Study of Comfort Properties of Natural and Synthetic Knitted Fabrics in Different Blend Ratios for Winter Active Sportswear

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DECLARATION

I, Wiah Wardiningsih, certify that:

a. except where due acknowledgement has been made, the work is that of the candidate alone;

b. the work has not been submitted previously, in whole or in part, to qualify for any other academic award;

c. the content of the thesis is the result of work which has been carried out in the School of Fashion and Textiles, RMIT University between March 2007 and March 2009.

d. any editorial work, paid or unpaid, carried out by a third party is acknowledged.

e. ethics procedures and guidelines have been followed.

Wiah Wardiningsih

June, 2009

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DEDICATION

This work is dedicated to my parents and my family

Output of the study

Conference paper

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Abstract

The objective of the present study is to produce base layer winter active sportswear fabrics using natural and synthetic fibres and their blends which will deliver good comfort properties. Polyester, wool and bamboo were selected for this study. Polyester is the most common fibre used in sportswear, wool is increasingly being used in sportswear and bamboo is a relatively new fibre that offers properties suitable for base layer sportswear. Bamboo is also regarded as a “green” and eco-friendly fibre.

Preliminary experiments were carried out to find the liquid moisture transfer performance of knitted fabrics made from each selected single fibre.

Preliminary experimental sample fabrics were produced as single jerseys with different cover factors. It was concluded that cover factor was influenced by loop length; whereas cover factor, physical and structural properties influenced the liquid moisture performance of fabrics, depending on the fibre type that was used.

Experimental single jersey sample fabrics were produced from different fibre blends including wool, polyester and bamboo. The physical and structural properties selected for testing were weight/m^2, thickness, stitch density (courses/cm wand wales/cm), porosity and optical porosity. The comfort properties selected for testing and analysis were liquid moisture transfer and a fabric classification with respect to the following properties: thermal conductivity, warm/cool feeling, stiffness and number of contact points. These parameters were assessed to determine the comfort properties of commercial and a range of experimental sample fabrics.

It was concluded that blended fibre influenced comfort properties of experimental sample fabric and the sample fabrics that are most suitable for base layer winter active sportswear are P100, W43P57, W35B65, W52B48, W60b40 (experimental sample fabrics and MRWB (Commercial sample fabric)

CHAPTER 1
BACKGROUND RESEARCH

1. Introduction

Sportswear textiles belong to a category called sporttech, which is one of the mainstream technical textiles (Anand & Horrocks 2000). The consumption of textile fibres and fabrics in sportswear and sporting related goods has seen a significant increase in the last decade or so. In an analysis by David Rigby Associates in 2002, it was stated that the worldwide consumption of textiles for sports increased from 841,000 tons in 1995 to 1,153,000 tons in 2005. The forecast made for 2010 was 1,382,000 tons. This reflects to a large extent the significant rise in interest of the population worldwide in active indoor and outdoor sports as well as in outdoor leisure pursuits (Shishoo 2005).

This rising interest is due to a number of social factors that include increased leisure time, increased considerations of wellbeing and good health, growth of indoor and outdoor sports facilities and the ever-increasing pursuit of the adult population of activities outside the home or workplace. Textile materials in various shapes and forms are being used in a wide range of applications in sportswear and sporting equipment, and the manufacturers of these products are often at the forefront of textile manufacturing technologies for enhancing the properties of performance fabrics and sportswear in order to fulfil various types of consumer and market demands.

In this chapter, the comfort of sportswear will be reviewed. As sportswear is clothing that is worn by people, the interaction between the consumers, clothing and the environment will be reviewed along with human physiology. Comfort related to sport apparel will be reviewed in terms of its definition, aspects, relation to textile properties and assessment. As this present study will focus on winter sportswear, the cold environment and protection from cold related to clothing will also be reviewed. Sportswear will be reviewed regarding its functionality requirements and in relation to winter sportswear. Fibres, fabrics, garments and finishes related to sportswear also will be discussed.

1.2. Interaction of human, clothing and environment

People wear clothing to protect their body from environment. As clothing is being worn, the human body interacts dynamically with it and the surrounding environment. There are four processes occurring interactively that determine the comfort status of the wearer. The processes are: physical processes in clothing and surrounding environments, physiological processes in the body, neurophysiological and psychological processes (Li & Wong 2006a).

These four types of processes occur concurrently. The laws of physics are followed by the physical processes in the environment and clothing, which determine the physical conditions for the survival and comfort of the body. The laws of physiology are followed by the thermoregulatory responses of the body and the sensory responses of skin nerve endings. The thermoregulatory and sensory systems react to the physical stimuli from clothing and the environment to create certain appropriate physiological conditions for the survival of the body and to inform the brain of various physical conditions that influence comfort status (Li & Wong 2006a).

The psychological processes are the most complicated. The brain needs to formulate subjective perceptions from the sensory signals from the nerve endings in order to evaluate and weigh these sensory perceptions against past experiences, internal desires and external influences. Through these processes, the brain formulates a subjective perception of overall comfort status, judgements and preferences. Alternatively, the psychological power of the brain can influence the physiological status of the body through various means such as sweating, blood-flow justification and shivering. These physiological changes will alter the physical processes in the clothing and external environment (Li & Wong 2006a).

On the basis of integration of all of these physical, physiological, neurophysiological and psychological processes and factors, the comfort status as the subjective perception and judgement of the wearer is determined (Li & Wong 2006a).

1.2.1. Neurophysiology of sensory perceptions

Skin stimuli and skin sensory system

The epidermis and the dermis are the two layers of human skin. The outer layer that consists of several layers of dead cells on top of a single living cell is the epidermis. The inner layer that consists of most of the nerve endings in the skin is the dermis. Sweat glands, hair follicles and fine muscle filaments are also located in the dermis. Below the dermis, there are layers of connective tissue and fat cells (Coren & Ward 1989; Li & Wong 2006a).

Corpuscular and non-corpuscular (or free nerve) endings are two types of nerve endings. Corpuscular nerve endings have small bodies or swellings on the dendrites, which are particularly responsive to touch stimuli. The free nerve endings in subcutaneous fat are associated with pain, and those projecting into the epidermis may be associated with cold or pain (Coren & Ward 1989; Li & Wong 2006a).

Transduction

Transduction is the process of the conversion of various external stimuli into the standard code by which nervous systems work and is the basic function of sensory receptors (Coren & Ward 1989; Li & Wong 2006a).

Neural pathways and responses

The neural signals from the nerve endings are passed to the brain to formulate sensation. The pathways to the brain depend on two major principles: the types of nerve fibres and the place where the pathway terminates in the cortex. Different types of nerve endings carry different types of information to the brain.

The nerve fibres can be classified in a number of ways: (1) by the types of stimuli that excite them; (2) by the way they respond to stimuli (slow or fast-adapting); and (3) by their receptive field (large ill-defined or small well-defined). The receptive field refers to the region of the skin that, when stimulated, causes responses in a particular neural fibre. The location of a nerve ending determines where its information goes to the brain, regardless of the type of fibre it represents. There are 31 pairs of nerves, through which all the sensory information from skin is passed on to the spinal cord. Through the dorsal roots, the nerve endings enter into the back portion of the spinal cord. For the head region, there are four cranial nerves collecting cutaneous information (Coren & Ward 1989; Li & Wong 2006a).

The information reaches the brain by two main pathways: medical and spinothalamic. The medical pathway, which is both rapid and large, receives inputs from large, myelinated, fast-conducting $A\beta$ fibres terminating in corpuscular endings. These fibres are responsive to touch, temperature and movement. However, the spinothalamic pathway, which is a slow pathway made up of many short fibres, carries information on temperature and pain. At the brain stem, the spinothalamic pathway is divided into two branches: paleospinothalamic and neospinothalamic. The paleospinothalamic branch, which specialises in dull and burning pain signalling, receives input from small, unmyelinated, slow-conducting C fibres that terminate in free nerve endings in the skin. The neospinothalamic branch, which specialises in sharp and prickling pain signalling, receives most input from small, myelinated, slow-conducting $A\delta$ fibres that terminate in free nerve endings in the skin. It also receives input from $A\beta$ fibres (Coren & Ward 1989; Li & Wong 2006a).

