne	10	0.130	0.005	16	0.087	0.004	24	0.067	0.003
Cotton 20Ne& Cotton 20Ne				17	0.402	0.013	25	0.299	0.014
Cotton 32Ne& cotton 20Ne				18	0.215	0.009	26	0.287	0.006
Polyester 100D& Cotton 20Ne				19	0.192	0.012	27	0.228	0.009
Polyester 150D& Cotton 20Ne				20	0.159	0.007	28	0.157	0.005
Cotton 32Ne Single	11	0.129	0.008						
Cotton 20Ne Single	12	0.262	0.016						

Table 4-8 The two-way ANOVA analysis of air resistance test

Factor	Between Structures -C and -D		Between Structures -C and -E		Between Structures -D and -E	
	F	P	F	P	F	P
Structure	$F_{(1,32)}$=742.33	0.000	$F_{(1,.32)}$=1149.0	0.000	$F_{(1,64)}$=16.305	0.000
Yarn	$F_{(3,32)}$=50.548	0.000	$F_{(3,32)}$=51.904	0.000	$F_{(7,64)}$=1505	0.000
Structure*Yarn	$F_{(3,32)}$=48.376	0.000	$F_{(3,32)}$=49.088	0.000	$F_{(7,64)}$=95.574	0.000

Note: When comparing Structure -C and -D, and comparing Structure -C and -E, sample Nos. 11 and 12 were excluded as they were knitted by single Cotton 32Ne and 20Ne yarns, respectively

A higher air resistance means that a smaller amount of air could flow through. For summer wear or sportswear, it is desirable to have lower air resistance so that more cold air can penetrate through to bring the heat away from body and accelerate sweat evaporation at the skin and fabric surface. As can be seen from test results listed in Table 4-7, for the majority of fabrics in Structure-E, they had relatively lower air resistance values than corresponding fabrics in Structures-C and D made of same yarn types (Viz. the air resistance of sample No.21 was lower than that of sample Nos. 7, 11 and 13, respectively; that of sample No.22 was lower than that of sample Nos. 8 and 14, respectively; that of sample No.23 was lower than of sample Nos. 9 and 15, respectively; that of sample No.24 was lower than that of sample Nos. 10 and 26, respectively; that of sample No.25 was lower than that of sample Nos. 12 and 17, respectively; that of Sample No.28 was lower than that of sample No.20). As confirmed by two-way ANOVA analysis, such differences were highly significant. The improved air resistance of Structure -E may be due to the reduced number of loops and larger inter-yarned space at the back side. The ANOVA analyses also showed that the effects of yarn types and the interactions of yarns and structures were significant (see Table 4-8). This was understandable as yarn linear density affected the compactness of fabrics.

4.3.2.4 The effect of knitting structure on water vapor permeability

Yarn	Sample No	Structure -C		Sample No	Structure -D		Sample No	Structure -E	
		mean	s.d.		mean	s.d.		mean	s.d.
Cotton 32Ne & Cotton 32Ne	7	946	16	13	964	19	21	995	3
Cotton 40Ne & Cotton 32Ne	8	975	11	14	1005	12	22	999	9
Polyester 100D& Cotton 32Ne	9	965	30	15	1013	13	23	946	10
Polyester 150D& Cotton 32Ne	10	1017	15	16	1012	30	24	964	24
Cotton 20Ne& Cotton 20Ne				17	903	40	25	925	24
Cotton 32Ne& cotton 20Ne				18	994	35	26	985	37
Polyester 100D& Cotton 20Ne				19	1007	21	27	944	7
Polyester 150D& Cotton 20Ne				20	936	24	28	954	6
Cotton 32Ne Single	11	1017	25						
Cotton 20Ne Single	12	1004	21						

Table 4-9 Water vapor permeability (g/m^2/day) measured according to BS 7209

Factor	Between Structures -C and -D	Between Structures -C and -E	Between Structures -D and -E

	F	P	F	P	F	P
Structure	$F_{(1,16)}=7.862$	0.013	$F_{(1,.16)}=0.002$	0.966	$F_{(1,32)}=5.245$	0.029
Yarn	$F_{(3,16)}=8.744$	0.001	$F_{(3,16)}=5.239$	0.100	$F_{(7,32)}=9.19$	0.000
Structure*Yarn	$F_{(3,16)}=1.887$	0.172	$F_{(3,16)}=10.16$	0.001	$F_{(7,32)}=4.322$	0.002

Note: When comparing Structure -C and -D, and comparing Structure -C and -E, sample Nos. 11 and 12 were excluded as they were knitted by single Cotton 32Ne and 20Ne yarns, respectively

Table 4-5 The two-way ANOVA analysis of water vapor permeability

The water vapor permeability values of fabric samples are listed in Table 4-9 and the results of associated two-way ANOVA analyses are listed in Table 4-10. Comparing three structures, it appears that most of fabrics in Structure-D had better moisture permeability than corresponding fabrics in Structures-C and E (P=0.013 and P=0.029 respectively), while differences between Structures-C and E were not significant (P=0.966). There were also generally significant effects of yarn types on water vapor permeability (P=0.001, P=0.1 and P=0.000, respectively), which was understandable as yarn linear density affected the compactness of fabrics.

The higher water vapor permeability of fabrics in Structure-D may be because they had relatively lower thickness, as fabric thickness was an important factor in determining moisture vapor resistance. Comparing Structures-C and E, although fabrics in Structure -E were thicker than corresponding fabrics in Structure-C made of the same yarns, the two did not have any significant differences in moisture vapor permeability, probably because the more open construction of Structure-E contributed to moisture transmissions. To further reduce the moisture permeability of fabrics in Structure-E, it may be necessary in future work to reduce the thickness of fabrics in Structure-E, while maintaining the open structure.

4.4 Conclusions

Using plating technique, Experimental No.1 was the initial effort to simulate the structure with two-yarned loops at the back side and one-yarned loops at the face side. Experimental No.2 further simulated plant structures with less loops at the back side serving as stems and more loops at the face side serve as leaves. It has been demonstrated that the biomimetics of branching structure of plants can improve the water absorption and one way transport properties of fabrics. Fabrics developed in such branching structure and made from different combinations of yarns exhibited faster water absorption and better moisture management properties, as measured on the Transplanar Water Transport Tester (TWTT) and Moisture Management Tester (MMT). Furthermore, the novel structures also improved the air permeability of fabrics. The improved water absorption rate, moisture management properties and air permeability were beneficial to clothing comfort. In the next chapter, weft tucking technique was employed to better emulate the branching network structure of plants.

5. Development of weft tucking structures to emulate the branching network of plants

5.1 Introduction

Although the plating method described in Chapter 4 can simulate plant structures to some extent, previous work fell short in the emulation of exact branching structure since only one of two yarns in the bottom layer formed loops in the top layer with the limited branch.

To overcome this deficiency and better emulate the branching network structure of plants, further research was carried out involving the tucking method. In the present chapter, various double-layered fabrics were developed which bundled two or more yarns in the back layer, and employed tuck stitches to separate them in the top layer, thereby creating additional continuous water transport channels through the yarns from the bottom fabric layer to the top layer.

5.2 Sample preparation

Three different knitted fabrics were developed to imitate the branching structure of a plant, and their water transport properties were compared with those of conventional knitted fabrics. Gauge E12 circular knitting machine with positive feeders was used to produce the fabrics. In Figure 5-1:

Structure-I: It represents the conventional knitted fabric, which is taken as the control fabric. In this structure, alternate needles knitted at alternate feeders. For example, the yarn forms loops (i.e. knits) only on long needles at the first feeder (i.e. the first row or course), while at the next feeder (i.e. the next row or course), the yarn forms loops on short (i.e. alternate) needles. The two sides of this fabric are identical. For those fabrics where polyester and cotton yarns were used, the two yarns were knitted at alternate feeders (e.g. the polyester yarns knitted on long needles and the cotton yarns on short needles).

Structure-II: In the first feeder, yarns knitted on each of dial and cylinder long needles. In the second feeder, loops were formed by short cylinder needles, and tucks by long dial needles. In the third feeder, long dial and short cylinder needles knitted; while in the fourth feeder long dial needles formed tuck loops, and long cylinder needles knitted. In this structure, the surface created by dial needles represented the technical back of fabrics which comes into contact with the skin. For the blended fabrics, polyester yarn was used in the first and third feeders and cotton yarn in the second and fourth feeders.

Structure-III: This structure involved a six feeder repeat. At the first feeder, the yarn knitted on long needles on both cylinder and dial. At the second feeder, tucks were formed on long dial needles, and knitted loops on short cylinder needles. At the third feeder, tucks were formed on long dial needles, while long cylinder needles formed loops. At the fourth, fifth and sixth feeders, needles followed the same knitting and tucking sequence as at the previous three feeders, except that different needles were involved. For the blended fabrics, polyester yarn was knitted at the first and fourth feeders and cotton yarn at the other feeders.

Structure -IV: For this structure, long cylinder and dial needles knitted at the first feeder, while at the next three feeders alternate cylinder needles knitted at alternate feeders and long dial needles tucked at all three feeders. Hence, three tuck stitches were formed on dial needles at three consecutive feeders. For blended fabrics, polyester was again supplied at the first feeder and cotton yarn at the other feeders.

Knitted fabrics were scoured and bleached before all measurements and testing. The finish procedure was as same as mentioned in Chapter 4.

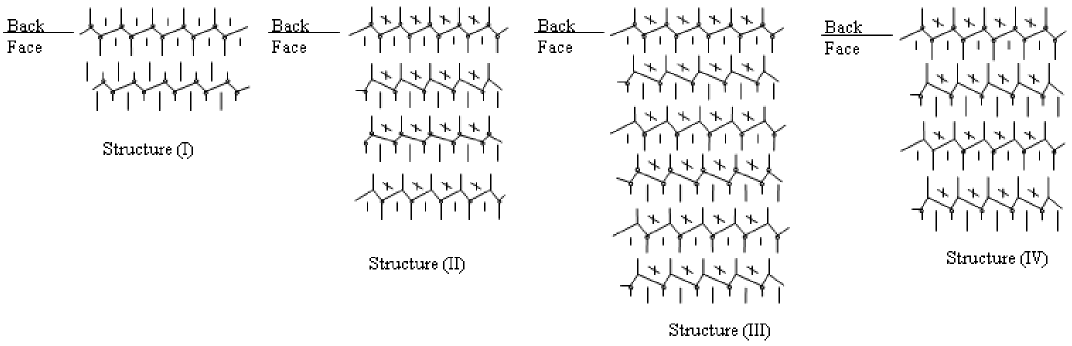
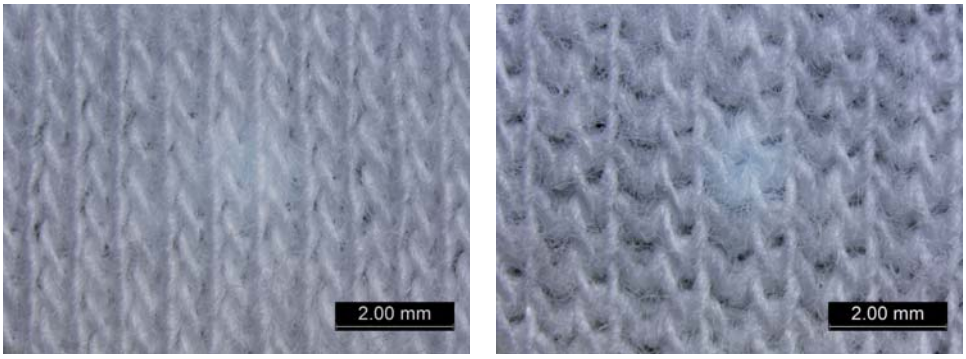
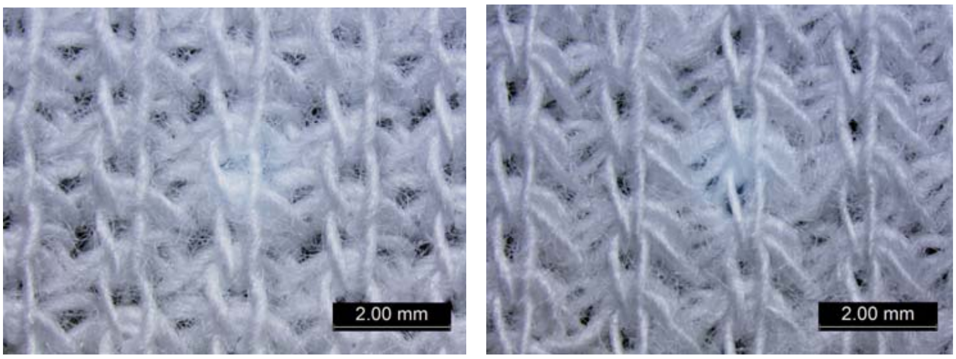


Figure 5-1 Knitting notation of the different structures produced (Dial needles formed the back of the fabric and cylinder needles the face (front))