1.2.2. Thermophysiology of the human body

The human body has the ability to regulate its internal temperature with a certain level of accuracy under changes in external and internal conditions. The temperature regulation works through biological mechanisms – specific central and peripheral nervous systems continuously detect the temperature fluctuations in the body and attempt to keep them in balance by means of biological actions (Li & Wong 2006b).

Hensel (1981) described physiological temperature regulation as a complex system containing multiple sensors, multiple feedback loops and multiple outputs. Figure 1.1 shows Hensel's model of autonomic temperature regulation in man. The control variable is an integrated value of multiple temperatures such as the central nervous temperature (T_{cn}), the extra-central deep body temperature (T_{db}) and the skin temperature (T_{sk}). Hensel defined the 'weighted mean body temperature' (T_{nb}) as the controlled variable for practical purposes:

$$T_{nb} = a\,T_i + (1 - a)\,T_{sk}\,, \quad a < 1 \tag{1.1}$$

Values of a were proposed between 0.87 and 0.9 by measuring T_i in the oesophagus. The rating ratio was assumed to be the relative contribution from T_{sk} and T_i in a linear control function.

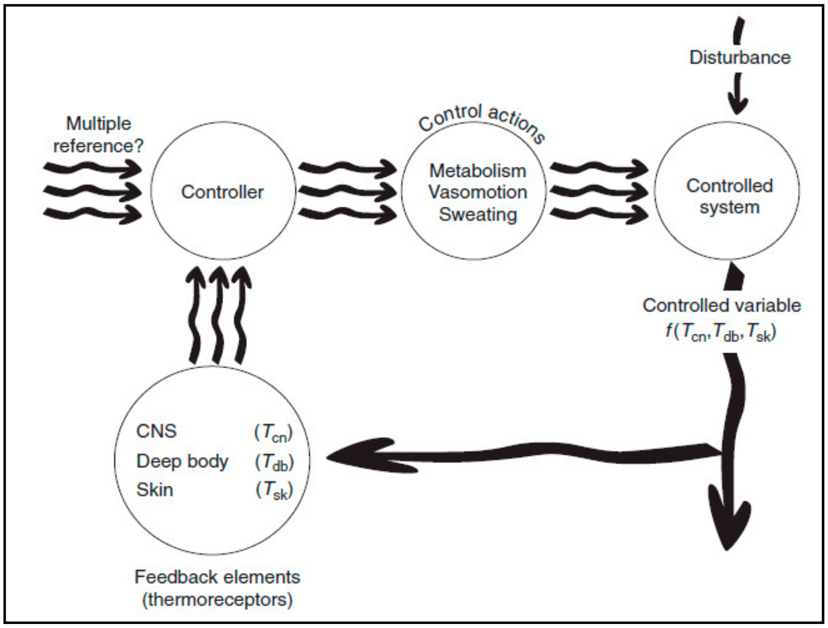


Figure 1.1.Schematic diagram of autonomic temperature regulation in man (Li & Wong 2006b)

The references (or set temperatures) for different control actions such as metabolism, vasomotion and sweating might be different. The heat dissipation mechanisms such as sweating driven by warm receptors may have a higher set temperature than heat-production mechanisms driven by cold receptors. Therefore, there is a zone of thermal neutrality in which no thermal regulation occurs. The thermal regulation mechanisms have been classified into three categories: autonomic regulation, behaviour regulation and technical regulation (Hensel 1981; Li & Wong 2006b).

The autonomic regulation responds to thermal disturbances from internal heat generated by exercise and environmental heat or cold. Thermoreceptors receive signals from the thermal disturbances and transfer them to the central nervous system via afferent nervous pathways. The receptors can respond not only to temperature but also much more effectively to temperature change. This means that rapid external cooling or warming may lead to a transient opposite change of internal temperature (Hensel 1981; Li & Wong 2006b).

Behavioural thermoregulation in humans is related to conscious thermal sensations and emotional feelings of thermal comfort and discomfort. Behavioural thermoregulation in response to heat and cold modifies the need for autonomic thermoregulatory responses. Hensel (1981) summarised various autonomic and behavioural components of temperature regulation. Technical thermoregulation can be considered an extension of the human regulatory system through technical inventions. Temperature regulation is shifted from the body to the environment using artificial sensors, controllers and effectors.

1.2.3. Summary

From review above it can be concluded that the human body always interacts dynamically with clothing and the surrounding environment. Four types of processes occur concurrently which follow different kind of laws. The comfort status of the wearer is determined on the basis of a combination of these physical, physiological, neurophysiological and psychological processes. Neurophysiological sensory perceptions deal with how the stimuli in the skin passed through nerve endings, transferring the stimuli into codes understood by the nervous system so that the brain can formulate the sensation. Thermophysiology, in turn, deals with the regulation of the internal temperature in the human body to keep the temperature in balance under changes in external and internal conditions.

1.3. Comfort

1.3.1. Comfort definition

Many researchers have defined comfort in relation to clothing. According to Kothari and Sanyal (2003), comfort is not easy to define because it covers both quantifiable and subjective considerations. Comfort is a situation where temperature differences between body members are small with low skin humidity and the physiological effort of thermal regulation is reduced to a minimum. Barker (2002) stated that comfort is not only a function of the physical properties of materials and clothing variables, but also must be interpreted within the entire context of human physiological and psychological responses. Personal expectation or stored modifiers that sort out or influence our judgement about comfort based on personal experiences must be also considered.

Holcombe (1986) stated that comfort as wellbeing and fundamental to that wellbeing is the maintenance of the temperature of our vital organs within a few degrees of 37^{o}C for them to function properly, otherwise the metabolic system can be extensively disrupted and sustained abnormal temperature will lead to death. Temperature control is achieved by changing skin temperature through changes to blood flow and by evaporation of water at the skin surface.

Nielsen (1991) viewed comfort in a physical sense as the body being in a heat balance with the environment (thermal comfort), that the body is not being subject to pressure from narrow or badly designed clothing (movement comfort) and that skin irritation does not occur from unpleasant contact with clothing (sensorial comfort).

Ishtiaque (2001) stated that clothing comfort is governed by the interplay of three components: body, climate and clothing. The human body, its microclimate and its clothing form a mutually interactive system. The body and its microclimate are invariable; the clothing system is the only variable.

Li and Wong (2006) summarised comfort into several components.

- Comfort relates to subjective perception of various sensations.
- Comfort involves many aspects of human senses such as visual (aesthetic comfort), thermal (comfort and warmth), pain (prickling and itching) and touch (smooth, rough, soft and stiff).
- The subjective perceptions involve a psychological process in which all relevant sensory perceptions are formulated, weighed, combined and evaluated against past experiences and present desires to form an overall assessment of comfort status.
- The body–clothing interactions (thermal and mechanical) play important roles in determining the comfort status of the wearer.
- External environment (physical, social and cultural) has a great impact on the comfort status of the wearer.

1.3.2. Comfort aspects

Wear comfort is a complex phenomenon but in general it can be divided into four main aspects (Bartels 2005)

- Thermophysiological wear comfort. This comprises heat and moisture transport processes through the clothing and directly influences a person's thermoregulation.
- Skin sensorial wear comfort. This deals with the mechanical sensations caused by textiles as it is in direct contact with the skin. Pleasant and unpleasant perceptions such as smoothness or softness, scratchiness, stiffness, or clinging to sweat-wetted skin may be created by textiles.
- Ergonomic wear comfort. This is characterised by the fit of the clothing and the freedom of movement it allows. The garment's construction and the elasticity of the materials are the main aspect of ergonomic wear comfort.
- Psychological wear comfort. This is of importance as well. It is affected by fashion, personal preferences and ideology.

1.3.2.1. Thermophysiological comfort

Thermophysiological wear comfort concerns the heat and moisture transport properties of clothing and the way that clothing helps to maintain the heat balance of the body during various levels of activity (Saville 2004).

Thermophysiological comfort has two distinct phases. During normal wear, insensible perspiration is continuously generated by the body. Steady state heat and moisture vapour fluxes are thus created and must gradually dissipate to maintain thermoregulation and a feeling of thermal comfort. In this case the clothing becomes a part of the steady state thermoregulatory system. In transient wear conditions, characterised by an intermittent pulse of moderate or heavy sweating caused by strenuous activity or climatic conditions, sensible perspiration and liquid sweat occur and must be rapidly managed by the clothing. This property is important in terms of the sensorial and thermoregulatory comfort of the wearer. Therefore, heat and moisture transfer properties under both steady and transient conditions must be considered to predict wearer comfort (Yoo & Barker 2005a; Barker 2002).

1.3.2.2. Sensorial comfort

Li and Wong (2006) stated that sensorial comfort is the elicitation of various neural sensations when textile comes into contact with skin. The skin sensorial wear comfort characterises the mechanical sensations that a textile causes at direct contact with the skin. The perception may be pleasant, such as smoothness or softness, but it may also be unpleasant, if the textile is scratchy, too stiff or clings to sweat-wetted skin (Shishoo 2005).

Sensorial comfort does not directly involve any temperature balance but is related to the way the person feels when clothing is worn next to the skin. Feeling wet and wet clinging can be a major source of sensorial discomfort in situations of profuse sweating (Kothari & Sanyal 2003).

Sensorial comfort is mainly determined by fabric surface structure and to some extent by moisture transport and buffering capacity. It is associated with skin contact sensation and is often expressed as a feeling of softness, smoothness, clamminess, clinginess, prickliness and the like. These descriptors can be related to specific, measurable fabric mechanical and surface properties including the number of surface fibres and contact points, wet cling to a surface, absorptivity, bending stiffness, resistance to shear and tensile forces, and coolness to the touch. These properties are mainly determined by fibre characteristics, yarn and fabric construction and fabric finish, but it is necessary to recognise that the extent of their relationship to comfort perception in clothing is also influenced by garment construction and properties (Yoo & Barker 2005b).

1.3.3. Comfort and textiles properties

There are specific physical textile properties that may be measured in an effort to predict the comfort performance of fabric. Basically a textile material should be evaluated in terms of the most general functional properties: thickness, weight, thermal insulation, resistance to evaporation and air penetration. There are three clothing factors that relate directly to thermal comfort. First is the overall thickness of the materials and air spaces between the skin and environment. Second is the extent to which air can penetrate the clothing by wind or wearer motion. Third is the requirement that fabric does not restrict the evaporation of perspiration (Andersson 1999).

Higgins and Anand (2003) summarised the important textile properties for comfort:

- Intrinsic thermal insulation

The intrinsic thermal insulation of a fabric can be determined by measuring its resistance to the heat transmission of heat by conduction. Intrinsic thermal insulation is proportional to the thickness of fabrics. It does not include the layer of air next to the fabric during use.

- Thermal insulation

Thermal insulation is the resistance of a fabric and the layer of air next to it during use to dry or conductive heat loss. Unlike intrinsic thermal insulation, thermal insulation varies with the ambient wind speed. As the speed increases, the thermal insulation provided by the layer of air decreases.

- Resistance to evaporative heat loss

Resistance to evaporative heat loss measures the ability of a fabric, together with the layer of air next to the fabric during use, to prevent cooling of the body by evaporation of heat generated during activity. Resistance to evaporative heat loss can be measured on either dry or damp fabrics.

- Thermal conductivity

The thermal conductivity of a fabric is determined by the rate of transmission of heat through fabric. It is reciprocal of thermal insulation or thermal resistance.

- Moisture vapour permeability

Moisture vapour permeability represents the resistance of a fabric to the transfer of water vapour, also known as insensible perspiration, released by body. Relative moisture vapour permeability is the percentage of water vapour transmitted through the fabric sample compared with the percentage of water vapour transmitted through an equivalent thickness of air. Low moisture permeability hinders the passage of perspiration through the fabric, leading to the accumulation of sweat in the clothing. The rate of water vapour transmission through the fabric is also usually reduced by increasing the fabric thickness.

- Water absorption

Water absorption is the capacity of a fabric to absorb the sweat generated by the body and the rate at which it is able to do so. To prevent wet clinging, the fabric's absorption should be low at the surface of the fabric which makes contact with the skin.

- Wicking

Wicking is the capacity of a fabric to transport absorbed sweat away from the point of absorption, usually the skin and the rate at which it does so.

- Air permeability

Air permeability is a measure of how well air is able to flow through a fabric. It can be measured on either dry or damp fabrics. A fabric which has good air permeability, however, does not necessarily have good moisture vapour permeability.

Air permeability is likely to be lower in fabrics where the absorption of water leads to swelling of the fibre and the yarn.

- Rate of drying

The rate of drying is the rate at which water is evaporated from the outer surface of a fabric. The rate of drying must be sufficient to achieve continuous wicking and to prevent the fabric from becoming saturated with sweat.

- Wind proofing

Wind proofing is a mechanism for reducing the heat loss from a garment by convection, thus improving the overall thermal insulation of clothing system.

- Surface coefficient of friction

The surface coefficient of friction of a fabric contributes to its sensory comfort. The coefficient of friction usually increases significantly when a fabric has become wet, leading to rubbing or chafing of the skin. A low coefficient of friction is also essential when one layer of fabric is required to move freely against another layer.

- Handle

The term *handle* describes the tactile qualities of a garment. It includes such properties as softness, compressibility, pliability and drape. These characteristics, although less important in specialised sportswear than in clothing worn on everyday basis, must not impair performance during sporting activity.

- UV resistance

UV resistance can be vital for clothing exposed to high levels of sunlight. It is particularly important in ski wear, when the wearer may not always be fully aware of the degree of exposure to UV radiation.

- Anti-microbial, anti-bacterial and anti-odour properties

Anti-microbial, anti-bacterial and anti-odour properties are important in garments which tend to remain in contact with sweat for long periods of time. Such items include sports socks, vests and underwear.

1.3.4. Assessment of comfort

Umbach (1988) suggested a five-level system for the analysis for wear comfort. At level 1 of this system the textiles are tested as fabric layers. The thermophysiological properties are determined by means of a thermophysiological model of human skin (skin model) simulating heat and moisture exchange from the skin. Thermal insulation and moisture transport qualities of fabrics are not only measured under stationary (normal) wear conditions, but also in transient situations, characterised by intermittent sweat pulse resulting from increased strenuous body activity. Thus a complete set of specific fabric quantities is available which, inserted in predictive formulae, yields themophysiological comfort. Consequently, at this level of analysis an accurate selection among a number of textile items possibly suitable for a particular garment is possible. Only the best items should be considered for the following evaluation levels.

The wear properties of clothing ensemble, consisting of several garments, are not only determined by the different fabrics included in the ensemble and their interaction with each other, but also by the interspaced air layers due to the garments' patterns. Therefore at level 2 of the evaluation system a life-sized moveable manikin is employed, representing a thermoregulatory model of a man.

With the thermal manikin the thermal insulation of garments can be measured and their moisture transport determined, exactly simulating their effects for the wearer in practical use. The manikin can perform body movements and therefore ventilation effects in the microclimate between the garment and their influence on thermal comfort can be evaluated. The effect of garment patterns on man's thermoregulation can also be investigated.

Using a manikin, a set of physiological quantities specific to the clothing system can be inserted into a predictive model, simulating the system's wear performance under all possible climatic and active conditions. From a number of clothing systems an accurate selection of the best items can be made.

The repeated accuracy of the test and predictive calculations of levels 1 and 2 of the system described, are so high that the wear trials with the subjects are in most cases not essential to the manufacturer or user. In some instances, however, it might be advisable to verify the test results of levels 1 and 2 of the system. For this purpose, controlled wear trials in a climatic chamber, level 3 of analysing system, are performed to check the result of the predictive calculations for one particular wear situation.

In the development of clothing the wear test of level 4 and level 5, with a limited or large number of subjects, would actually be restricted to small items optimised systematically in their comfort characteristic through levels 1 to 3 of the system. The wear test of levels 4 and 5, which are conducted under the real ambient conditions of the clothing's field of application, indicate whether parameters not included in the predictive calculations have some bearing on the physiological comfort perceived by the wearer.

1.3.4.1. Wear trials

Various methods can be used to evaluate or predict clothing comfort. According to Meinander et al. (2004) the thermal insulation properties of clothing can be defined through physical measurement using thermal manikins or through wear trials using human test subjects. Kim, Yoo and Shim (2006) stated that user tests or trials are the only way to provide realistic and comprehensive evaluations of the performance of clothing. However, it is infeasible to use these to test a variety of clothing systems because they are costly and it is difficult to control variables to determine where the subjective sensations come from. When tests are used for extreme conditions, the difficulty of these problems becomes more serious. A wide range of environmental conditions cannot be tested with human subjects for safety reasons, even though consumers can actually be exposed to such conditions. Therefore, it is important to use information from laboratory levels in the planning of test a field level.