Structure I Structure II



Structure III Structure IV

Figure 5-2 The technical back surfaces of the different fabric structures

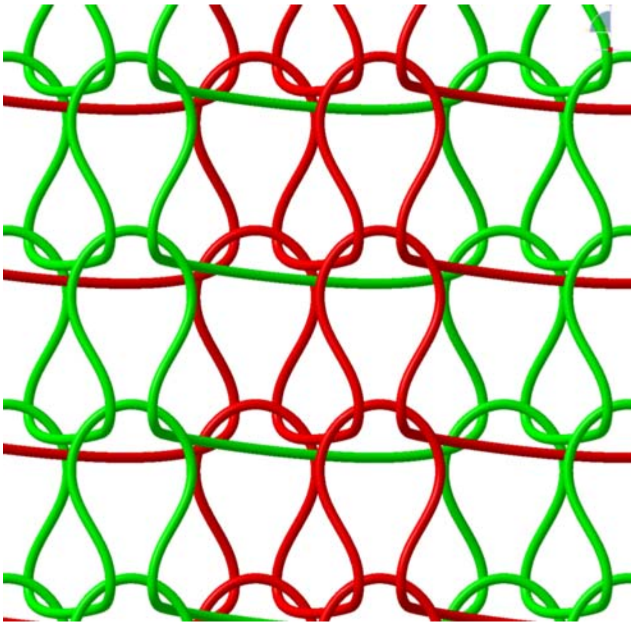


Figure 5-3 The ideal pattern of Structure I

Figure 5-4 The ideal cross-sectional pattern of Structure I

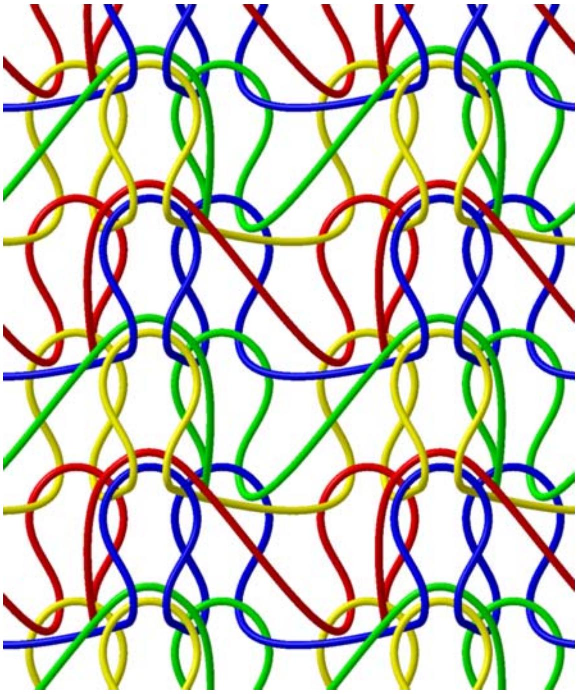


Figure 5-5 The ideal pattern of Structure II

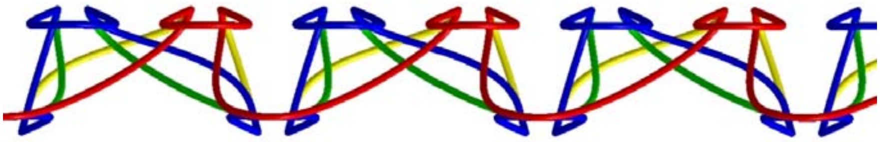


Figure 5-6 The ideal cross-sectional pattern of Structure II

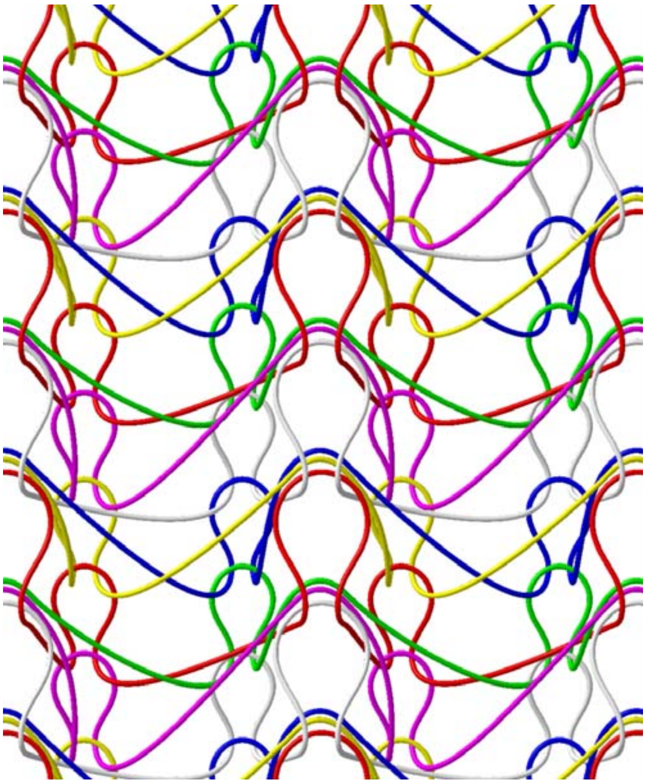


Figure 5-7 The ideal pattern of Structure III

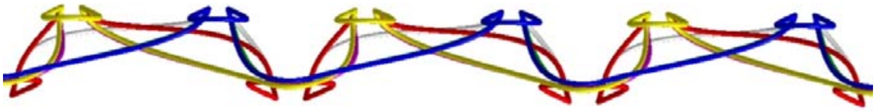


Figure 5-8 The ideal cross-sectional pattern of Structure III

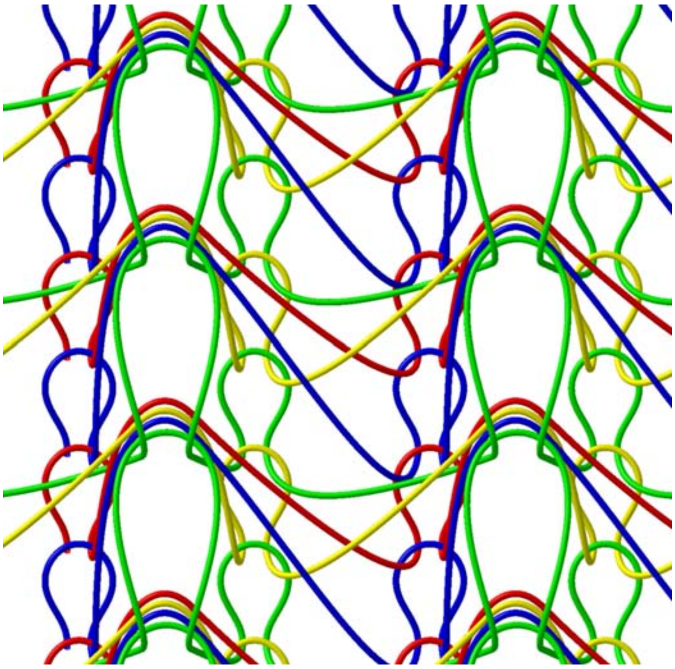


Figure 5-9 The ideal pattern of Structure IV

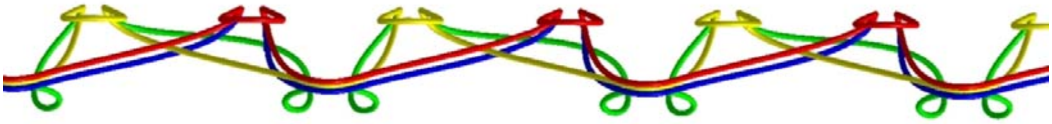


Figure 5-10 The ideal cross-sectional pattern of Structure IV

Figures 5-3, 5-4, 5-5, 5-6, 5-7, 5-8, 5-9 and 5-10 were the ideal patterns of Structures - I, II, III and IV. From the view of cross-sectional pictures, the plant structures show branching shape(developed by Catia, V5 R19).

The photographs of the technical back surfaces of the four knitted structures are shown in Figure 5-2. To better understand the effect of the structures, two trials were conducted. In the first trial (Trial No. 1), the same cam settings were maintained during the knitting of all fabrics, thereby maintaining constant loop lengths throughout. In the second trial (Trial No. 2), the cam settings and yarn feed rates were adjusted to produce plant based development fabrics similar in weight to the corresponding control fabrics.

32Ne cotton yarn, 20Ne cotton yarn and 150 D polyester yarn were used to produce different knitted fabrics, the specifications of fabrics produced in Trial No. 1 and No. 2 are given in Table 5-1.

Table 5-1 Fabric details and test results for Trial No. 1 and Trial No. 2

Sample No.	Yarn	Structure	Mass (g/m^2)	Thickness (mm) (0.5gf/cm^2)	Density (loops/cm^2)	
					Back	Face
Trial No. 1						
1	Cotton 32Ne	Control(I)	214	1.23	169	169
2		(II)	201	1.36	79	159
3		(III)	187	1.33	48	143
4		(IV)	204	1.29	42	169
5	Cotton 20Ne	Control(I)	360	1.42	178	178
6		(II)	325	1.49	84	169
7		(III)	328	1.69	52	157
8		(IV)	355	1.69	48	193
9	Cotton 32Ne & Polyester 150D	Control(I)	203	1.21	179	179
10		(II)	232	1.42	79	159
11		(III)	218	1.49	61	182
12		(IV)	201	1.48	44	177
13	Cotton 20Ne & Polyester 150D	Control(I)	288	1.33	174	174
14		(II)	242	1.67	77	154
15		(III)	261	1.7	52	156
16		(IV)	247	1.68	37	149
Trial No. 2						
17	Cotton 32Ne	(III)	196	1.39	59	176
18		Control(I)	199	1.27	149	149
19		(IV)	204	1.29	42	169
20		Control(I)	206	1.22	154	154
21	Cotton 20Ne	(III)	328	1.69	52	157
22		Control(I)	326	1.48	139	139
23		(IV)	355	1.69	48	193
24		Control(I)	360	1.42	178	178
25	Cotton 32Ne & Polyester 150D	(III)	218	1.49	61	182
26		Control(I)	213	1.25	192	192
27		(IV)	201	1.48	44	177
28		Control(I)	203	1.21	179	179
29	Cotton 20Ne & Polyester 150D	(III)	261	1.7	52	156
30		Control(I)	262	1.39	144	144
31		(IV)	247	1.68	37	149
32		Control(I)	248	1.43	130	130

5.3 Results and Discussion

Table 5-2 TWTT, MMT, Air resistance and Water vapor permeability results

Sample No.	Yarn	Structure	Initial absorption rate (g/s)		One-way transport		Air resistance (kPa s/m)		Water vapor permeability (g/m^2/day)	
			mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.
Trial No. 1										
1	Cotton 32Ne	Control(I)	2.12	0.032	-39.71	1.72	0.146	0.006	1024	25
2		(II)	2.45	0.052	15.79	0.98	0.102	0.004	1025	6
3		(III)	2.38	0.118	33.26	5.53	0.069	0.005	1054	32
4		(IV)	2.35	0.008	16.23	13.37	0.098	0.007	1075	2
5	Cotton 20Ne	Control(I)	2.21	0.025	-86.97	6.15	0.545	0.019	977	53
6		(II)	2.62	0.025	40.66	34.20	0.396	0.007	994	74
7		(III)	2.51	0.058	45.07	7.89	0.183	0.014	991	12
8		(IV)	2.44	0.111	41.50	14.51	0.327	0.014	986	38
9	Cotton 32Ne & Polyester 150D	Control(I)	1.91	0.062	-78.58	15.20	0.047	0.002	981	8
10		(II)	1.68	0.062	335.83	53.9	0.066	0.007	1033	26
11		(III)	2.29	0.041	422.51	40.41	0.068	0.009	1043	11
12		(IV)	2.14	0.065	254.87	21.63	0.033	0.002	1028	22
13	Cotton 20Ne & Polyester 150D	Control(I)	2.07	0.065	-27.49	14.56	0.124	0.009	994	6
14		(II)	1.72	0.144	231.11	5.11	0.052	0.003	1008	31
15		(III)	2.52	0.065	369.41	8.14	0.080	0.004	985	9
16		(IV)	2.41	0.035	227.12	9.05	0.049	0.004	1009	22
Trial No. 2										
17	Cotton 32Ne	(III)	2.43	0.100	59.49	14.45	0.084	0.005	1020	31
18		Control(I)	2.18	0.073	20.28	10.03	0.099	0.005	999	25
19		(IV)	2.35	0.118	16.23	13.37	0.098	0.007	1075	2
20		Control(I)	2.07	0.086	2.657	12.92	0.115	0.006	1037	40
21	Cotton 20Ne	(III)	2.51	0.058	45.07	7.893	0.183	0.014	991	12
22		Control(I)	2.30	0.061	12.17	6.081	0.281	0.011	980	17
23		(IV)	2.44	0.111	41.50	14.51	0.327	0.014	986	38
24		Control(I)	2.21	0.025	-86.97	6.154	0.545	0.019	977	53
25	Cotton 32Ne & Polyester 150D	(III)	2.29	0.041	422.51	40.41	0.067	0.009	1043	11
26		Control(I)	1.86	0.141	-40.77	39.87	0.068	0.004	1042	2
27		(IV)	2.14	0.065	254.88	21.63	0.033	0.002	1028	22
28		Control(I)	1.91	0.062	-78.58	15.21	0.047	0.002	981	8
29	Cotton 20Ne & Polyester 150D	(III)	2.52	0.065	369.41	8.147	0.080	0.004	985	9
30		Control(I)	2.15	0.090	-11.51	5.495	0.085	0.003	979	35
31		(IV)	2.41	0.035	227.12	9.056	0.049	0.004	1009	22
32		Control(I)	2.2	0.083	-1.287	6.119	0.074	0.006	1006	20

5.3.1 The effect of knitting structure on initial water absorption rate

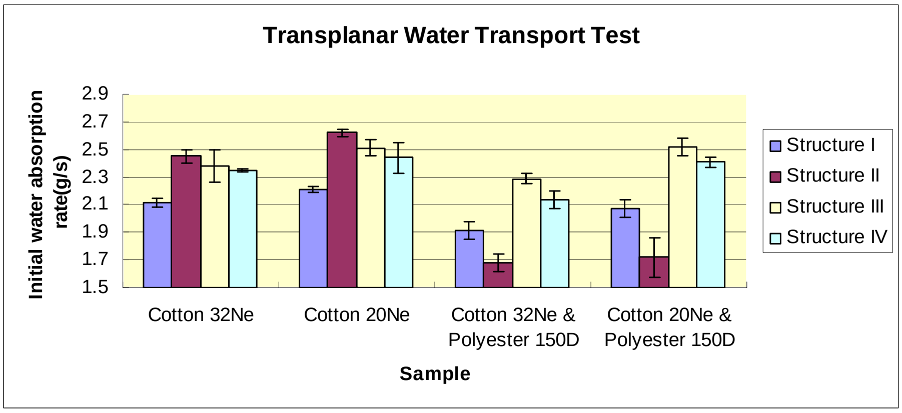


Figure 5-11 The initial water absorption rates of Trial No. 1 samples

The initial water absorption rates of the various Trial No.1 samples are shown in Table 5-2 and Figure 5-11. The ANOVA analysis showed that knitted structure ($F_{\text{structure}\ (3,\ 32)} = 38.102$, $P = 0.000$), yarn ($F_{\text{yarn}\ (3,\ 32)} = 48.942$, $P = 0.000$) and interaction between fabric structure and yarn ($F_{\text{interaction}\ (9,\ 32)} = 15.583$, $P = 0.000$) had significant effects on the initial water absorption rates of fabrics.

To assess the differences between different fabric structures, one-way ANOVA was conducted to calculate the F-value and P-value. Within each yarn group, the significance of differences between control structure and three plant structures was determined.

For cotton fabric samples produced in Trial No. 1, all of which had a similar loop length, plant based fabric structures (i.e. Structures-II, III and IV) exhibited significantly faster initial water absorption rates than corresponding control

(Structure-I) fabrics. When fabrics containing 32Ne cotton yarn were compared, Structure-II (sample No. 2), Structure-III (sample No. 3) and Structure-IV (sample No. 4) had 15.6%, 12.3% and 10.4% faster initial water absorption rates, respectively, than control sample (Structure-I, sample No. 1), these differences being statistically significant ($p<0.05$). Although the average initial absorption rates of different plant-structures were different, the differences were not statistically significant. Comparing sample No. 2 and No. 3, gave $F_{(1, 4)} = 2.028$, $P = 0.228$; comparing sample No. 2 and No. 4, gave $F_{(1, 4)} = 1.481$, $P = 0.291$; and comparing sample No. 3 and No. 4, gave $F_{(1,4)} = 0.221$, $P = 0.663$. The fabric samples, containing the 20Ne cotton yarn (sample Nos. 5-8), exhibited similar trends.

For polyester and cotton blend fabrics (sample Nos. 9-16), Structure-III fabrics (sample Nos. 11 and 15) and Structure-IV fabrics (sample Nos. 12 and 16) exhibited initial water absorption rates which were significantly faster than respective Structure-I control fabrics (sample Nos. 9 and 13). In contrast to this, Structure-II samples (sample Nos. 10 and 14) exhibited initial water absorption rates which were significantly slower than those of respective control samples. This indicates that there was an interaction between fabric structure and yarn type. A possible explanation for this is that, for Structure-II fabrics, polyester yarns presented at the back fabric surface (due to knitted polyester stitches present at the back of the fabric and tuck stitches formed by cotton yarns in the next course) reduced water absorption rates. With regard to pure cotton fabrics, Structure-II fabrics exhibited fastest initial water absorption rates, followed by Structures-III and IV fabrics. The explanation for this may be found in the fact that Structure-II fabrics had the largest number of loops at the back in contact with water. In other words, more cotton was initially in contact with water, enabling more water to be absorbed. Of three plant structure based fabrics, Structure-IV had the least number of loops at the back.

According to the results of Trial No. 1, the initial water absorption rates of Structure-III and Structure-IV fabrics were faster than those of control samples for all types of yarns and it was therefore decided, to focus on these two structures in Trial No. 2.

Apart from the effect of fabric structure, the type of yarn also had a significant effect on initial water absorption rates, with coarser (20Ne) cotton yarns producing faster initial water absorption rates than finer (32Ne) ones, which was consistent with the findings of an earlier study (Kim, 2003b). It also emerged that polyester-cotton blend fabrics had slower initial water absorption rates than pure cotton fabrics, which was attributed to the fact that polyester yarns had lower water absorptions than cotton yarns.

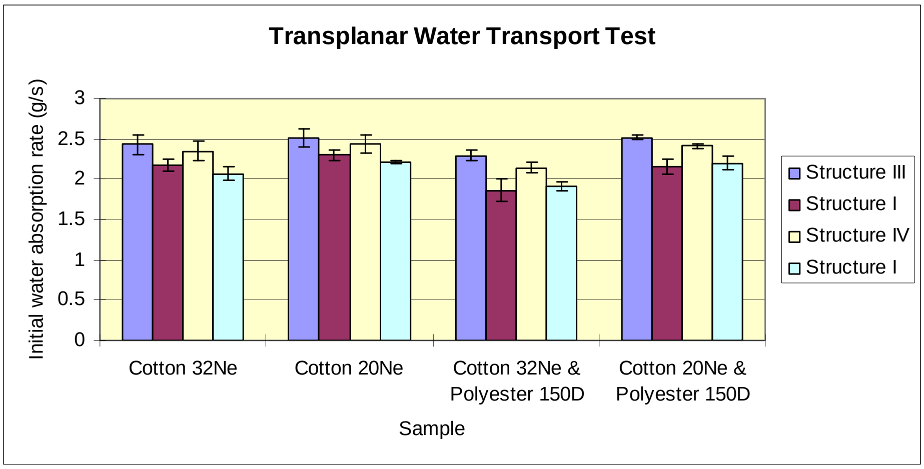


Figure 5-12 The initial water absorption rates of Trial No. 2 samples

Figure 5-12 compares the initial water absorption rates of Structures-III and IV fabrics produced in Trial No. 2 with those of Structure-I control fabrics. As can been seen, Structures-III and IV fabrics exhibited initial water absorption rates which were significantly faster than those of corresponding control fabrics, irrespective of yarn types. For the fabrics with 32Ne cotton yarn, the initial water absorption rates of Structures-III and IV fabrics were 11.5% and 13.5%, respectively, faster ($p < 0.05$) than those of respective Structure-I control fabrics. For the other set of cotton fabrics containing the 20Ne cotton yarn, corresponding figures were 9.1%, and 10.4% ($p < 0.05$), respectively. For polyester and cotton blend fabrics (sample Nos. 25-32), significant increases in initial water absorption rates were observed for plant based fabric structures (i.e. Structures-III and IV) relative to corresponding control fabrics. Structure-III fabrics absorbed water 23.1% ($F_{(1,4)} = 26.442$, $P = 0.007$) faster and Structure-IV 12.0% ($F(1,4) = 19.354$, $P = 0.012$) faster than corresponding Structure-I fabrics containing 32Ne cotton and

150D polyester yarns. Similar trends were observed for the set of fabrics containing the 20Ne cotton and 150D polyester yarns.