1.3.4.2. Thermal manikin

Thermal manikins are widely used for the analysis of the thermal interface between the human body and its environment. Particular applications are found in the determination of thermal properties of clothing and in the evaluation of the local body heat fluxes in complex environments such as in a vehicle cabin. Recent developments of sweating manikins, as well as breathing manikins, allow even more realistic simulations of the human thermal interaction with the environment (Holmer 2004).

Manikins are complex, delicate and expensive instruments but they have many advanced and useful features. A human-shaped thermal manikin normally measures convective, radiative and conductive heat losses in all directions over the whole surface or a defined, local surface. The spatial resolution can be quite high depending on the number of segments of the manikin's surface. Some manikins in use have more than 30 individually regulated segments. A value for the whole body heat loss can be determined by summing up the area weighted values. For the same exposure conditions, a thermal manikin measures heat losses in relevant, reliable and accurate ways. The method is quick, easily standardised and repeatable (Holmer 2004).

According to Holmer (2004), significant performance features of a thermal manikin are

- relevant simulation of human body heat exchange
- whole body and heat fluxes
- measurement of three-dimensional heat exchange
- integration of dry heat losses in a realistic manner
- objective measurement of clothing thermal insulation
- quick, accurate and repeatable measurement
- cost-effective instrument for comparative measurements and product development

1.3.4.3. Skin model

The skin model is a thermoregulatory model of the human skin. It tests the thermophysiological wear comfort of textile materials. The skin model is internationally standardised (ISO 11092). The measuring unit is made of sintered stainless steel. Water, which is supplied by channels beneath the measuring unit, can evaporate through the numerous pores of the plate, just like sweat from the pores of the skin. Additionally, the measuring unit is kept at a temperature of 35°C. Thus, heat and moisture transport are comparable to those of the human skin (Bartels 2005)

According to Bartels (2005), different wear situations can be simulated with the skin model:

- Normal wear situations

These are characterised by an insensible perspiration, that is, wearers do not recognise they are sweating. Nevertheless, at least 30 grams per hour of water vapour is evaporated through the semi-permeable membrane skin.

- Heavier sweating

Wearers recognise they have started to sweat, but are not sweat-wetted yet, for example, when walking upstairs. In these situations, the skin produces vaporous sweat impulses, which can be simulated by the Skin Model by measuring the buffering capacity against vaporous sweat

- Heavy sweating situations with a high amount of liquid sweat on the skin

Here, the buffering capacity against liquid sweat and the liquid sweat transport defined as ‘moisture permeability’ are most important for good wear comfort. This is important for sport textiles.

- The wear situation directly after an exercise

This situation is also of great relevance to sport textiles. Then, the textile might be soaked with sweat and lose its thermal insulation. This leads to the so-called post-exercise chill, which is very unpleasant. The post-exercise chill can be avoided by using a short-drying-time fabric.

One of the current skin models is the Hohenstein skin model. This model uses a porous sintered metal plate as a measuring surface. Water vapour and fluid water are released in a controlled manner in a climatic chamber, thus simulating perspiration of human skin and different wear situations with different levels of sweat production. This modern measuring technique supplies more accurate and detailed results. While the manual evaluation of the measuring data from a series of wear tests could take up to three months, computers are now able to complete this in just a few hours (Umbach 2007).

1.3.4.4. Liquid moisture transfer

The Moisture Management Tester is used to test the liquid water transfer and distribution properties of fabrics. The principle of the apparatus design is that when moisture transports through a fabric, the contact electrical resistance of the fabric will be changed. The value of the resistance change depends on two factors: the components of the water and the water content in the fabric. When the influence of the water components is fixed, the electrical resistance measured is related to the water content in the fabric (Hu, Li & Yeung 2006).

The Moisture Management Tester is designed to objectively and accurately measure fabric moisture-management properties. The specimen is held flat by the top and bottom sensor with a certain pressure. Then a certain weight of predefined test solution (synthetic sweating – AATCC Test Method 15) is put into the sweat gland and introduced onto the top surface of the fabric. Meanwhile, the computer dynamically records the resistance change between each couple of proximate metal rings, which act as detectors, to detect the fabric wetted area in order to measure the size of the wetted area and the time it takes for the fabric to get wet. The solution transfers in three directions after arrival at the top surface of the fabric:

1. It spreads outward on the top surface of the fabric.
2. It transfers through the fabric from the top surface to the bottom surface.
3. It spreads outward on the bottom surface of the fabric and then evaporates (Hu, Li & Yeung 2006).

1.3.4.5. Sensorial comfort assessment

Sueo Kawabata was one of those working on devices that simulate the human sensation of touch. Using these, the subjective sense of touch, known as the ‘textile hand’, can be translated into exact physical parameters. Measurement of the shear stiffness has been shown to correlate extremely well with the subjective evaluation of the fabric hand. When determining the shear stiffness, the force required to produce a parallel movement in a horizontally fixed textile strip is measured. (Umbach 2007)

At the Hohenstein Institutes, Umbach (2007) and his colleagues analysed the influencing variables on skin sensory perception and developed a new measuring and evaluation process. It can measure:

- a surface index using an image analysis system that expresses the number and length of these spacers as a numerical value
- the number of contact points between the textile and the skin
- a wet cling index

- the stiffness of the textile as another influencing variable affecting skin sensory wear comfort
- the sorption index that shows how quickly a textile material is able to absorb liquid sweat and transport it away from the body

1.3.5 Summary

Researchers have defined comfort related to clothing in different forms. Some define comfort only in terms of physical and physiological aspects. Some relate comfort to psychological, physical and physiological aspects. But they all agree that clothing comfort is influenced by many factors. There are four main aspects in wear comfort but the present study will focus on two aspects only: thermophysiological wear comfort and skin sensorial wear comfort.

The important textile properties for comfort are: intrinsic thermal insulation, thermal insulation, resistance to evaporative heat loss, thermal conductivity, moisture vapour permeability, water absorption, wicking, air permeability, rate of drying, wind proofing, surface coefficiency of friction, handle, UV resistance, anti-microbial, anti-bacterial and anti-odour properties.

There are five levels of assessment of wear comfort. At level 1 of this system the textiles are tested as fabric layers. At level 2 the textiles are tested as clothing ensemble using a life-sized moveable manikin, representing a thermoregulatory model of a man. At level 3 the textiles are tested as clothing ensemble in wear trials in a climatic chamber. At levels 4 and 5, the textiles are tested as clothing ensemble in wear trials conducted under the real ambient conditions of the clothing’s field of application with a limited or large number of subjects

In the present study, the assessment will be performed at level 1 and will only assess the textile properties that are considered important for base layer winter active sportswear applications using available testing instruments.

1.4. Cold environment

A cold environment can be defined as an environment in which larger than normal body heat losses can be expected. The climatic factors governing heat losses are: air temperature, mean radiant temperature, air velocity and humidity. Factors such as snow and rainfall affect heat exchange primarily by interaction with clothing heat transfer properties. Heat exchange between the body and the environment takes place at the skin surface by convection, radiation, conduction, evaporation and via the human airways (respiration) (Holmer 2005).

In a cold environment the large temperature gradient between the skin surface and the environment is usually sufficient to allow control of the heat balance by convection and radiation. Additional sweat evaporation may be required only at extremely high levels of metabolic heat production. For efficient cooling the evaporated sweat needs to be transported as water vapour through the clothing and air layers adjacent to the skin and/or by convection through openings in the clothing (Holmer 2005).

Breathing air at low temperatures cools the airways of the respiratory system and adds to the skin heat losses. The cold air is warmed and saturated with water vapour in the lungs and airways. The amount of airway cooling increases with lower air temperature. It increases with increased minute ventilation but remains a relatively constant fraction of the metabolic heat production (Holmer 2005).

The airway heat losses may amount to 15±20% of the total heat production of the body. Airway heat losses are not under any physiological control, but may be reduced by simple covers of mouth and nose or by special masks for heat and moisture regain (Holmer 2005).