The possible mechanisms of the faster water absorption rate of plant structured knitted fabrics as follows:

The tucks connecting the back side and the face side can serve as the branches, as they bundled yarns together on one end and separated them on the other end. Structures-II, III and IV had two, three and four branches respectively, for creating branch net work to reduce water resistance in this system.

The plant based structures created more number of loops at the face side than that at the back side. Loop number of Structures-II, III and IV was two, three and four times at the face side than at the back side, respectively. This promoted faster water evaporation at the face side, creating the cohesion-tension force, which forced liquid water to transport from the back side to the face side.

Additionally, more number of loops at the face side and less number of loops at the back side resulted in loops at the face side with smaller diameter, and loops at the back side with larger diameter. This created a net capillary force pulling liquid water from the back side to the face side.

5.3.2 The effect of knitting structure on one-way transport capacity

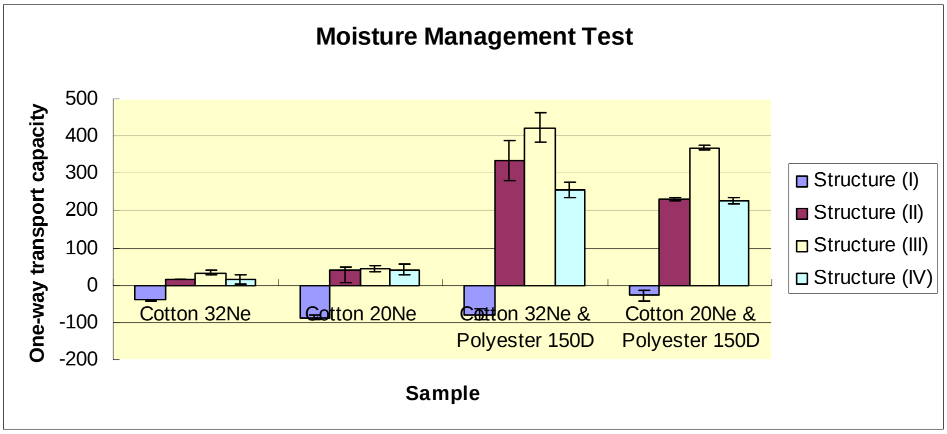


Figure 5-13 The one-way water transport results of Trial No. 1 samples

The MMT one-way water transport test results are presented in Table 5-2, with the results of Trial No. 1 and No. 2 being summarized in Figures 5-13 and 5-14, respectively.

According to the two-way ANOVA analysis, fabric structure and yarn type significantly affected ($F_{\text{yarn}\ (3,\ 32)} = 385.555$, P = 0.000; $F_{\text{structure}\ (3,\ 32)} = 372.102$, P = 0.000) the one-way water transport properties of fabrics, the interaction between yarn type and fabric structure also having a significant effect ($F_{\text{interaction}\ (9,\ 32)} = 52.160$, P = 0.000).

In Trial No. 1, Structures-II, III and IV fabrics exhibited significantly higher one-way water transport values than those of Structure-I fabrics. For the various types of yarns, Structure-II fabrics exhibited 139 - 940% higher one-way water transport values than corresponding Structure-I fabrics, corresponding values for Structures-

III and IV fabrics, being 183 - 1443% and 141 - 925%, respectively.

All Structure-I fabrics exhibited negative one-way water transport values, indicating that there were no one-way water transport in the trans-planar direction (from the back to the face) of fabrics. This means that more water was presented at the back surface of fabrics, which would be in contact with the skin than at the face side of fabrics.

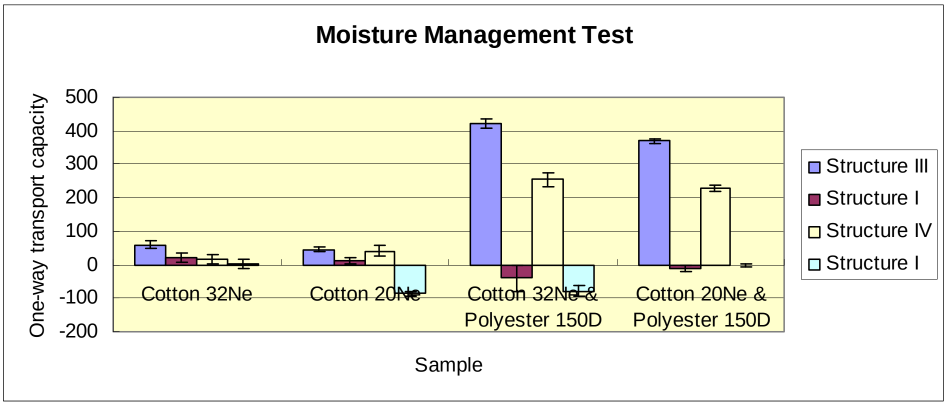


Figure 5-14 The one-way water transport results of Trial No. 2 samples

The fabrics produced in Trial No. 2, where control fabrics were of a similar weight as plant based fabrics, exhibited similar trends in terms of one-way water transport, as those observed in Trial No. 1. Here Structures-III and IV plant based fabric structures exhibited significantly ($p<0.5$) higher one-way water transport values than Structure-I control fabrics, irrespective of yarn type.

Yarn type had a significant effect on one-way water transport values. Plant based fabric structures containing the polyester yarn at the back exhibited higher one-way water transport values than 100% cotton fabrics. This was due to the hydrophobic nature of polyester yarns, which caused it to retain less water at the back of fabrics.

5.3.3 The effect of knitting structure on air resistance

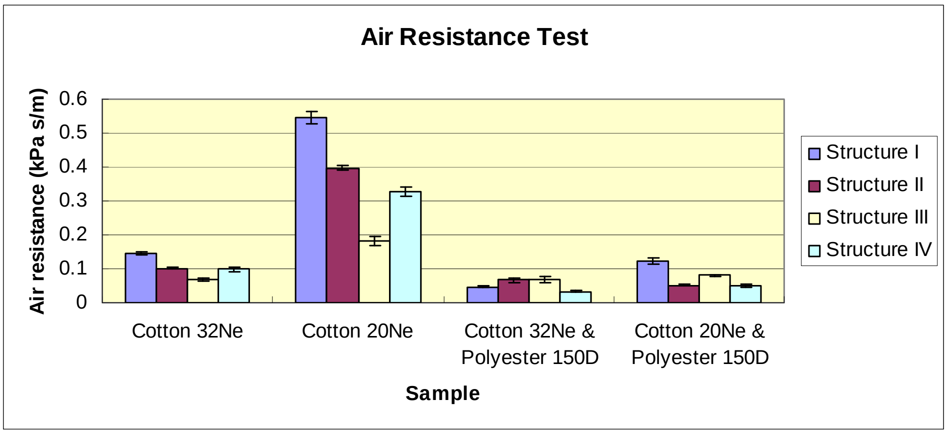


Figure 5-15 The air resistance of Trial No. 1 samples

The air resistance of a textile fabric has a significant effect on its comfort. The results of air resistance tests carried out on Trial No. 1 and No. 2 fabric samples are shown in Figures 5-15 and 5-16, respectively. Two-way ANOVA analysis indicated that fabric structure and yarn type significantly affected fabric air resistance ($F_{\text{yarn}\,(3,\,64)} = 5303$, $P = 0.000$; $F_{\text{structure}\,(3,\,64)} = 635.126$, $P = 0.000$). The interaction between yarn type and fabric structure also had a significant effect on fabric air resistance ($F_{\text{interaction}\,(9,\,64)} = 329.69$, $P = 0.000$).

For 100% cotton fabrics, Structure-I fabrics had a higher air resistance than plant based fabric structures, while in the case of blended fabrics, there was little difference between the air resistance of plant based fabric structures and that of corresponding control fabrics. This was possibly due to the latter fabrics being thinner than the former.

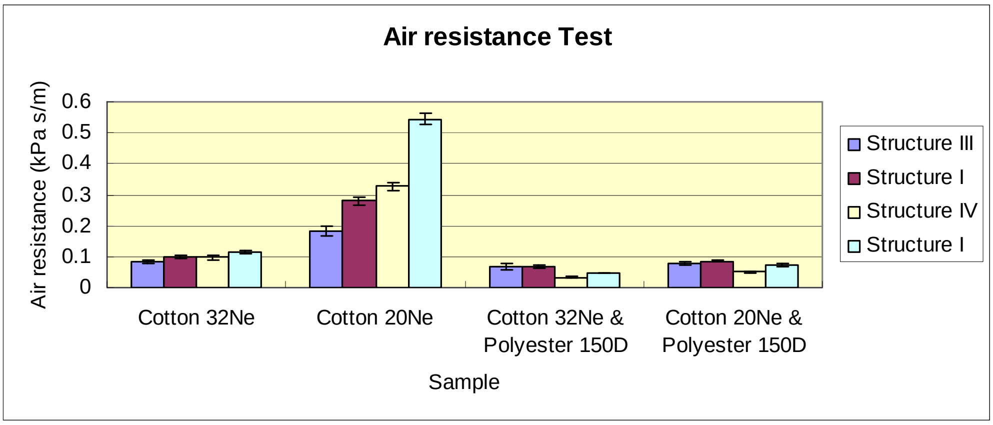


Figure 5-16 The air resistance of Trial No. 2 samples

The air resistance results of Trial No. 2 fabrics exhibited a similar trend to that observed for Trial No. 1, for most of yarns. For fabrics containing the 20Ne cotton yarns, a significantly higher air resistance was observed for plant based fabric structures than for control fabrics. For fabrics with the same structure, a significantly lower air resistance was observed for the finer yarn than for the coarser one.

5.3.4 The effect of knitting structure on water vapor permeability

The results of water vapor permeability tests are presented in Table 5-2. Statistical analysis showed that structure ($F_{\text{yarn}\ (3,\ 32)} = 5.636$, $P = 0.003$) and yarn type ($F_{\text{structure}\ (3,\ 32)} = 3.260$, $P = 0.035$) significantly affected the water vapor permeability of fabrics. In general, the average water vapor permeability of plant based fabric structures was higher than that of control fabrics, although in most cases the differences were not significant at the 95% confidence level. For effective cooling, high water vapor permeability was desirable for transmitting moisture evaporated at the skin surface (Hes & Araujo, 2010). However, the developed plant structured knitted fabrics had no significant advantage in water vapor permeability due to increased thickness. Light-weight and thin fabrics should be developed in the future using fine yarn and fine gauge machine for improving water vapor permeability and overall comfort.

5.4 Conclusions

This chapter has shown that plant based fabric structures which mimick the branching network of a plant using tucking stitch, has significantly faster initial water absorption rates and higher one-way water transport values than corresponding control fabric structures. Of plant based fabric structures studied, Structure-III, involving two tucking courses sandwiched between two knitting courses, showed the most potential in terms of the various fabric comfort related properties for the different types of yarns covered. Such a structure has a potential application as sportswear and summer wear fabrics, although further study is needed to reduce thickness of fabrics.

6. Development of warp knitting structures to emulate the branching network of plants

6.1 Introduction

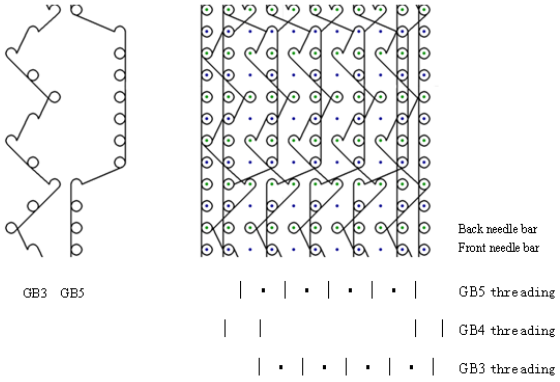
Circular knitting technique was previously employed to simulate plant structures to some extent in knitted fabrics, however these weft knitting plant constructions, due to the limitation of operation principle of weft knitting technique, do not fully meet our requirements in which two or more yarns forming one multi-yarned loop at the back side individually separate to form two or more single-yarned loops at the face side, to create directly continuous channels of liquid water transport through the yarns travelling from the bottom layer to the top layer. In this chapter, the Raschel warp knitting technique was employed to further mimick plant structure.

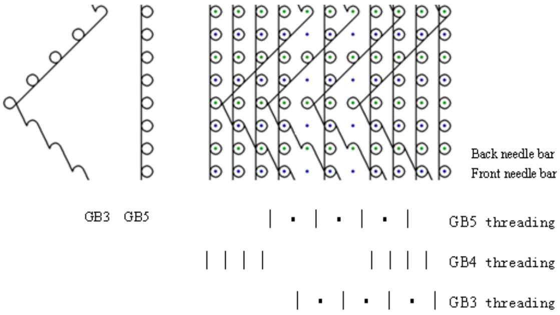
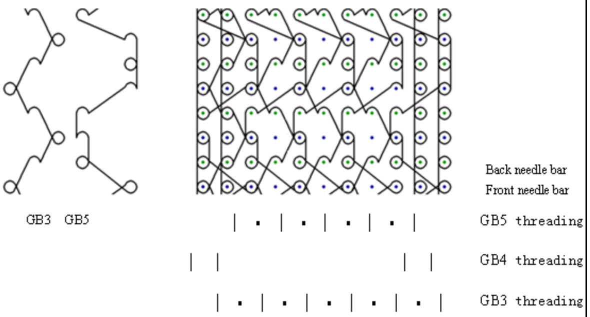
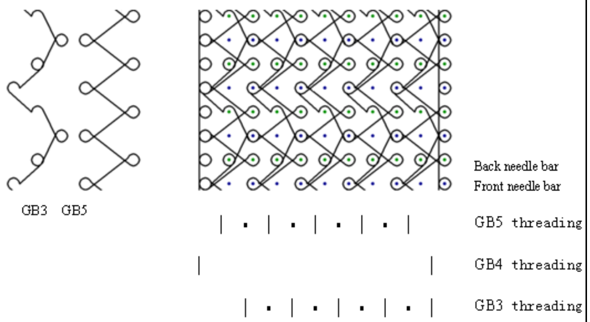
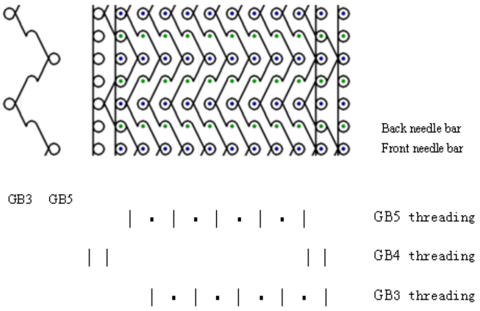
6.2 Sample preparation

Double-needle bar Raschel warp knitting machine (machine gauge E22) was used to implement the principle that the two yarns were combined together to form a two-yarned loop on every other needle of the front needle bed for creating the surface in contact with the skin; these two yarns ran separately to form two single-yarned loops on every needle of the back needle bed for creating the outer surface. Table 6-1 shows all warp knitting notations utilized in this study.

Even though there was only one warp knitting principle for plant structured fabric formations, the combinations of movement of two guide bars can be varied. Differences among these four plant knitting structures were varying lapping movements (i.e. the direction and extension of the overlap and underlap movements) which determine fabric pattern appearance, openness, thickness and mass. For instance, Structure-II with shorter underlap movements (0 needle distance and 1 needle distances) had a lower fabric weight, on the contrary, Structure-IV with longer underlap movements (1 needle distance and 2 needle distances) had a higher fabric weight. In Table 6-1, the back and face fabric sides were created by the ground bars No.3 (GB3) and No.5 (GB5); while the ground bar No.4 (GB4) was used to knit the smooth edge of fabrics.

Table 6-1 The knitting notation, thread position and lapping movement of guide bars

Structure	Lapping movement
	Structure I: GB3:1-2-2-3/1-2-0-1/2-1-3-2/2-1-1-0/2-1-3-2 /2-1-0-1// GB4: 1-0-1-0// GB5:3-2-3-2/3-2-3-2/0-1-0-1/0-1-0-1/0-1-0- -1/0-1-3-2//

	Structure II: GB3:1-2-2-3/3-4-4-5/3-4-2-3/1-2-0-1// GB4:1-0-1-0// GB5:1-0-1-0//
	Structure III: GB3:1-0-2-3/2-3-3-3/1-0-0-1/0-1-3-2. GB4:1-0-1-0. GB5:3-4-3-2/2-1-2-3.
	Structure IV: GB3:3-4-2-1/3-4-2-1// GB4:1-0-1-0// GB5:3-2-1-2/1-0-1-2//
	Control structure: GB3:3-4-2-1/3-4-2-1. GB4:1-0-1-0. GB5:3-4-2-1/3-4-2-1.

During the knitting process of plant structured fabrics, the every other needles of the front needle bed knitted; all needles of the back needle bed were operated. Structures- I, II, III and IV were to simulate plant structures.

For the purpose of comparison, the last one was a control structure which was similar to weft circular simple double rib fabrics. By using two full sets of threaded guide bar and knitting on the front and back beds alternately, the control structure possessed the technical face side comprising straight wales, but the technical back comprising inclined stitches, where they were towards the right in odd courses and towards the left in even courses. Table 6-1 presents the knitting notation and thread position.

With regard to sample preparation, there were two groups of samples, the samples of group No.1 used 150 D nylon (threaded in GB3) and 150 D polyester (threaded in GB5) yarns; group No.2 used 150 D (75 D*2) polyester yarn (threaded in both GB3 and GB5).

Explanations of thread position were given by the followings.

In sample group No.1,
GB3: “|” represents one 150D nylon yarn threaded, “·” represents no yarn threaded.
GB5: “·” represents no yarn threaded, “|” represents one 150D polyester yarn threaded.
In sample group No.2,

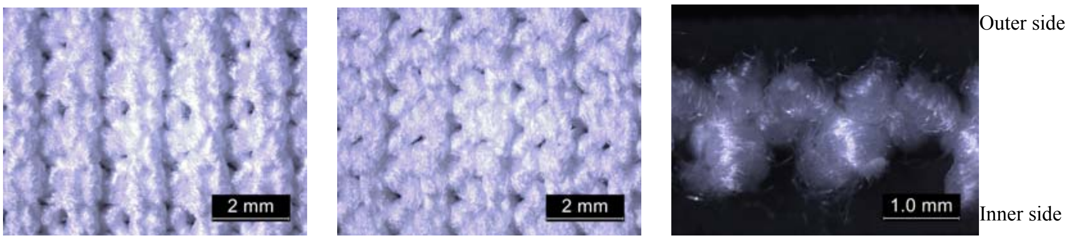
GB3: "|" represents one 75D*2 polyester yarn threaded, "·" represents no yarn threaded.

GB5: "·" represents no yarn threaded, "|" represents one 150D polyester yarn threaded

Table 6-2 presents the mass, thickness and loop density of all samples in two groups. Figure 6-1 shows the back surface, face surface and cross-section of all fabrics in this chapter. It can be seen that the back side of plant structured fabrics had rougher surfaces than that of the face side and control fabrics. This feature could generate the smaller contact area while in touch with the skin. At the cross-section of plant structured fabrics, one loop at the back side corresponded to two loops at the face side like two branches generating out from one stem. However, the control fabric had relatively smooth surface; and one loop at the back side had one corresponding loop at the face side. Figures 6-2 to 6-11 present theoretical patterns of all warp knitted fabrics (developed by Catia 6.0). It helped to understand the structure with ideal loop conditions.

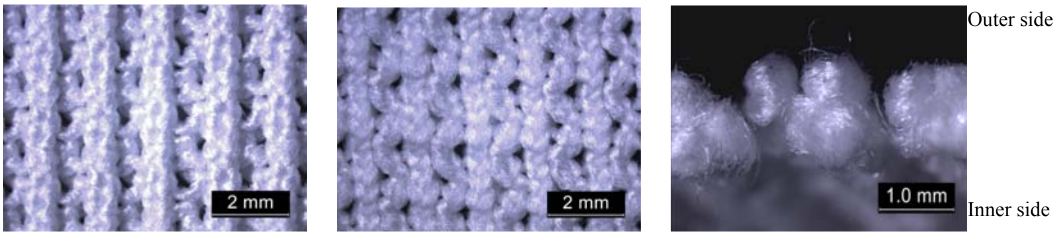
Table 6-2 Fabric description

Sample No	Yarn	Structure	Mass g/m^2	Thickness (mm) (0.5gf/cm^2)	Density (loop/inch^2)	
					Back	Face
Group No.1						
1	Polyester (150 D) & Nylon (150 D)	Control I	248	1.28	1584	1584
2			241	1.49	704	1408
3		Control II	248	1.28	1584	1584
4			241	1.42	672	1344
5		Control III	284	1.64	1682	1682
6			279	1.58	756	1512
7		Control IV	284	1.64	1682	1682
8			288	1.78	792	1584
Group No.2						
9	Polyester (75D*2 & 75D*2) & Polyester (75D*2 & 75D*2)	Control I	253	1.18	1947	1947
10			255	1.45	810	1620
11		Control II	241	1.09	1802	1802
12			241	1.04	960	1920
13		Control III	265	1.03	2240	2240
14			267	1.35	756	1512
15		Control IV	290	1.39	2442	2442
16			285	1.38	850	1700



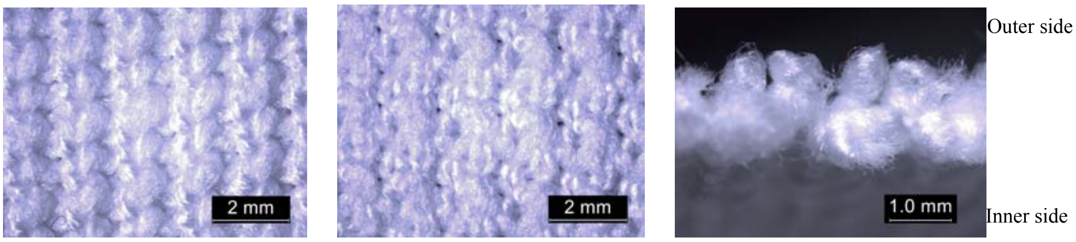
Back side Face side Cross-section

Structure I



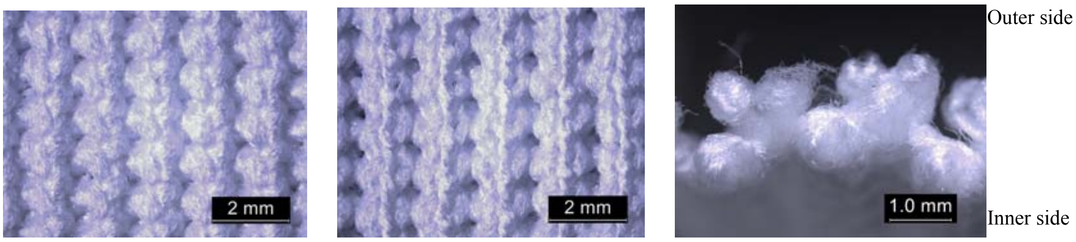
Back side Face side Cross-section

Structure II



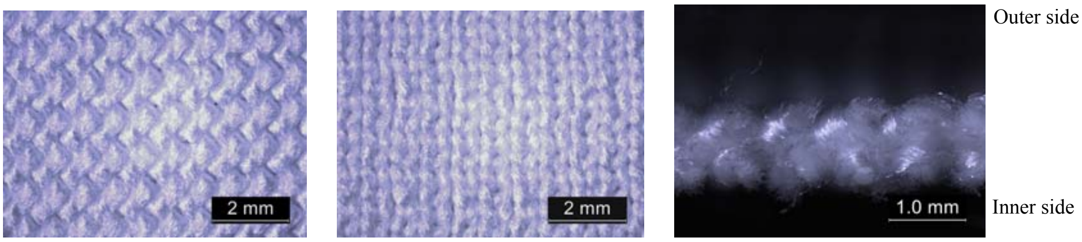
Back side Face side Cross-section

Structure III



Back side Face side Cross-section

Structure IV



Back side Face side Cross-section

Control structure

Figure 6-1 The technical back, face surfaces and cross-section of the different fabric structures

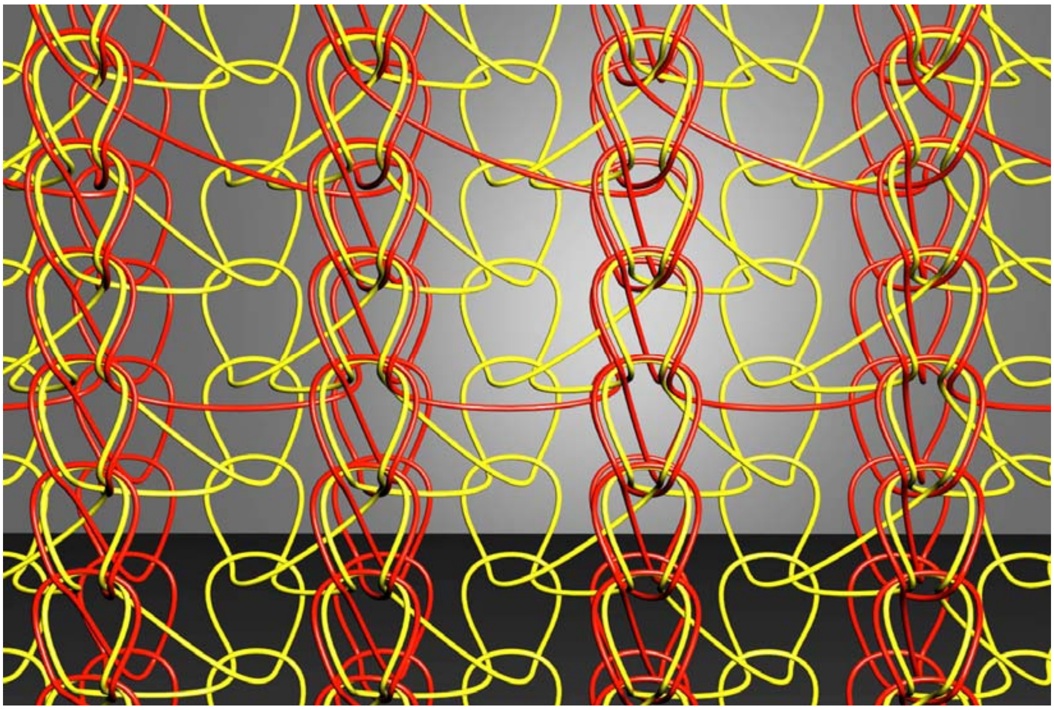


Figure 6-2 Plant structure I (the back side)

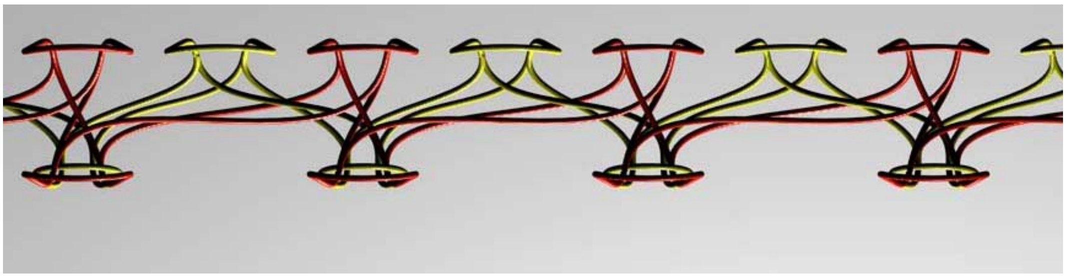


Figure 6-3 Plant structure I (the cross-section)

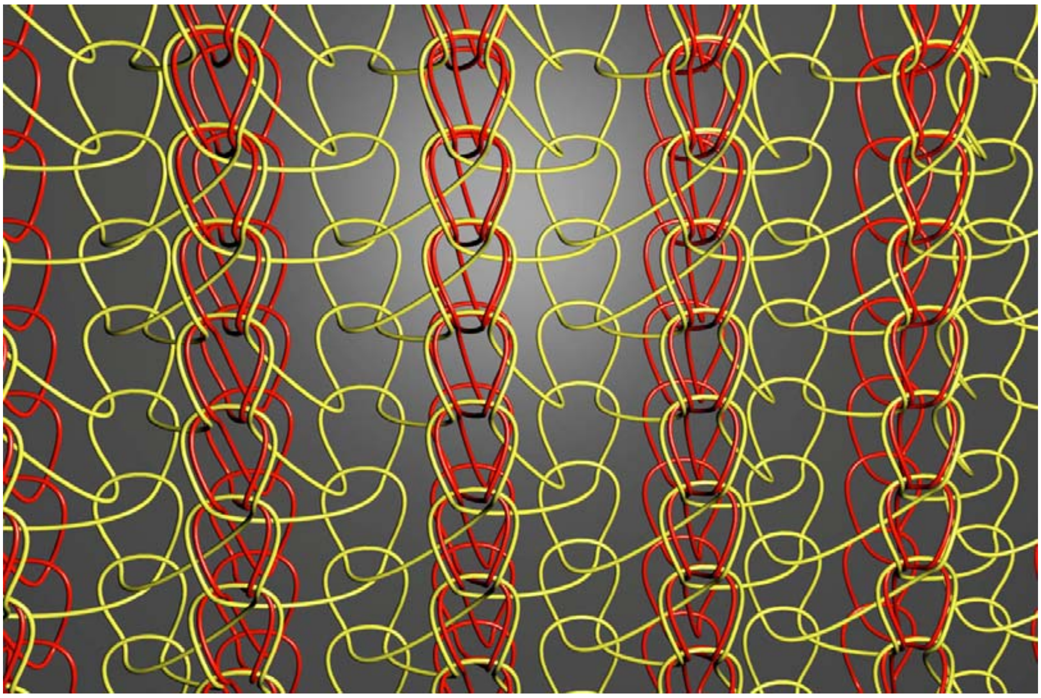


Figure 6-4 Plant structure II (the back side)

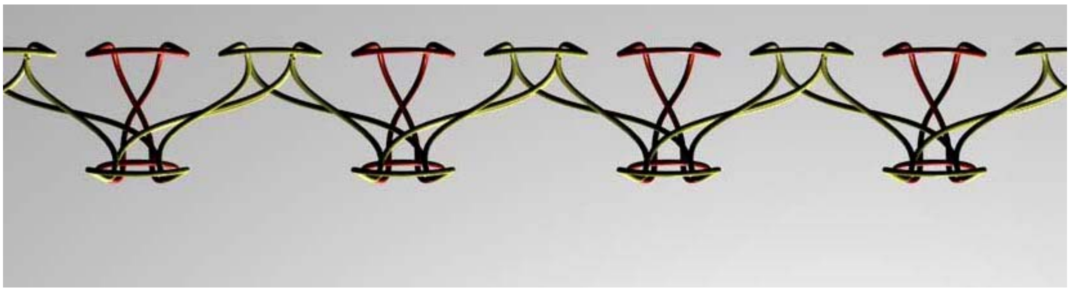


Figure 6-5 Plant structure II (the cross-section)