1.4.1. Energy metabolism, heat production and physical work in a cold environment

Assessment of the protection necessary in a cold environment requires information about the energy metabolism of the individual. Metabolic rate is related to the intensity of physical work and can be determined easily from measurements of oxygen consumption. Tables are readily available that allow its estimation during different types of activity (ISO 8996, 2004). With few exceptions, the values for metabolic rate also indicate the level of metabolic heat production. In most types of muscular work mechanical efficiency is negligible. Typically, winter sports may involve activities from very low to extremely high levels of heat production. For certain types of sports, for example, downhill skiing, the event is of such short duration (less than 1±2 minutes) that prevention of local cooling becomes more important than the overall heat balance. Table 1.1 can be used for a rough estimation of the metabolic rate and associated heat production in various types of sports and forms of physical activity (Holmer 2005).

Table 1.1.Examples of metabolic energy production associated with different types of sports and physical activities (Holmer 2005)

Class	**Average metabolic rate (W/m^2)**	**Examples**
0 Resting	65	Sleeping, resting
1 Low	100	Spectators at sporting events, casual walking (speed up to 3.5km/h), shooting, curling, fishing
2 Moderate	165	Hiking (average person),walking at a speed of 3.5 to 5.5km/h, alpine skiing (average person)
3 High	230	Intermittent activities in ball games (bandy, ice hockey), walking at a speed of 5.5 to 7km/h, hiking (well-trained)
4 Very high	290	Climbing, running or walking at a speed greater than 7km/h, alpine skiing (well-trained)
Very, very high (2 h)	400	Long-distance events in cross-country skiing Protection against cold
Intensive work (15 min)	475	Sprint events in cross-country skiing
Exhaustive work (5 min)	600	Sprint events in skating

1.4.2. The equation of human heat balance

Appropriate protection against cold is provided when the human body is in heat balance at acceptable levels of body temperatures (for example, skin and core temperatures). This implies that heat losses are equal to metabolic heat production (Holmer 2005).

The following equation describes the heat balance:

$$S = M - C - R - E - RES \tag{1.4}$$

Where

S = the rate of change in body heat content, W/m^2

M = the metabolic heat production, W/m^2

C = the convective heat exchange, W/m^2

R = the radiative heat exchange, W/m^2

E = evaporative heat exchange, W/m^2

RES = the airway heat loss, W/m^2

There are two principal thermal properties that determine clothing effects on heat exchanges by convection, radiation and evaporation: thermal insulation and evaporative resistance (Holmer 2005).

Thermal insulation *(I)* defines the resistance to heat transfer by convection and radiation by clothing layers. It accounts for the resistance to heat exchange in all directions and over the whole body surface. It is an average of covered as well as uncovered body parts. This definition allows the introduction of clothing in the heat balance equation. The insulation of clothing and adjacent air layers is defined as the total insulation value *(I_T)* and is defined by the following equation (Holmer 2005):

$$I_T = \frac{t_{sk} - t_a}{R + C} \tag{1.5}$$

Where

I_T = Total Insulation value, m^2 °C/W or in clo-units (1 clo = 0.155m^2 °C/W)

C = the convective heat exchange, W/m^2

R = the radiative heat exchange, W/m^2

t_{sk} = the mean skin temperature, °C

t_a = the air temperature, °C

Evaporative resistance *(R_e)* defines the resistance to heat transfer by evaporation and vapour transfer through clothing layers. As for insulation, it also refers to the whole body surface. In reality, the property is a resistance to vapour transfer. Heat transfer takes place only when sweat evaporates at the skin and is transported to the environment by diffusion or convection. The evaporative resistance of clothing layers and adjacent air layers *(R_{eT})* is defined by the following equation (Holmer 2005).

$$R_{eT} = \frac{p_{sk} - p_a}{E} \tag{1.6}$$

Where

R_{eT} = evaporative resistance, m^2/W

p_{sk} = the water vapour pressure at the skin surface, kPa

p_a = the ambient water vapour pressure, kPa

E = evaporative heat exchange, W/m^2

The human heat balance can now be written as follows. It can readily be seen how clothing affects heat exchange and the effect can be quantified.

$$S = M - \frac{t_{sk} - t_a}{I_T} - \frac{p_{sk} - p_a}{R_{eT}} - RES \tag{1.7}$$

Where

S = the rate of change in body heat content, W/m^2

M = the metabolic heat production, W/m^2

RES = the airway heat loss, W/m^2

I_T = Total Insulation value, m^2 °C/W or in clo-units (1 clo = $0.155m^2$ °C/W)

t_{sk} = the mean skin temperature, °C

t_a = the air temperature, °C

R_{eT} = evaporative resistance, m^2/W

p_{sk} = the water vapour pressure at the skin surface, kPa

p_a = the ambient water vapour pressure, kPa

Heat balance is achieved when the value of S is zero. This can occur for various combinations of the variables of the equation. However, only certain values for the physiological variables (M, t_{sk} *and* p_{sk}) are compatible with acceptable and tolerable conditions. These conditions can be analysed in terms of various scenarios for activity, climate and clothing (Holmer 2005).

1.4.3. Requirements for protection

Based on the human heat balance equation, the required values for I_T and R_{eT}, for combinations of activity and climate can be calculated. The appropriate strategy for efficient cold protection is to optimise clothing insulation so as to avoid or minimise evaporative heat exchange. The value of p_{sk} in the equation becomes only slightly higher than ambient p_a and the evaporative heat loss will be small. Accordingly, the possible values of ambient t_a for which heat balance can be maintained are primarily determined by the clothing insulation value (Holmer 2005).

Insulation requirements increase steeply at low activity levels in the cold. The low levels of metabolic heat production require high thermal resistances to create heat balance. In contrast, high activity levels produce substantial heat that must be transferred instantly to the environment in order to prevent overheating of the body. This is best done by reducing the insulative layer. There is a minimal level of insulation (clothing), however, that must be provided even at very high activity levels. This is to prevent direct skin cooling and discomfort from low skin temperatures. With such minimal insulation, increased sweating and sweat evaporation must complement the other heat losses for preserving good heat balance and avoiding overheating (Holmer 2005).

Wind accelerates heat loss from a warm surface. In many sports the travelling speed may create a significant relative air velocity around the body surface. Accordingly, surface layers of the body should provide high resistance to air penetration in order to minimise microclimate cooling. The outer garment of the clothing ensemble, preferably, should be made of materials with low air permeability. The surface layer of the outer garment should be water repellent or waterproof (Holmer 2005).

1.4.4. Summary

The human body needs protection in a cold environment due to the possibility of the occurrence of larger heat losses. Information about the energy metabolism of the individual is needed to determine the required protection. Appropriate protection against cold is provided when the human body is in heat balance. Optimisation clothing insulation is the appropriate strategy for efficient cold protection.

1.5. Sportswear

1.5.1 Sportswear as a technical textile

Technical textiles are textile materials and products manufactured primarily for their technical and performance properties rather than their aesthetic or decorative characteristics. Terms such as performance textiles, functional textiles, engineered textiles and high-tech textiles are also used in various contexts, sometimes with a relatively specific meaning (performance textiles are frequently used to describe the fabrics used in activity clothing), but more often with little or no precise significance (Anand & Horrocks 2000).

Sportswear is one of the 12 main application areas defined by Techtextil, the leading international trade exhibition for technical textiles (Anand & Horrocks 2000). The applications are listed in Table 1.2.

Table 1.2.Main application areas in technical textile (Anand & Horrocks 2000)

No	Area	Application
1.	agrotech	agriculture, aquaculture, horticulture and forestry
2.	buildtech	building and construction
3.	clothtech	technical components of footwear and clothing
4.	geotech	geotextiles and civil engineering
5.	hometech	technical components of furniture, household textiles and floor coverings
6.	indutech	filtration, conveying, cleaning and other industrial uses
7.	medtech	hygiene and medical
8.	mobiltech	automobiles, shipping, railways and aerospace
9.	oekotech	environmental protection
10.	packtech	packaging
11.	protech	personal and property protection
12.	sporttech	sport and leisure

1.5.2. Functionality requirements for active sportswear

The human body has an operating temperature of 37°C, which it attempts to maintain under varying circumstances. The body temperature rises during physical activity and can generate heat that ranges between 100 watts at rest and 1000 watts during periods of intense physical activity. Thus, it is necessary to transport heat from the body to the environment so as to maintain the body temperature at 37°C. The heat transport to the environment is achieved through a dry flux (conduction, convection and radiation) and a latent flux produced by perspiration. The body perspiration vapour and liquid sweat must have the opportunity to pass immediately away from the skin and possibly to the outer surface of the clothing (Kothari & Sanyal 2003).