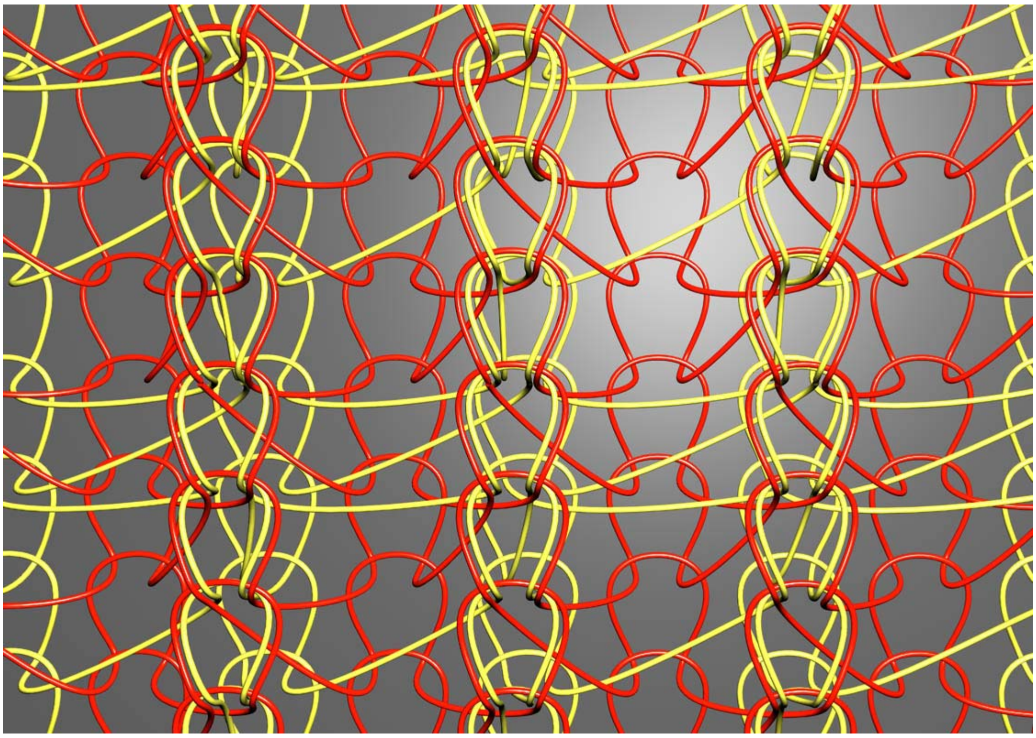


Figure 6-6 Plant structure III (the back side)

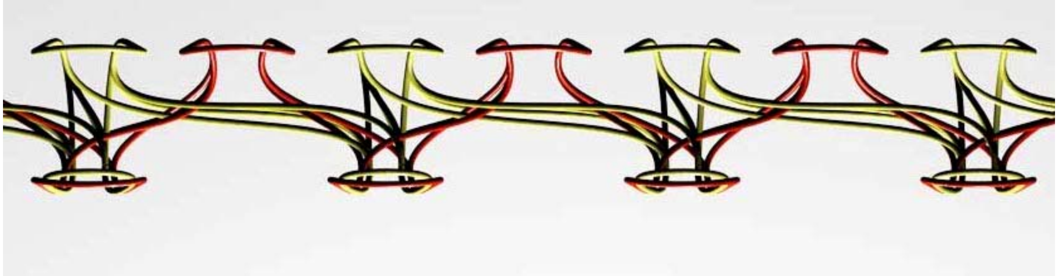


Figure 6-7 Plant structure III (the cross-section)

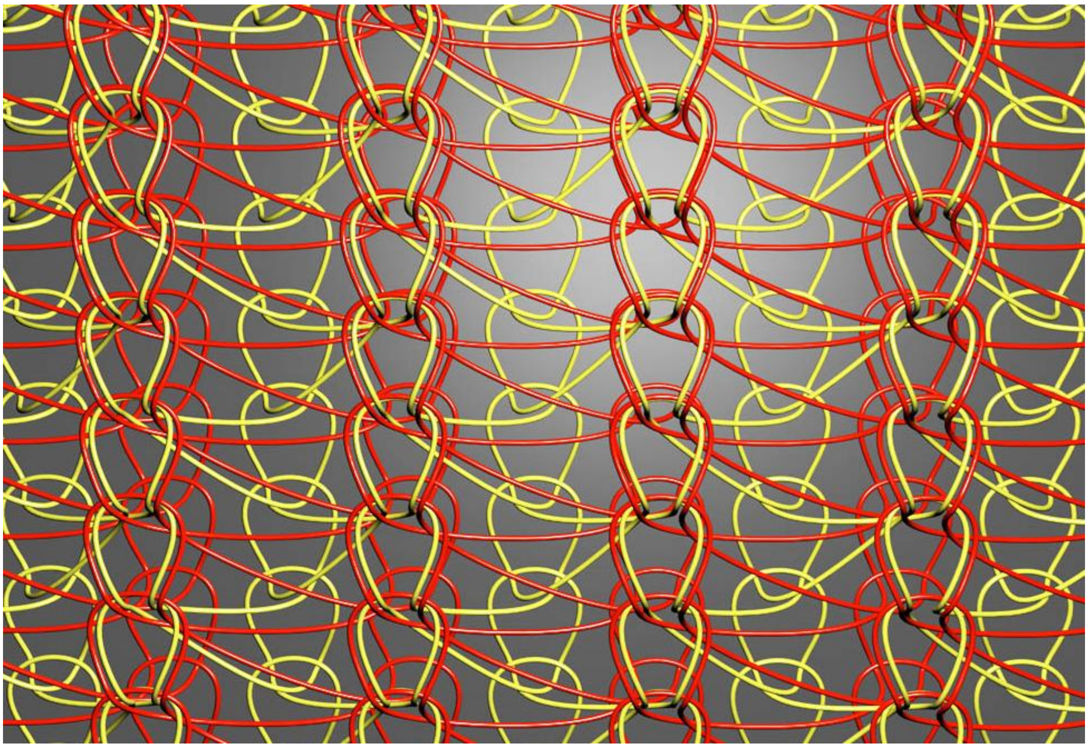


Figure 6-8 Plant structure IV (the back side)

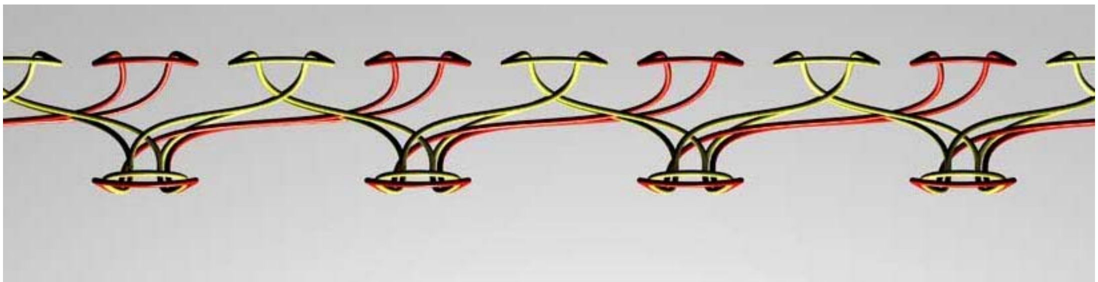


Figure 6-9 Plant structure IV (the cross-section)

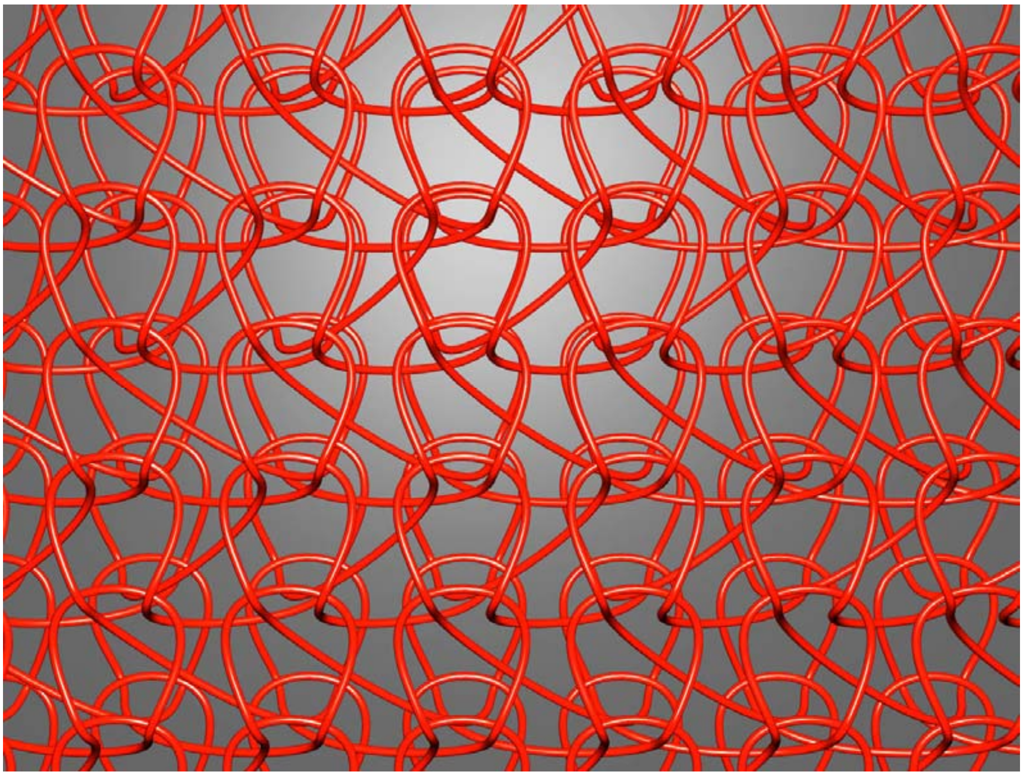


Figure 6-10 Control (the back side)

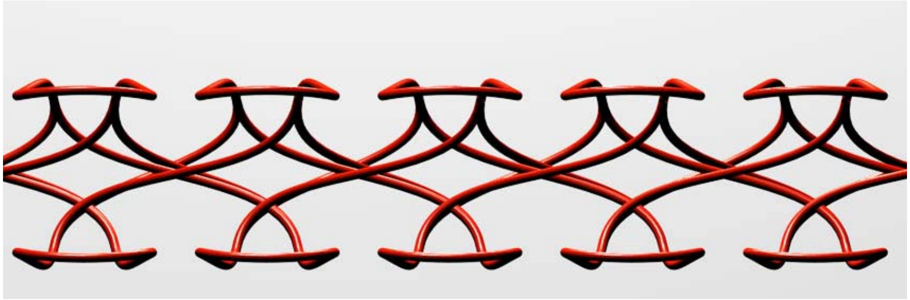


Figure 6-11 Control (the cross-section)

Two experiments were conducted in this chapter. In Experiment No.1, sample Nos. 1-16 were evaluated by TWTT, MMT, air resistance, and water vapor permeability tests.

In Experiment No.2, wicking rate (according to AATCC Committee RA63), water retention (according to GB21655, China), and water evaporation rate (according to GB21655, China) were conducted on sample Nos. 9- 16 for supplementary evaluations. The detail processes were given as follows.

Water evaporation rate

The amount of 0.2ml water was dropped on fabric surface. At the time of 0 min, 5 min, 10min, 15min, 20min, 25min and 30 min, the fabric was weighed. The calculation is conducted by following equations:

$$\begin{aligned} &\Delta m_i = m - m_i \\ &E = \frac{\Delta m_5 - \Delta m_1}{25\,\mathrm{min}} \times 100 \end{aligned} \qquad (6\text{-}1)$$

Where m_i is the weight of fabrics at 5 min, 10min, 15min, 20min, 25min and 30 min, m is the weight of wetted fabrics at initial time. The measurement was repeated five times and the average values calculated.

Water retention

Fabric was immersed into water for 5 min saturation. And then it was hanged vertically, naturally. After water stopped dropping from fabrics (the time interval between two drops was above 30s, this was regarded as no water dripped from fabrics), the fabric was weighed. The water retention is calculated by

$$\text{water retention}(\%)=\frac{M-M_0}{M_0}\times 100 \qquad (6\text{-}2)$$

where M_0 is the weight of dry fabric, M is the weight of wetted fabric without dropping water. The measurement is repeated five times and the average value calculated.

Wicking rate

In vertical wicking test, a fabric strip of 30 mm wide and 250 mm long was hanged vertically from a clamp in a way that the lower 30 mm of the sample was immersed in water. The time that it took until the 20-mm mark started to bleed was recorded. Specimens were tested in both lengthwise and widthwise directions. Initial wicking rate is defined as below:

$$\text{wicking rate(mm / s)}=\frac{\text{wicking distance(20mm)}}{\text{wicking time}} \qquad (6\text{-}3)$$

The measurement was repeated three times and the average value calculated.

6.3 Results and discussion

6.3.1 Experimental No.1

Table 6-3 The testing results of transplanar water transport test, one-way transport, air resistance and water vapor permeability

Sample No	Yarn	Structure	Initial Absorption rate (g/s)		One-way transport		Air resistance (kPa s/m)		Water vapor permeability (g/m^2/day)	
			mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.
Group No.1										
1	Nylon (150D) & Polyester (150D)	Control I	1.62	0.07	168.09	62.09	0.175	0.004	1237	87.6
2			1.83	0.10	-279.8	22.77	0.072	0.003	1333	36.2
3		Control II	1.62	0.07	168.09	62.09	0.175	0.004	1237	87.6
4			1.86	0.09	-403.7	34.52	0.091	0.005	1335	20
5		Control III	1.51	0.14	267.99	143.52	0.160	0.006	1142	32.1
6			1.83	0.12	-284.9	149.29	0.098	0.003	1177	9.5
7		Control IV	1.51	0.14	267.99	143.52	0.160	0.006	1142	32.1
8			1.86	0.04	89.09	37.58	0.093	0.006	1139	33.3
Group No.2										
9	Polyester (75D *2) & Polyester (75D *2)	Control I	1.43	0.05	239.68	22.63	0.538	0.025	1102	23.9
10			1.67	0.11	262.82	13.51	0.106	0.011	1029	12.9
11		Control II	1.34	0.07	216.13	10.26	0.593	0.028	1088	39.8
12			1.59	0.10	258.81	3.76	0.032	0.003	1096	34.4
13		Control III	1.50	0.04	267.22	13.69	0.6	0.018	1086	25.6
14			1.69	0.06	256.03	16.35	0.454	0.010	1094	40.7
15		Control IV	1.53	0.08	247.36	10.14	0.657	0.058	1073	31.8
16			1.69	0.09	263.79	16.19	0.130	0.005	1054	10.4

6.3.1.1 Transplanar water transport test (TWTT)

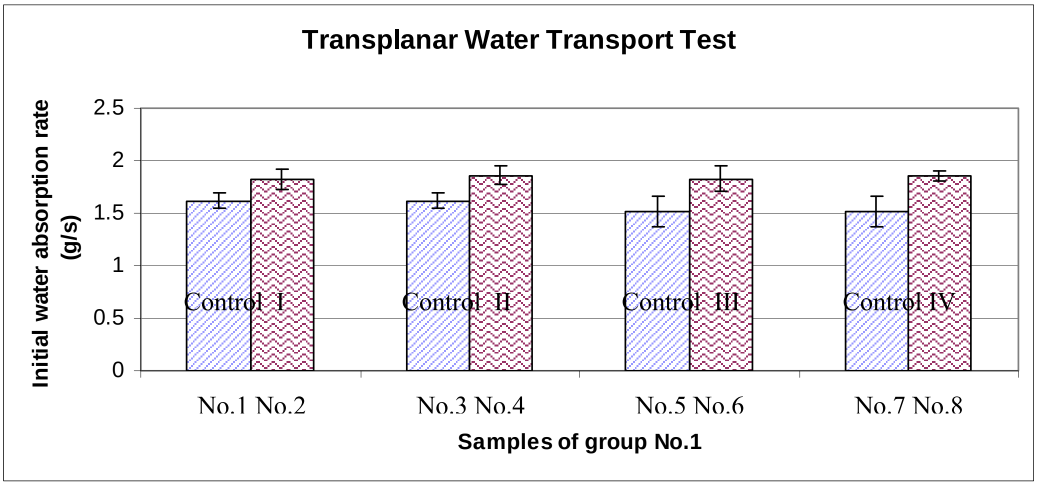


Figure 6-12 The TWTT results of sample group 1

The initial behavior of water transport occurring in the first ten seconds was measured by TWTT. The mean values and standard deviation are given in Table 6-3. As the results in Figure 6-12 indicate, plant based fabric structures exhibited faster initial water absorption rate than corresponding controls, after comparing the sample No.1 with No.2, No.3 with No.4, No.5 with No.6, and No.7 with No.8. The initial water absorption rates of plant structures were 12.3%, 14.8%, 21.2% and 23.2% higher, respectively. The increases were statistically significant (P=0.043, 0.023, 0.043 and 0.017).