According to Kothari and Sanyal (2003), there are basically three types of sports participants and their requirements of sportswear in terms of functional and other properties are different:

- Top level professionals primarily require functional power with aesthetic appeal as they strive for record-breaking performance.
- The seriously competing amateur involved in a sports club as a potential professional athlete needs to have sportswear with at least minimum functional effectiveness and at reasonable cost.
- Those who enjoy sports activities for its benefits in respect of health, hobbies and social contact need the sportswear materials to provide a minimum/reasonable physical function but they are more conscious of comfort and sensitivity.

Kothari and Sanyal (2003) broadly classified the requirements for active sportswear into:

- Functional: for top-level competition active sportswear requires super lightweight, low-fluid resistance, super high tenacity and stretchability. For those seeking comfort and healthy pursuits, critical features include thermal retention, UV resistance, cooling capacity, sweat absorption and fast-drying, vapour permeability, water proofing and so on to provide relaxation without fatigue.
- Aesthetic: from the sensivity or aesthetic point of view, softness is key. Surface texture, handle, lustre, colour variation, transparency and comfort in wear are also important factors.

Meanwhile, according to Ishtiaque (2001) (Table1.3), the predominant requirements of most active sportswear are:

- protection : from wind and adverse weather
- insulation : protection from cold
- vapour permeability: to ensure that body vapour passes outward through all layers of the clothing system
- stretch: to provide the freedom of movement necessary in sports

Table1.3.The different functions of materials required for various classes of active sportswear (Ishtiaque 2001)

Sportswear	Required function
Shirts for tennis, volley ball, golf (+ slacks), football, rugby, baseball uniform, athletic (+short) track suits	Sweat absorbing, fast drying, cooling
Skiwear, windbreaker, rain wear	Vapour permeability, water proofing
Skiwear, windbreakers, track suits	Sunlight absorbing and thermal retention
Swimming race and skating costume, ski jump and downhill skiing suits, cycling costume	Low fluid resistance (for water and air)
Swimwear, leotards, skating costume	Stretchability, opacity
Skiwear, snowboard wear, base ball uniform, football uniform	High tenacity, resistance to abrasion

Moisture-handling properties of textiles during intense physical activities have been regarded as major factor in comfort performance. The comfort perceptions of clothing are influenced by wetness or drying of the fabric and thermal sensations resulting from the interactions of fabric moisture and heat transfer-related properties. The garment worn next to the skin should have good sweat absorption and sweat-releasing property to the atmosphere and fast-drying property for more tactile comfort (Kothari & Sanyal 2003).

1.5.3. Winter sportswear requirements

Winter sports are normally performed in the cold environmental conditions. In a condition of 0°C without wind, humans can exercise at sufficient levels to adequately maintain core temperature while wearing one clo of thermal insulation .The clo unit is an index of clothing thermal resistance. One clo represents the clothing necessary to allow a resting individual to be in a comfortable state when the ambient temperature is 21°C. As the ambient temperature decreases, a significantly greater amount of clothing is required to maintain core temperature. In contrast to the small amount of clothing commonly worn during exercise in warm to hot environments, exercise in cool to cold environments requires that selections of clothing insulation be made at appropriate levels (Crow & Osczevski 1998; Gavin 2003).

Clothing selection for outdoor winter activities is a complex task. The ideal role of a clothing system is to maintain the thermal balance of the user in various environmental conditions despite the user's level of activity. The balance between heat production and heat dissipation is difficult to maintain. Too little clothing with low thermal insulation may lead to hypothermia while an excessive amount may lead to discomfort due to significant increases in body temperature and excessive sweating and skin wetness. Excessive skin wetness is associated with sensorial discomfort while wet clothing also reduces its thermal insulation. Reduced sweat accumulation in clothing during exercise can also reduce the probability of post-exercise chill and thermal discomfort (Crow & Osczevski 1998; Gavin 2003).

In general the principal thermoregulatory challenge during exercise in the cold is the dissipation of metabolic heat which can be alleviated by removing layers of clothing as the body warms. Thus the ideal winter clothing in dry, cold conditions blocks air movement but allows for water vapour to escape through the clothing if sweating occurs (Crow & Osczevski 1998; Gavin 2003).

Common clothing ensembles used in cold environments are comprised of two or more clothing layers: base layer, possibly middle layer and outer layer. Most of the skin surface is not in contact with the ambient environment but with the ambient environment under outer, middle clothing and the underwear itself. Thus, the base layer has a special function in relation to the sensation of the fabric on the skin interface. It may also be of importance for the resulting micro environment over the skin (Nielsen 1991).

1.5.4 Summary

The requirement of sportswear depends on the sport participants and the sport level activity. For winter sport that is normally performed at the cold conditions, clothing selection for the outdoor winter activities is a complex task. The main purpose of winter sportswear is to maintain the thermal balance of the user in cold environmental conditions. The ideal winter clothing cold conditions blocks air movement from outside but allows for water vapour to escape through the clothing if sweating occurs. Common clothing ensembles used in cold environments comprise two or more clothing layers, each layer having a different purpose.

The present study will focus on sportswear production that has good comfort properties. From sportswear functionality requirements, the physical attributes of sportswear can be determined and from these attributes, the required physical properties of fibre that can be used to produce sportswear also can be determined. This leads to fibre selection for fabric production (Table 1.4).

Table 1.4 Functionality requirements, physical attributes of sportswear and required physical properties of fibre

Functionality requirements	Sportswear physical attributes	Required physical properties of fibre
Top-level competition	Light weight	Small specific gravity
	Super high tenacity	High fibre strength
	Stretchability	Good elasticity and recovery
	Resistance to abrasion	High fibre strength
Comfort	Thermal retention	Thermal conductivity Good thermal insulator
	UV resistance	UV protective characteristic
	Sweat absorption	Good absorbency, high moisture regain
	Feels dry	Good wicking ability
	Water proofing	Easy to finish
	Fit	Good elasticity and recovery
Sensitivity and aesthetics	Softness	Small fibre diameter
	Colour variation	Easy to dye
	Opacity	Light admitting, light obstructing

1.6. Fibres in active sportswear

1.6.1 Natural fibres

Cotton

Cotton is a natural vegetable fibre composed mainly of cellulose and cultivated from a seed-pod-forming plant. Cotton is hydrophilic fibre, 8.5% moisture regain. It has poor elasticity, 3–10% elongation at breaking point. It has 74% recovery at 2% elongation; 45% at 5%. The wrinkle recovery is poor, and wrinkles in use. Cotton does not build up static electricity. The strength is good, with tenacity of 3–5 grams and increases 10% when wet (Gioello 1982).

Cotton fabric is able to absorb high levels of moisture. Unfortunately the wicking property between inner and outer surfaces of the fabrics made of cotton fibres is very poor. This makes cotton unsuitable for use against the skin during strenuous activity. When cotton becomes wet, it dries out slowly. This can lead to rapid and undesired heat loss once activity has stopped. Absorption of moisture also leads to an increase in the weight of the garment and this may impair sporting performance. However, cotton fabrics are easier to clean than those based on many synthetic fibres (Higgins & Anand 2003).

Wool

Wool is a natural animal fibre composed mainly of protein that is formed by the covering or fleece of the sheep. Wool is hydrophilic fibre, with 13% moisture regain. Wool has good elasticity, with 20–40% elongation at breaking point. The wool recovery is high, 99% recovery at 2% elongation, 65% at 20%. Wool has fair static electricity, is easily charged by friction on dry, cold days with low humidity. Wool strength is fair, losing 20% strength when wet (Gioello 1982).

Wool has good wicking ability and is a good insulator even when wet. Wool fibres have the highest moisture regain of all fibre at a given temperature and relative humidity. Hence wool is able to absorb more moisture than cotton before becoming saturated. Also wool has a natural degree of water repellence in gentle or misty rain, which adds to both thermophysiological and sensory comfort. However, wool is slow to dry and has a high wet surface coefficient of friction. As a result, there is a risk of skin abrasion when using wool (Higgins & Anand 2003).