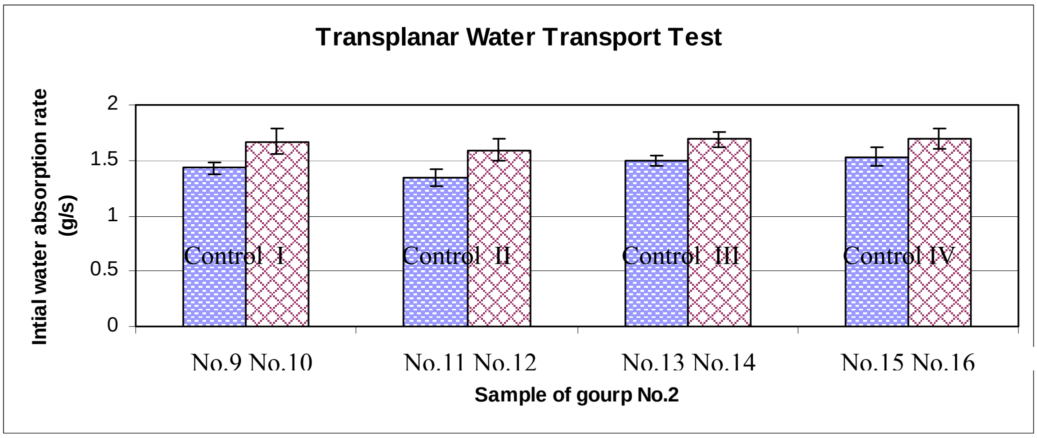


Figure 6-13 The TWTT results of sample group 2

As shown in Figure 6-13, identical trends as sample group 1 were found in sample group 2. The plant structures had 16.8%, 18.7%, 12.6% and 10.5 % higher rates of initial water absorption respectively, and the differences were highly significant. Comparing sample No.9 with No.10 gave p=0.028; comparing sample No.11 with No.12 gave p=0.025; comparing sample No.13 with No.14 gave p=0.015; and comparing sample No.15 with No.16 gave p=0.047.

Comparing plant structured knitted fabrics with respective control fabrics (knitted with same yarn and similar mass), in both group 1 and group 2 the average initial water absorption rates of plant structured knitted fabrics were significantly faster than control fabrics. In other words, knitting structure altered liquid water transport through thickness significantly. The characteristics of quick liquid absorption could maintain a dry touch feeling to the skin, and being capable of transporting water from the skin to the outer surface and then quickly dispersing it. Slightly higher initial water absorption rates observed in Structures - III and IV might be caused by higher fabric weight.

6.3.1.2 One-way transport capacity

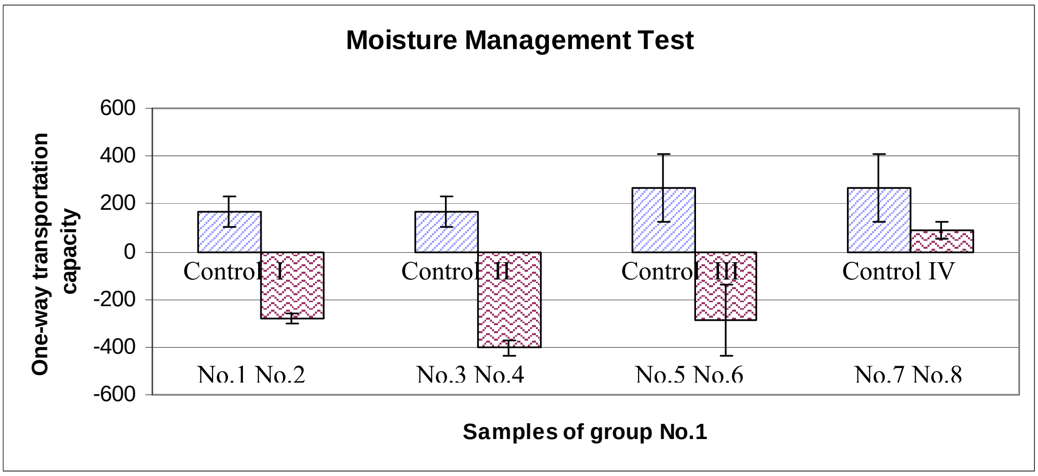


Figure 6-14 The one-way transport results of sample group 1

With regard to samples in group 1(see Figure 6-14), control structures had higher one-way transportation capacity than plant structures significantly. The reason might be that material composition affected one-way transport values. In sample group 1, both polyester and nylon yarns appeared on two surfaces in control structures. But in plant structure samples, although nylon and polyester were combined together, polyester and nylon yarns did not twist during the process of knitting. In warp knitting technique, yarn threading in the front needle bar appeared at the back side of fabrics due to its position. On one hand, the pins of the tester cannot distinguish the surface area when the back side of fabrics was not smooth. On the other hand, nylon yarn was threaded on GB3 which was positioned in the front of machine; as a consequence, it covered the back surface. The better water absorbing capacity of nylon than polyester resulted in more water retained at the back side. This might lead to apparently lower one-way transport in plant structures.

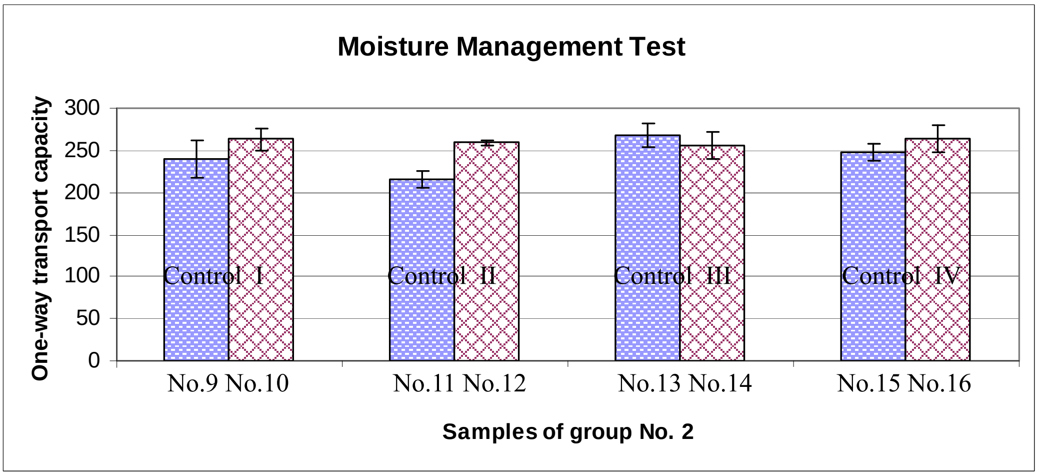


Figure 6-15 The one-way transport results of sample group 2

Of sample group 2(see Figure 6-15), sample No. 12 had significantly higher one-way transport value than sample No. 11; the differences of other pairs were not statistically significant. This might be attributed to inappropriate contact between electronic pin sensors in MMT and the back surface of plant knitted fabrics. Pins touched areas between loop columns which were not the back side surface. Consequently, the back surface was unrealistically greater than actual, and water quantity measured by tester at the back side increased.

6.3.1.3 Air resistance

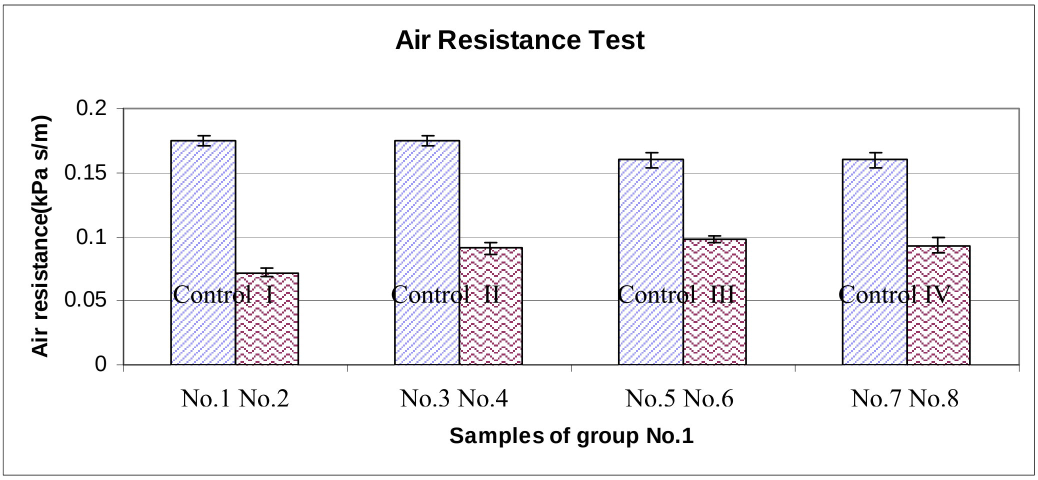


Figure 6-16 The air resistance results of sample group 1

It can be seen from Figure 6-16, all plant structured fabrics possessed much lower air resistance than corresponding control fabrics. Sample No.2 gave 58.9% reduction against sample No.1; sample No.4 gave 48% reduction against sample No.3; sample No.6 gave 38.8% reduction against sample No.5; and sample No.8 gave 41.9% reduction against sample No.7. These declines were significant as indicated by the p values being less than 0.05, respectively.

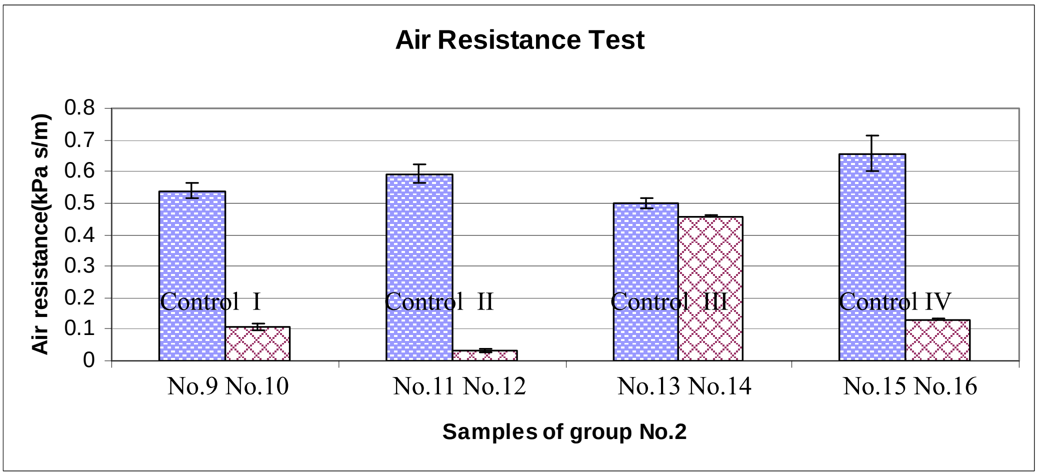


Figure 6-17 The air resistance results of sample group 2

Exactly, the identical observation was found within group 2(see Figure 6-17). Also, the capacity of plant structures were significantly better to pass air through fabrics than conventional structure ($p<0.05$). The 10% - 94.6 % decreases were observed in two groups. The plant structured samples showed lower air resistance although slightly higher thicknesses were observed. That might be that these plant structures had some pores which easily passed through by air (see Figure 6-1).

Structures-I and II with higher openness exhibited lower air resistance than Structures-III and IV, this was likely attributed to the fact that the length of lapping of guide bars was shorter in Structures-I and II than in Structures-III and IV.

6.3.1.4 Water vapor permeability

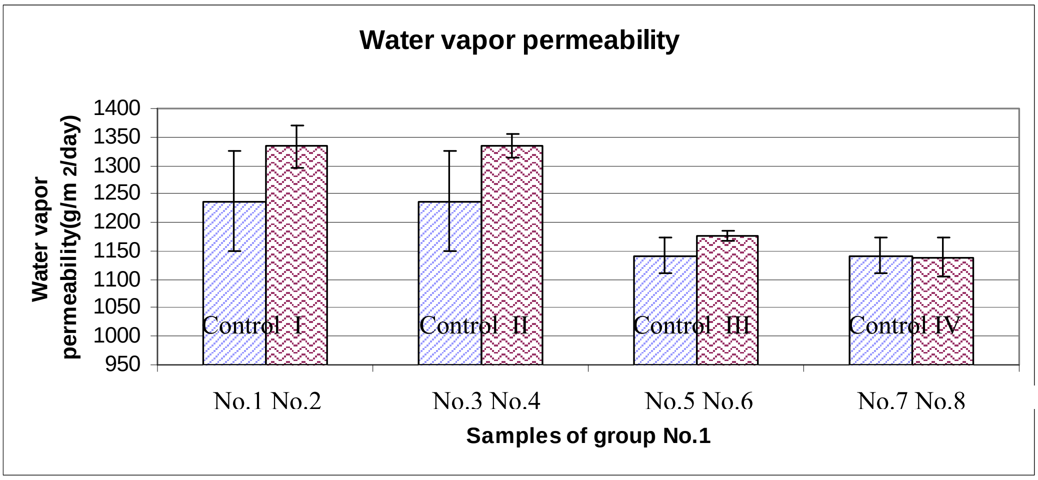


Figure 6-18 The water vapor permeability results of sample group 1

For the fabric samples produced in group 1, plant Structures-I, II and III exhibited slightly higher water vapor permeability than control structure, with the exception of Structure-IV (see Figure 6-18). However, the differences were no significant as indicated by the p values, which were 0.156, 0.132, 0.310 and 0.584 respectively.

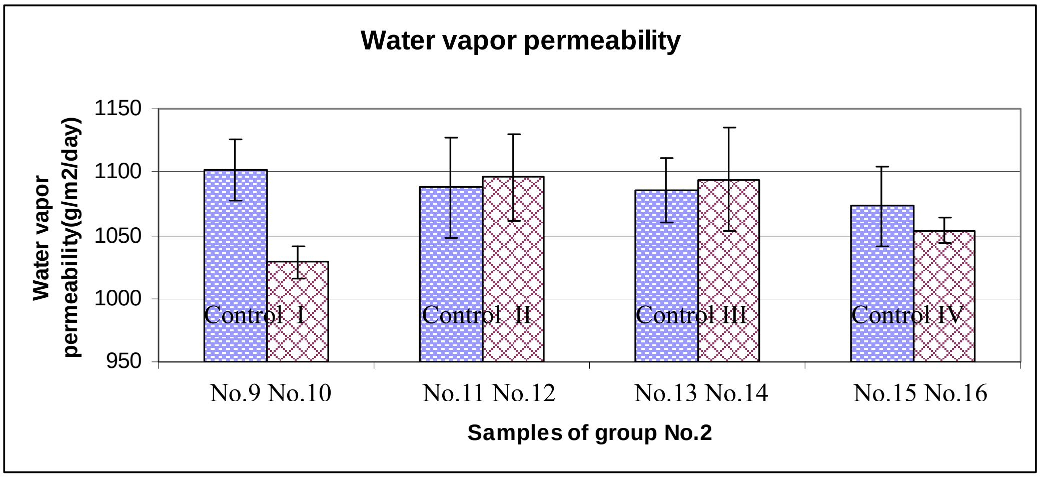


Figure 6-19 The water vapor permeability results of sample group 2

In group 2 (see Figure 6-19), apart from a significant difference found between the sample No.9 and sample No.10, the rest comparisons were not significant (P=0.010, 0.800, 0.782 and 0.383 respectively).

Water vapor permeability much depended on fabric thickness and porosity. The higher fabric thickness and lower porosity, the lower water vapor permeability. Although plant structures were more porous as indicated by much lower air resistance against control structures, they were relatively thicker under the same weight due to the bulkier structure. As a consequence, the differences between plant structures and controls in terms of water vapor permeability were not significant in most cases.

6.3.2 Experimental No.2

Table 6-4 The evaporation rate, water retention and wicking rate results of plant structured fabrics and corresponding control fabrics

No	Structure	Evaporation rate(g/h)		Water retention (%)		Wicking rate(2cm) (mm/s)			
						Warp		weft	
		mean	s.d.	mean	sd	mean	s.d.	mean	s.d
9	Control	0.15	0.004	278.8	7.7	1.62	0.28	1.04	0.07
10	Plant I	0.24	0.024	256.2	6.5	2.18	0.11	1.04	0.08
11	Control	0.16	0.024	281.8	8.7	1.65	0.25	1.43	0.05
12	Plant II	0.26	0.012	186.4	3.8	1.76	0.14	1.2	0.03
13	Control	0.19	0.042	225.6	3.8	1.64	0.26	1.32	0.08
14	Plant III	0.19	0.026	271.8	6.9	2.11	0.14	1.82	0.09
15	Control	0.16	0.004	205.2	2.5	1.35	0.08	1.31	0.05
16	Plant IV	0.19	0.006	281.1	13.6	2.36	0.33	1.07	0.04

6.3.2.1 Water evaporation rate

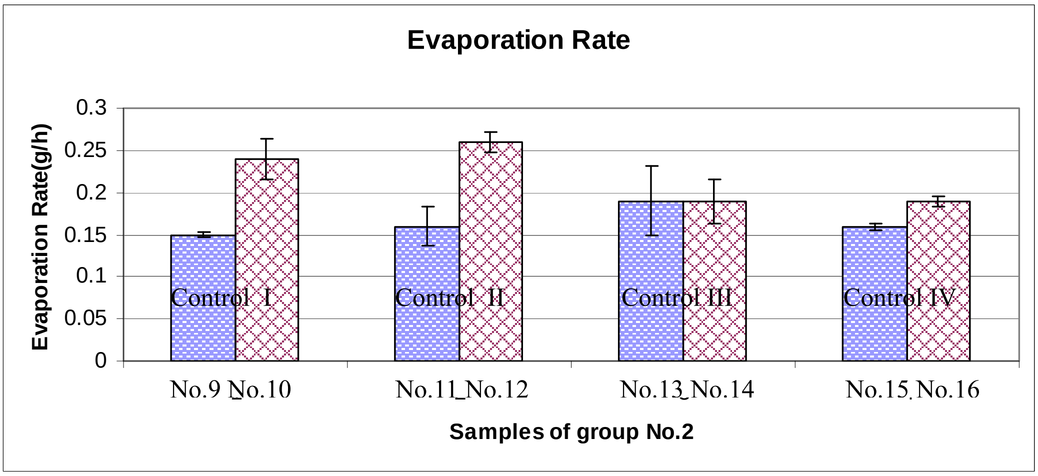


Figure 6-20 Evaporation rate results of sample group 2

With the increase ranging from 18% to 25%, plant structured fabrics exhibited significantly higher evaporation rates with the exception of Structure- III (p= 0.797), indicating a better evaporation ability than conventional rib-like warp knitted fabrics, under similar fabric parameters such as yarn material, weight, etc(see Figure 6-20).

6.3.2.2 Water retention

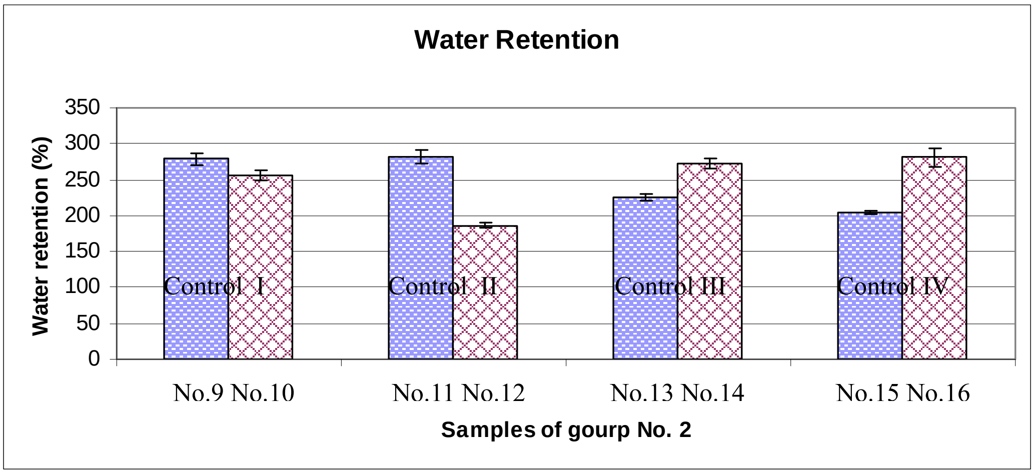


Figure 6-21 Water retention results of sample group 2

It can be seen from Figure 6-21, where plant structured samples are compared with control fabrics of similar weight, sample Nos. 14 and 16 had higher water retentions than corresponding control sample Nos. 13 and 15. In contrast to this, plant structured sample Nos. 10 and 12 had lower water retentions than corresponding control sample Nos. 9 and 11. This was because the constructions of plant structured sample Nos. 10 and 12 were more loose, which led to lower air resistance and higher water evaporation observed in the above (see Figures 6-1, 6-17 and 6-18).

6.3.2.3 Wicking rate

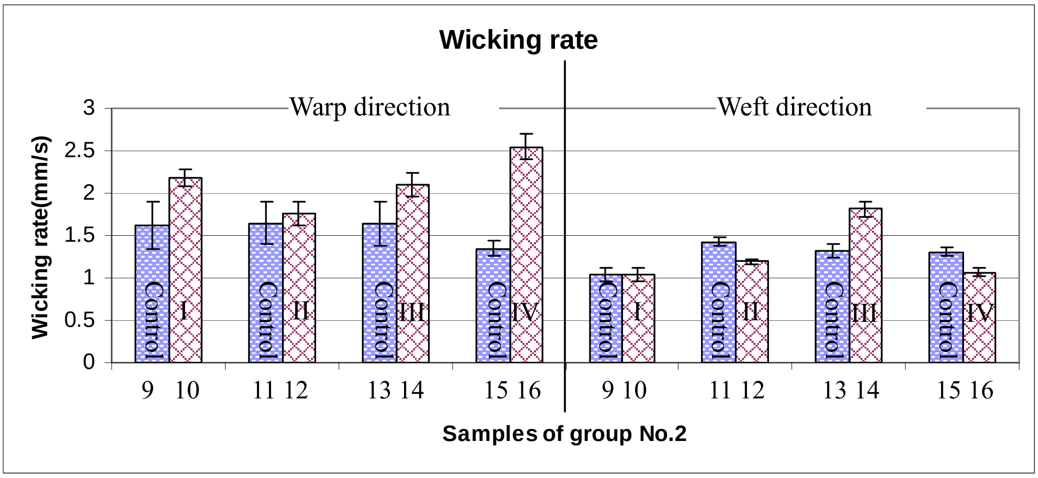


Figure 6-22 Wicking rate results of sample group 2

As is shown in Figure 6-22, Structures -I, III, and IV exhibited significantly faster warp direction wicking rates than control structures, apart from Structure-II (P>0.05). In the weft direction, only Structure-III fabrics containing polyester filaments can wick water faster than control fabrics; Structures-I and IV were little different from their respective control fabrics in terms of weft direction wicking rates. The Structure-I fabrics exhibited 34.6% faster rates in warp direction than control structures, corresponding values for Structures-II, III and IV fabrics, being 6.7%, 28.7%, and 74.8% respectively. The relatively lower wicking rates observed in Structure-II was possibly due to the fact that many large pores created by short lapping movements imparted water transport through yarn connections.

It is noted that no agreement can be observed between the results of the trans-planar water transport test and the vertical wicking test, which was understandable as they were associated with different aspects of water transport behavior. Fast wicking rates presented long distances wetted by water along the plane direction at a certain period of time, while fast initial water absorption rates presented a large amount of water transport by fabrics at the transverse section at a fixed time interval.

6.4 Conclusions

Warp knitting technique was applied to simulate the branching network in plant structures successfully. Two groups of samples were developed using different yarns. Based on objective testing results, this study demonstrated that warp knitted plant knitted fabrics, which mimicked the plant structure networks, had significantly faster initial water absorption rates and vertical wicking rates than conventional fabrics with similar mass. In terms of air resistance, plant structures also had much lower values than control structures. As for water vapor permeability, it seemed that the new plant structured warp knitting fabrics had no advantage. This may be due to the fact that the yarns and machine gauge were relatively coarse, resulting in relatively thicker fabric. Finer gauged machines are desirable in future development. The present investigation also showed that plant structured constructions with larger pores could result in relatively higher water evaporation rate and lower water retention against conventional knitting constructions.

7. Mechanisms of liquid water transport through knitted fabrics with branching network

7.1 Introduction

This chapter analyzes the possible mechanisms of improved liquid transport in plant structured knitted fabrics. Plants have exceptional water transport properties, and the amount of water transported by plants is much greater than the evaporation from an uncovered water surface. From the point view of water transport in plants, three main mechanisms are proposed, although the debate continues. The most satisfactory explanations for the rise of water in plants are cohesion-tension mechanism, minimum flow resistance of branching structure, and capillary action.

Here, it needs to point out that although plant structured fabrics had less number of loops at the back side than control fabrics, initial water absorption rates did not reduce with the decrease of the contact area between fabric surfaces and water. There are some possible explanations. The below sub-sections are dedicated to explain the three possible mechanisms of water transport in plant structured knitted fabrics.

7.2 Cohesion-tension mechanism

One of the principal factors responsible for pumping water from the bottom to the top is cohesion-tension mechanism. Due to the evaporation of water from leaves, one water molecule is lost and another is pulled along by the processes of cohesion and adhesion. Transpiration pull, causing by ultimately the constant evaporation, is the main phenomenon driving the flow of water in the xylem tissues of large plants.

As transpiration takes place, it creates a drive force drawing water from one molecule to another all the way through an entire span of xylem cells. Meanwhile, water molecules adhere to capillary walls and cohere to each other, thereby creating a certain amount of tension. Thus, this phenomenon is termed as “cohesion-tension”.

With regard to the knitted fabrics with branching network, the loop number of the face side is twice more than that of the back side. In other words, the surface area is enlarged. Water evaporation by the face surface speeds up water transport. Once water loss occurs at the outer surface, the initial condition originating the cohesion-tension force is generated. A new water molecule fills in blank place due to intermolecular attractions commonly observed in the process of water traveling upwards. Lager area exposed to air could originate fast water evaporation rates, as a result, water can be transported quickly.

7.3 Minimum flow resistance of branching structure

The interconnected tubes of xylem extend throughout plants, from the roots up through the stems and branches to the tiny vein-lets of the leaves. The branching network and tapering of the xylem in plants minimizes the resistance to fluid flow between a point and volume as proven by Bejan (2000, 2002, & 2004). This contributes to the efficiency of water flow.

Regarding plant structured fabrics, two or more yarns are combined together to form a two-yarned loop serving as a stem at the back; these two yarns are separated to form two single-yarned loops imitating branches out from a stem at the face side; as a result, branching network at the cross-section is shaped to reduce water resistance in this system. Figures 7-1 and 7-2 present the cross-sectional view of weft tucking structure and warp knitting structure. According to patterns shown, one loop at the back side is formed by two or more yarns, these yarns branching out from the back form two single-yarned loops at the face side. Additionally, the continuous pathways of formation of yarns are also able to deliver water from the inner side to the outer side.

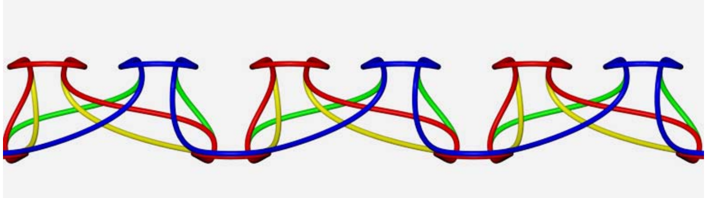


Figure 7-1 The cross-sectional view of one weft knitted structured fabrics

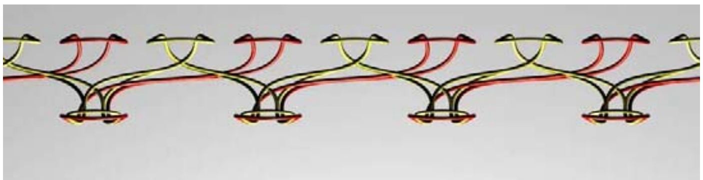


Figure 7-2 The cross-sectional view of one warp knitted structured fabrics

7.4 Capillary action

Capillary action is generated by the adhesive force between surface tensions in the meniscus of water and the wall of a tube. Even though water can rise 1 meter or more in a very narrow tube, air must be present above the column for the forces to work, which is not generally the case in a plant; unless cavitations take place in the xylems, in which case capillary action helps water movement.

In view of plant structured fabrics, on one hand, the feature of design creates two continuous conduits for transporting liquid water from the back side to the face side. These two conduits are the inter-yarned space and the yarns themselves. On the other hand, larger number of loops at the face side and less number of loops at the back side result in smaller sized loops at the face side, and larger sized loops at the back side. This creates a net capillary force pulling liquid water from the back side to the face side.

In terms of textile materials, pores are partially responsible for the movement of liquid water in the transverse direction. The basic mechanism involved is thought to be the capillary action. However, the capillaries in fabrics vary, the finer ones being those between fibers within yarns and the coarser ones being those between yarns in size and shape. In case of liquid absorption, it is obvious that coarser capillaries could retain more mass of liquid due to their large volume and dominate absorption behavior.

Capillaries in plant structured knitted fabrics are not uniform through the thickness and generally tapered from the back to the face side as conical channels for simplicity. Based on the basic capillary theory, discontinuous liquid rise in capillaries with varying cross-sections was studied by Tsori (2006), who introduced a cone-opening angle α. It has been shown that in cone shaped tube possessing hydrophilic surfaces, as α is increased from zero, the meniscus' position changes continuously until, when α attains a critical value, the meniscus jumps to the top of capillary. We apply this theory as one of the mechanisms to explain that plant knitted structured fabrics have higher initial water absorption rate than conventional structure fabrics.

The theory of discontinuous liquid rise in conical capillary is applicable to the narrow capillaries, the criterion of narrow capillary being $\kappa R \ll 1$ where $\kappa = (\sigma/g\rho)^{-1/2}$, ρ is the liquid mass density, σ is the surface tension of the liquid-gas interface and g is the gravitational acceleration. In the present case, the liquid is water and hence using standard values of water (ρ = 1 g/cc, σ = 72 g/s^2 and g = 980 cm/s^2), we have $\kappa = 0.36893$. The equilibrium capillary height h, above the water bath level is given as

$$h = c\kappa^{-2}\cos\theta / R \quad (7\text{-}1)$$

where the value of c can be taken as 2, and the contact angle θ for cellulose and water can be assumed as approximately 35°. Denoting the radius of any vertical capillary at base level by R_0, the equilibrium heights corresponding to capillary size at the back side of all fabrics was calculated from actual measurement of loop density on fabric surfaces, viz.

$$R_0 = \sqrt{\frac{1(cm^2)}{loopdensity(loopnumber / cm^2) * \pi}} \qquad (7\text{-}2)$$

Calculated R_0 and h are given in Tables 7-3 and 7-4 for cotton 20Ne and 32Ne fabrics of weft tucking fabrics and polyester warp knitted fabrics. The fabric descriptions were given in Tables 7-1 and 7-2. All capillaries involved in all plant fabrics are therefore narrow capillaries and the theory of discontinuous liquid rise in a conical capillary can be applied in the present case.

Table 7-1 The fabric description of weft tucking knits

Sample No.	Yarn	Structure	Weight (g/m^2)	Thickness (mm)	Density (loops/cm^2)	
					Back	Face
Weft tucking knits						
1	Cotton 32Ne	Control(I)	214	1.23	169	169
2		Tuck plant (II)	201	1.36	79	159
3		Tuck plant (III)	187	1.33	48	143
4		Tuck plant (IV)	204	1.29	42	169
5	Cotton 20Ne	Control(I)	360	1.42	178	178
6		Tuck plant (II)	325	1.49	84	169
7		Tuck plant (III)	328	1.69	52	157
8		Tuck plant (IV)	355	1.69	48	193
17	Cotton 32Ne	Tuck plant (III)	196	1.39	59	176
18		Control(I)	199	1.27	149	149
19		Tuck plant (IV)	204	1.29	42	169
20		Control(I)	206	1.22	154	154
21	Cotton 20Ne	Tuck plant (III)	328	1.69	52	157
22		Control(I)	326	1.48	139	139
23		Tuck plant (IV)	355	1.69	48	193
24		Control(I)	360	1.42	178	178

Table 7-2 The fabric description of warp knits

Sample No	Yarn	Structure	Mass (g/m^2)	Thickness (mm)	Density ($loop/inch^2$)	
					Back	Face
Warp knitted fabrics Group No.1						
1	Polyester 150 D & nylon 150 D	Control	248	1.28	1584	1584
2		Warp plant (I)	241	1.49	704	1408
3		Control	248	1.28	1584	1584
4		Warp plant (II)	241	1.42	672	1344
5		Control	284	1.64	1682	1682
6		Warp plant (III)	279	1.58	756	1512
7		Control	284	1.64	1682	1682
8		Warp plant (IV)	288	1.78	792	1584
Warp knitted fabrics Group No.2						
9	Polyester 75D*2 & Polyester 75D*2	Control	253	1.18	1947	1947
10		Warp plant (I)	255	1.45	810	1620
11		Control	241	1.09	1802	1802
12		Warp plant (II)	241	1.04	960	1920
13		Control	265	1.03	2240	2240
14		Warp plant (III)	267	1.35	756	1512
15		Control	290	1.39	2442	2442
16		Warp plant (IV)	285	1.38	850	1700

Table 7-3 R_0 and h values of weft tuck knitted fabrics

Sample	Structure	Calculated R_0 (mm)	Equilibrium Height h (mm)
1	Control(I)	0.4346	27.69
2	Tuck plant (II)	0.6335	18.99
3	Tuck plant (III)	0.8168	14.73
4	Tuck plant (IV)	0.8675	13.87
5	Control(I)	0.4232	28.43
6	Tuck plant (II)	0.6085	19.78
7	Tuck plant (III)	0.7797	15.44
8	Tuck plant (IV)	0.8115	14.83
17	Tuck plant (III)	0.7372	16.32
18	Control(I)	0.4626	26.01
19	Tuck plant (IV)	0.8675	13.87
20	Control(I)	0.4551	26.44
21	Tuck plant (III)	0.7796	15.44
22	Control(I)	0.4781	25.17
23	Tuck plant (IV)	0.8115	14.83
24	Control(I)	0.4232	28.43

Table 7-4 R_0 and h values of warp knitted fabrics

Sample	Structure	Calculated R_0 (mm)	Equilibrium Height h (mm)
1	Control	0.4072	9.33
2	Warp plant (I)	0.9164	4.14
3	Control	0.4072	9.33
4	Warp plant (II)	0.9601	3.96
5	Control	0.3835	9.91
6	Warp plant (III)	0.8533	4.45
7	Control	0.3835	9.91
8	Warp plant (IV)	0.8145	4.66
9	Control	0.2880	13.20
10	Warp plant (I)	0.8533	4.45
11	Control	0.3580	10.62
12	Warp plant (II)	0.6720	5.65
13	Control	0.3313	11.47
14	Warp plant (III)	0.7964	4.77
15	Control	0.2641	14.39
16	Warp plant (IV)	0.7590	5.01

It can be seen from Tables 7-3 and 7-4 that for all fabrics, h>>R_0, and the height variations of the meniscus surface are negligible as compared to the total height. The schematic diagram of the typical simplified conical capillary representing the present case is given in Figure 7-3, where θ contact angle, R_0 is the bottom radius of cone capillary, h is the capillary height, α is the angle between tilted plane of cone capillary and vertical plane.