Silk

Silk is a natural animal fibre composed mainly of protein derived from the cocoon of cultivated or uncultivated silkworms. Silk is hydrophilic fibre, with 11% moisture regain. Silk has good elasticity: 20% elongation at breaking point. Silk has poor recovery if stretched beyond 2% elongation. It has little static electricity. Silk has good strength in a dry state, but weakens and loses 15% of strength when wet (Gioello 1982).

Silk is a soft, strong natural fibre and has luxurious handle. It has good wicking ability. Silk also has high thermal conductivity and therefore feels cool to the touch. Silk is not, however, an easy fibre to care for, which is a disadvantage in sportswear that is worn frequently (Higgins & Anand 2003).

1.6.2 Regenerated cellulose fibres

Viscose rayon

Viscose rayon is a manufactured fibre composed of regenerated cellulose coagulated from a solution of cellulose xanthate. Viscose rayon has good absorbency. It is hydrophilic fibre with 13% moisture regain. It has good elasticity with 15–30% elongation at breaking point. Viscose rayon has 82% recovery at 2% elongation and 30% recovery at 20% elongation. It does not build up electric static. It has fair to good strength, good tensile strength when dry, and loses 30–40% of strength when wet (Gioello 1982).

Like cotton, viscose is 100% cellulose but it contains a higher proportion of amorphous material. This makes it more absorbent than cotton. In addition, the slightly irregular surface of viscose fibres contributes to comfort against the skin when worn. Fabrics composed of viscose fibres, however, are difficult to launder. This limits their value for exercise and sports clothing (Higgins & Anand 2003).

Lyocell

Lyocell is a 100% cellulosic fibre derived from wood-pulp produced from sustainable managed forests. The wood-pulp is dissolved in a solution of hot *N*-methyl morpholine oxide (NMMO or amine oxide). The solution is then extruded (spun) into fibres and the solvent extracted as the fibres pass through a washing process. The manufacturing process is designed to recover >99% of the solvent, helping minimise the effluent. The solvent itself is non-toxic and all the effluent produced is non-hazardous. The direct dissolution of the cellulose in an organic solvent without the formation of an intermediate compound differentiates the new generation of cellulosic fibres (Mbe 2001).

Lyocell has all the benefits of being a cellulosic fibre, in that it is fully biodegradable, it is absorbent and the handle can be changed significantly by the use of enzymes or chemical finishing techniques. It has a relatively high strength in both the wet and dry state which allows for the production of finer yarns and lighter fabrics. The high strength also facilitates its use in various mechanical and chemical finishing treatments both under conventional and extreme conditions (Mbe 2001).

Lyocell fibres have a uniform circular cross section and a smooth surface. Fabric derived from lyocell fibres have the comfort associated with other cellulosic fibres, but have the added advantage of higher tensile and tearing strength. Lyocell fibre is available commercially as Lenzing Lyocell and Tencel (Higgins & Anand 2003).

Bamboo

Regenerated bamboo fibre is obtained from the bamboo plant, which is an abundant and cheap natural resource. Bamboo is widespread in Asian countries, and the bamboo fibre used in textile applications is obtained from *Phyllostachys heterocycla pubescens*, a species known as Moso bamboo (Erdumlu & Ozipek 2008). Classified as a grass, the bamboo plant grows quickly, taking three to five years to reach harvest readiness, compared with trees that have 15-year growth cycles on average and from which lyocell, rayon and another regenerated fibres are derived (Rodie 2007). Bamboo also requires little water, is naturally regenerative and inherently pest resistant. In addition, bamboo cultivation and utilisation is one solution to the problem of global warming because the plant absorbs five times more greenhouse gases and yields 35% more oxygen than the equivalent stand of tree (Textile World 2008)

Regenerated cellulose bamboo fibre was first manufactured in 2002 by Hebei Jigao Chemical Fibre Co Ltd in China. Bamboo fibre is obtained from bamboo pulp, which is extracted from the bamboo stem and leaves by wet spinning, including a process of hydrolysis-alkalisation and multi-phase bleaching that is quite similar to that of viscose rayon fibre (Erdumlu & Ozipek 2008).

Because of the distinctive characteristics of regenerated bamboo fibre, such as its natural antibacterial and biodegradable properties, high moisture absorption capacity, softness, brightness as well as UV protective characteristics, bamboo textile products have started to edge into the textile market. With its high moisture absorption capacity (moisture regain 13%) and fast-drying behaviour due to its unique microstructure (there are several voids in the cross section of bamboo), bamboo fibre ensures comfort in various applications. Since chemical additives are not needed to obtain anti-bacterial characteristics, such products are not believed to cause skin allergies (Erdumlu & Ozipek 2008).

1.6.3. Synthetic fibres

Polyester

Polyester has poor absorbency with 0.4–0.8% moisture regain. It has good elasticity, 19–23%. It has very good recovery: 97% recovery at 2% elongation, 80% recovery at 8% elongation. Polyester has high strength, and no loss of strength when wet (Gioello 1982).

Polyester is the single most popular and common fibre used for technical textiles (Figure 1.2) (Macdonald 2006). It is also the most used in active wear and sportswear. In its unfinished state, polyester fibre is hydrophobic and has a much lower water absorption capacity than cotton. Its wicking rate, although slow compared with other synthetic fibres, is faster than that of cotton. Polyester fibre is also cheap to manufacture, easy to care for and has excellent washing and wearing properties (Higgins & Anand 2003).

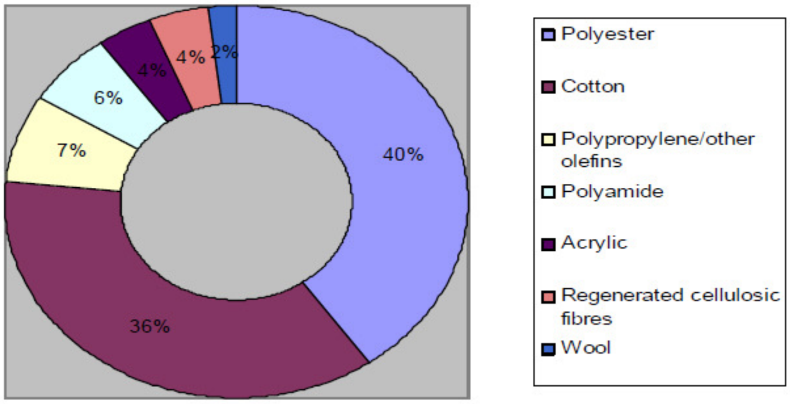


Figure 1.2 Breakdown percentage of total fibre used globally in 2004

When polyester is intended to come into contact with the skin in a garment, it is usually treated to improve its wicking ability. This is achieved by applying a hydrophilic coating to each polyester filament. The resulting hydrophobic core and hydropylic surface allow moisture to migrate along the outer surface of filament without being absorbed. Unfortunately coatings of this type do not stand up to long-term laundering. An alternative method is the modification of the surface chemistry of the polyester filament itself. This is a more expensive method but it has the advantage of being permanent. This treatment increases the hydrophilic characteristic of the fibre and therefore increases the ability of fabrics made from such fibres to release soil. Fabrics made from polyester are exceptionally durable to degradation during repeated wash/wear cycles (Higgins & Anand 2003). Polyester fabrics are prone to smell retention.

Polyamide

Polyamide has fair to poor absorbency with 4–4.5% moisture regain. It has good elasticity: 26–40% elongation at breaking point. It has 100% recovery at 8% elongation. It has high strength and exceptionally strong fibre (Gioello 1982).

Polyamide fibres such as nylon 6 and nylon 6.6 have higher moisture absorption rates and better wicking ability than polyesters but dry more slowly. They are more expensive than polyester fibres and the use tends to be limited to swimwear and cycling clothing or as reinforcing fibre in blends used for sports socks. A number of variants of polyamide fibres are available, for example, anti-microbial, high-wicking and extra soft grades (Higgins & Anand 2003).

Polypropylene

Polypropylene fibre is made by melt-spinning polypropylene. Polypropylene is obtained by the polymerisation of propylene monomer. Polypropylene fibre has the small specific gravity of 0.91 and is lightest among synthetic fibres. It possesses high tensile strength, and its material (propylene) costs are lowest. Polypropylene drawbacks are being unable to be dyed and being less heat-resistant, in addition to an insufficient resistance to light. Polypropylene fibre is relatively environmentally friendly. Polypropylene fibre hardly generates harmful substances when burnt because it consists of only carbon and hydrogen. Recycling is very easy because its molecular structure is simple. Polypropylene uses less energy to manufacture than many other synthetic.