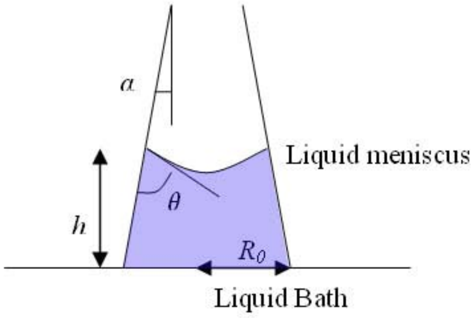


Figure 7-3 Schematic illustration of cone capillary and definitions of parameters on hydrophilic

surface (hydrophilic surface, $\cos\theta > 0$, negative α , and positive h)

In a tube with water, the Laplace pressure is balanced by the hydrostatic pressure, therefore,

$$P_0 + \frac{c\sigma}{r} = P_0 + \rho g h \quad (7\text{-}3)$$

$$r(h) = \frac{c\sigma}{\rho g h} \quad (7\text{-}4)$$

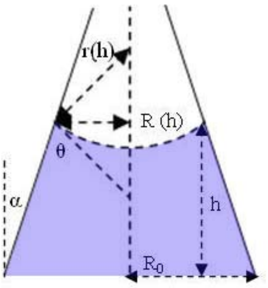


Figure 7-4 Cone capillary

According to geometric relationship in Figure 7-4, Equations 7-5 and 7-6 were obtained:

$$r(h) = -R(h)/\cos(\alpha+\theta) \quad (7\text{-}5)$$

$$R(h) = R_0 + h\tan\alpha \quad (7\text{-}6)$$

Equation 7-7 was derived by Equations 7-4, 7-5 and 7-6

$$\cos(\alpha+\theta) = \frac{1}{c}\bar{h}(\bar{R}_0 + \bar{h}\tan\alpha) \quad (7\text{-}7)$$

When $\alpha \to 0$, equation 7-7 equals to equation 7-1 ($h = c\kappa^{-2}\cos\theta / R$). Where $\kappa = (\sigma/g\rho)^{-1/2}, \bar{h} \equiv \kappa h, \bar{R}_0 \equiv \kappa R_0$.

We define

$$\frac{1}{c}\bar{h}(\bar{R}_0+\bar{h}\tan\alpha)=f(\bar{h}) \qquad (7\text{-}8)$$

The minimum of $f(\bar{h})$ is obtained by $\bar{h}^*=-\bar{R}_0/(2\tan\alpha)$ (obtained by $f'(\bar{h})=0$). For a given value of contact angle θ, the critical value of the opening angle α_c is given by the condition $f(\bar{h}^*)=\cos(\theta+\alpha_c)$. As α is increased past α_c, the meniscus "jumps" all the way to the top of the capillary. Where $f(\bar{h}^*)$ is the minimum of $f(\bar{h})$, R$_0$ is the radius of the capillary at the water level, α_c is the critical value of α.

The critical value of opening angle α_c is given by the condition

$$\bar{h}^*=-\frac{\overline{R_0}}{2\times\tan\alpha_c} \qquad (7\text{-}9)$$

$$f\left(\bar{h}^*\right)=\cos\left(\theta+\alpha_c\right) \qquad (7\text{-}10)$$

The critical opening angle α_c can be calculated by solving equations 7-9 and 7-10 by using the tabulated values of base radius. θ = 35° of cotton material, θ = 75° of polyester material. The actual values of α and the critical values of α_c for cotton and polyester are given below:

Table 7-5 Actual α and critical α_c of weft tuck knitted fabrics

Sample	Structure	Actual α	α_c
1	Control(I)	0	Not exist
2	Tuck plant (II)	0.135591	0.008287032422
3	Tuck plant (III)	0.253947	0.01372416632
4	Tuck plant (IV)	0.324377	0.01546512894
5	Control(I)	0	Not exist
6	Tuck plant (II)	0.119001	0.007648449328
7	Tuck plant (III)	0.19251	0.03693073675
8	Tuck plant (IV)	0.269347	0.03992838686
17	Tuck plant (III)	0.22253	0.03310208638
18	Control(I)	0	Not exist
19	Tuck plant (IV)	0.324377	0.04546014921
20	Control(I)	0	Not exist
21	Tuck plant (III)	0.19257	0.03692426599
22	Control(I)	0	Not exist
23	Tuck plant (IV)	0.235631	0.03992742843
24	Control(I)	0	Not exist

Table 7-6 Actual α and critical α_c of warp knitted fabrics

Sample	Structure	Actual α	α_c
1	Control	0	Not exist
2	Warp plant (I)	0.298345	0.04698329621
3	Control	0	Not exist
4	Warp plant (II)	0.325989	0.05092836820
5	Control	0	Not exist
6	Warp plant (III)	0.263767	0.04146674678
7	Control	0	Not exist
8	Warp plant (IV)	0.224947	0.03818651356
9	Control	0	Not exist
10	Warp plant (I)	0.306133	0.04146674678
11	Control	0	Not exist
12	Warp plant (II)	0.31251	0.02697634343
13	Control	0	Not exist
14	Warp plant (III)	0.268044	0.03668728568
15	Control	0	Not exist
16	Warp plant (IV)	0.26837	0.03365036035

Since $\alpha >> \alpha_c$ as shown in Tables 7-5 and 7-6, the meniscus would ‘jump’ all the way to the top of the conical capillary. In contrast, the capillaries in the control fabrics having plain interchanged knit structure are straight, therefore, the rise of liquid will take place in a continuous manner; a finite (longer) time may be required for reaching the top. However, the average pore radius at the back side of plant fabrics being in general greater than those of corresponding control fabrics, the volume of water absorbed by the conical capillary of plant structures would naturally be higher. This may be the reason of improved initial water absorption rate demonstrated by plant fabrics over the control ones in TWTT tests.

7.5 Conclusions

In this chapter, cohesion-tension, branch network, as well as capillary action were proposed to explain the possible mechanisms of water transport through plant structured fabrics. The enlarged surface area possessed by plant knitted structured fabrics could generate high water evaporation from the surface; as a result, more water can be continuously driven from the bottom to the top due to cohesion-tension force. Two or more yarns combined together at the back were separated at the face; this could build a branching network, resulting in a low water resistance at the transverse direction. The improved water absorption and transport may also be caused by the improved capillary action. From a simplified analysis, it can be concluded that the geometry of conical capillaries in plant structure satisfied the requirement of discontinuous water rise in a tube. In other words, water can jump all the way to the top in discontinuous manner.

8. Conclusions and Suggestions for Further Work

8.1 Introduction

This chapter summarizes the research work, the results and insights yielded from this study, also presents limitations and suggestions for future research. The present study proposed an innovative design concept termed “plant knitting structure” with the aid of knitting technology. The study set out to explore the possibility of simulating branching network at the transverse section of fabrics, concerning the design principles and methods. The innovations involving design concepts, principles and methods proposed in this thesis have been validated and show a potential in commercial values. This study laid a foundation for the further research of plant structured knitted textiles. In this chapter, the purposes of this study are emphasized firstly. Then, the key issues that are crucial to the research of plant structured knitted fabrics and the major characteristics of design innovations are summarized. The values and significances of results obtained in this study are highlighted. Finally, limitations and recommendations are proposed.

8.2 Restatement of study purpose

With the improvement of living standard, people are keen on leading a healthy life in such busy and high pressure living environment. As a consequence, more and more people participate out-doors exercises and activities. People are not satisfied with normal functional clothing and are increasingly concerned about the comfort and multiple functions of clothing. The comfort of fabrics is related to many aspects such as hand-feel, thermal properties and liquid water transport properties, etc. In summer and heavy exercise condition, liquid water transfer from the inner layer of fabrics next to the skin to the outer surface so as to maintain the skin dry becomes essential.

Hence, moisture management fabrics have been developed to meet these demands. Different techniques are applied to improve moisture management properties, which include:

1. Changing fiber cross-sections to enhance wicking capacity.
2. Grafting hydrophilic bonds in molecule chain to improve the hydrophility of fibers.
3. Spinning hydrophilic and hydrophobic fibers into blended yarns.
4. Placing hydrophilic and hydrophobic yarns into two surfaces of fabrics.
5. Changing surface hydrophility properties by chemical treatment.

Although there are a considerable number of moisture management fabrics on the market, no work has been conducted on mimicking the branching network in the transverse direction of knitted fabrics for improved liquid water transport.

After realizing the limitations of most existing research, this study was to mimic the branching network of plants through innovative knitting structures so as to minimize the resistance to water transport at the transverse direction of textile fabrics.

8.3 Summary of major findings

To mimick the branching network in knitting structures in the transverse direction, it is desirable to form multi-yarned loops at the back side and then split the multiple yarns into individual yarns to form single-yarned loops at the face side. However, this is impossible with circular knitting due to its inherent limitation. One of structures close to the requirements was to use weft plating technique as described in Chapter 4. One yarn was plated to form loops together with another yarn at the back so that the loops at the back are formed by two yarns bundled together, simulating the coarse stem of a plant. Another circular knitting structure approximately mimicking the branching network (described in Chapter 5) was achieved by weft tucking technique, in which one yarn ran to the face and back sides of fabrics to simulate a continuous conduit to deliver water from the back side to the face side, and another two or three yarns formed the tuck on the back side to connect loops on the back side; these tucks can be regarded as branches in plant structure.

With the Raschel warp knitting technique, it is possible to form multi-yarned loops at the back side and then split the multiple yarns into individual yarns to form single-yarned loops at the face side. A number of fabrics with such novel structures have therefore been produced and reported in Chapter 6.

The novel knitting structures mimicking the branching network of plants significantly improved liquid water transport properties, based on the comparison between plant structured knitted fabrics and fabrics in the corresponding conventional knitting structures. It was found that plant structures possessed significantly higher initial water absorption rates than control structures. Possible explanations were given as follows: The open surface area of the outer surface was enlarged, whereas the surface area of the inner surface next to the skin was reduced. As a result, the condition generating a “cohesion-tension” force was created. Additionally, due to branch networks shaped at the cross-section, minimum water resistance was another reason to facilitate fast liquid transport. Wicking capillary force was increased due to smaller loop size at the outer side and larger loop size at the inner side.

Furthermore, plant structured fabrics also had enhanced one-way transport capacity, due to the less number of loops at the back side, which tend to retain less water. Plant structured fabrics possessing porous construction, had significantly lower air resistance in comparison with control fabrics. The developed plant structured knitted fabrics had no significant advantage in water vapor permeability due to increased thickness and pores containing more still air.

In terms of water evaporation rate and vertical wicking rate, warp knitted plant structured fabrics had faster rates than corresponding control fabrics. As for water retention, two of warp knitted plant structured fabrics could hold higher water content, while others with larger holes retained less amount of water.

In addition, the present study improved the understanding on the relationship between fabric parameters and some moisture management properties. For example, fabrics with higher weight were associated to higher initial water absorption rate. High fabric thickness could result in low water vapor permeability. Large holes in fabrics deteriorated vertical wicking rate and water retention properties.

8.4 Significance and implications of study

Although a great deal of commercial fabrics have been developed for the improvement of wicking and moisture management properties, there is the lack of research on the effect of knitting structures upon liquid water transport properties. Understanding the effect of knitting structure on liquid water transport and moisture management properties is crucial for the development of moisture management fabrics. From this study, it can be concluded that knitting structures mimicking the branching network of plants have a potential to accelerate water transport at the transverse direction of fabrics. This study also implied that the influences of fabric constructions on water transport may be more complex than previously expected. It is believed that the present research has made a contribution to the application of boimimetics in textiles from the respect of promoting the development of moisture management fabrics.

8.5 The limitations of the study

Through the present investigation, innovative knitting structures were developed and the potential advantages of plant structured knitted fabrics were proven. Nevertheless, the present study still has several limitations due to the constraints in time and resources. These include:

1. The present investigation has focused on the innovation of novel knitting structures for moisture management. However, fabric parameters were not optimized.

2. The liquid water transport properties of fabrics are affected by weight, thickness, and fiber composition and finishing. Due to differences in fiber composition, weight, thickness, etc among weft and warp knitted plant structured fabrics developed in this study, they cannot be directly compared. The newly developed fabrics also cannot be directly compared with commercial fabrics due to possibly different finishing.

3. Although the water transport and air resistance of the newly developed plant structured knitted fabrics was enhanced, the water vapor permeability of developed samples including plant structured and control fabrics were relatively low for

summer wear or sportswear applications.

4. The present study only used objective measurements to evaluate the developed fabrics. Subjective wearer trials were not carried out to evaluate the comfort of fabrics.

8.6 The recommendations for future research

In this study, the design concept, principles and fabrication methods of plant structured knitted fabrics have been investigated. It is envisaged that this research can be developed further in the following directions:

In the present study, cotton and polyester were the primarily materials used and thus the variety of fiber types was limited. Perhaps further study can be conducted using a wide range of fibers so as to yield fabrics of different end-uses. If finer yarns and finer machine gauge can be available, lighter-weight fabrics can be produced in the novel plant structure for sportswear and summer wear applications. It is also worth applying plant structured fabrics to cushions, mattress, seating and medical uses. Additional studies regarding the effect of fiber materials, yarn types, yarn finenesses, fabric construction parameters are useful.

Different plant structures invented in this study may be most suited for different end-uses. More research on the optimization of constructional parameters, such as loop length and density, to achieve an optimum balance amongst liquid water transport properties, acceptable and appropriate mass, thickness, hand-feel, and physical properties for different commercial applications is recommended.

The concept of mimicking the plant structure in knitted fabrics to improve liquid transport properties is innovative. However, the overall comfort of a fabric is associated with other factors, such as thermal properties and hand-feel. To develop a fabric with excellent comfort, other properties should be considered and optimized. More extensive studies might be helpful to improve the entire comfort properties of fabrics.

Yarn and pore distributions in fabric cross-section can provide additional important information on fabric structures. The quantification of the construction of fabrics is rather difficult and complex. Thus work calls for better methods to investigate fabric construction.

Warp knitting structures can vary. Even for two yarns combined together, there are various combinations of two needle bars motion to yield the simulation of a branch network. Moreover, the variations of combining two or more yarns should be further explored to make fabrics for different end uses.

Our understanding of the mechanism of liquid water transport in plant structured fabric is still rather qualitative and much limited. It is therefore desirable to develop a theoretical model to better understand and optimize water transport in plant structured knitted fabrics. The challenge here is the quantification of numerous fabrics including fiber types, yarn construction, fabric structure and pore size and distribution.

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