Polypropylene fibres are used increasingly in sportswear although their percentage share of the market is still quite small. The fibres have very low moisture absorbency but excellent wicking ability. As polypropylene does not wet out, its thermal insulation is retained during and after strenuous activity. Also polypropylene is a very lightweight fibre. Fabric made from polypropylene may shrink if washed at high temperature. This fibre is also relatively more difficult to finish (Higgins & Anand 2003).

Acrylics

Acrylic is manufactured fibre in which the fibre-forming substance is any long-chain synthetic polymer composed of at least 85% by weight of acrylonitrile units. Acrylic is a hydrophobic fibre with 1–2% moisture regain. It has good elasticity: 25–46% elongation at breaking point. It has 92–99% recovery at 2% elongation. It has fair strength and is 20% weaker when wet (Gioello 1982).

Acrylic fibres are generally used in sportswear and active wear in the form of high pile fleece fabrics. In this application they are crimped, creating bulky fabrics with good thermal insulation. They have low water absorbency but can effectively wick liquid sweat. They are also light in weight. Their disadvantages are that they are prone to static build-up and have a tendency to pill during wear (Higgins & Anand 2003).

Elastomeric fibres

Elastomeric fibre is manufactured fibre in which the fibre-forming substance is a long-chain synthetic polymer comprised of at least 85% of segmented polyurethane. It has poor absorbency, hydrophobic fibre, 0.75–1.3% moisture regain. It has very high elasticity: 440–770% elongation at breaking point. It has 93.5–96% recovery at 5% elongation. It has poor strength but compensates with high fibre stretch. Elastomeric fibres are able to stretch over 500% without break (Gioello 1982).

Elastomeric fibres are frequently used in small quantities in garments to increase stretch and support. Swimwear may for example contain 15–40% of elastomeric fibre and knitted sportswear 3–10%. Elastomeric fibres do not affect the thermophysiological comfort of garments that contain them (Higgins & Anand 2003).

1.6.4. Specialised synthetic fibres

Synthetic fibre can be modified during manufacture to improve its thermophysiological and sensory properties. A number of different techniques are available for producing such fibres, including the following:

- Block copolymers can be added to the base polymer before extrusion.
- Fibres can be extruded with different cross sections.
- Fibres can be coated after treatment (Higgins & Anand 2003).

One of the most common modifications made in order to provide improved comfort is the use of superfine fibres or microfibres with the filaments having a linear density well below 1 decitex. The use of these fibres enables very dense fabrics to be created in which the fibre surface is significantly increased and the space between the fibre is reduced. This leads to the increase of capillary action for better thermal regulation (Higgins & Anand 2003).

Modified polyester

Specialised polyester fibres have been developed in order to produce a more natural handle, to increase absorbency, to provide better thermal resistance and to reduce static (Higgins & Anand 2003).

Another technique employed is the introduction of voids into the core of the fibre. These help to improve wicking and thermal resistance. One example of such a fibre, which has been designed specially for sportswear, is Welkey, produced by Teijin Ltd in Japan. The fibre has a hollow core and a proliferation of smaller holes throughout the body of the fibre. These help to increase capillary action and the wicking of sweat away from the skin. The increased number of air spaces inside the fibres also increases its thermal resistance (Higgins & Anand 2003).

DuPont offers a modified polyester fibre called CoolMax. This is a four-channel fibre with a cross-section that resembles a double scallop. CoolMax has been developed specifically for sportswear. It offers improved wicking capability and moisture vapour permeability. DuPont claims that CoolMax dries significantly more quickly than many other fabrics used in sportswear (Higgins & Anand 2003).

DuPont has also developed Thermolite for use under cold weather conditions. Thermolite fibres are offered in several variants. One of these is Thermolite Base, which is particularly suitable for use next to the skin (Higgins & Anand 2003). Novel properties of Thermolite is a lightweight, hollow fibre offering more warmth and better moisture control than any other fibre of the same thickness.

Polyester microfibres are now widely used in sportswear. They are used in both underwear and outerwear. If treated with a fluorocarbon finish, fabrics made from polyester microfibres have a high resistance to water penetration while still remaining permeable to moisture vapour. Fabrics made from polyester microfibres also combine improved handle with strength and durability (Higgins & Anand 2003).

Modified polyamides

Specialised polyamide fibres include Hydrofil, produced by Honeywell. Hydrofilia is a polyamide block copolymer containing 85% nylon 6 and 15% polyethylene oxide diamine. This modification provides significantly improved water absorbency, up to the levels associated with celullosic fibres (Higgins & Anand 2003).

Polyamide microfibres such as Tactel Micro, Microfine, Supplex and Microfibre, all from DuPont, are used in fabric to produce superior wind protection, a soft feel and good moisture vapour transmission (Higgins & Anand 2003).

1.6.5. Fibre blends

Two or more fibres may be blended into a single yarn to improve the thermophysiology and other properties of the individual components. Knitted fabric made from polyester/wool blends or polypropylene/wool blends, for example, can improve wicking and insulation properties of single fibre in single layer fabrics (Higgins & Anand 2003).

One example is the DriRelease yarn made by Optimer, Inc. This is a fibre blend comprising 85–90% of a fibre of low moisture absorption such as polyester and 10–15% of a hydrophilic staple fibre such as cotton. The resultant fabrics have soft handle and good wicking properties but low absorbency. Furthermore, the effect is permanent unlike some of the chemical finishes that are applied to polyester in order to improve wicking. DriRelease fabrics dry substantially more quickly than cotton. However, they dry more slowly than fabric produced using DuPont's CoolMax fibres. Another example of a blended fibre is Damart. This is made from blends of 85% polyvinyl choride (PVC) and 15% acrylic. Fabrics made from Damart are used in a wide range of thermal apparel (Higgins & Anand 2003).

1.6.6. Summary

Natural, regenerated and synthetic fibres are used in sportswear. Each of the fibres has different properties that are useful in sportswear. Blended fibre is used to obtain specific properties that are not available in a single fibre. The synthetic fibres are also being modified to attain different properties from the initial fibres.

In the present study, the fibres that will be used for base layer sportswear are wool as it has good wicking ability, good elasticity and good recovery; bamboo as it has good moisture absorbency; and new fibre with natural anti-microbial and polyester as it has good strength, good elasticity, good recovery, is cheap and popular in sportswear (Table1.5).

Table 1.5 Fibres and their properties

Fibres	Absorbency	Elasticity	Recovery	Strength	Wicking ability	Comments
Cotton	good, hydrophilic, 8.5%	poor, 3–10%	74%	good , 20–43 cN/tex	very poor	slow to dry
Wool	good, hydrophilic, 13%	good, 20–40%	high, 99%	fair, loses 20% strength when wet	good	slow to dry
Silk	good, hydrophilic, 11%	good, 20%	poor	good strength in dry state,	good	difficult to care in use
Viscose Rayon	hydrophilic, 13%	good, 15–30%	82%	fair to good, 18–26 cN/tex	poor	difficult to launder
Lyocell	good, hydrophilic, 12 %	12–16%		high, 37–45 cN/tex	poor	
Bamboo	hydrophilic, 13%	14–24%		22–25 cN/tex	poor	new fibre, natural antibacterial, biodegradable
Polyester	poor, hydrophobic, 0.4–0.8%	good, 19–23%	good, 97%	high	faster than cotton	most popular. cheap, easy to care for
Polyamide	fair to poor, 4–4.5%	good, 26–40%	good, 100%	very high strong fibre	better than polyester	more expensive than polyester fibres
Poly-propylene	very poor hydrophobic, <0.1%	good, poor than polyester	good, poor than polyester	high	excellent	lightest among synthetic fibres, unable to be dyed
Acrylics	hydrophobic, 1–2%	Good 25–46%	good, 92–99%	fair strength, 20% weaker when wet	good	have a tendency to pill during wear

1.7. Fabric

Fabric is a manufactured assembly of fibres and/or yarn that has substantial surface area in relation to its thickness and sufficient cohesion to give the assembly useful mechanical strength (Denton & Daniels 2002).

Based on the nature of the yarn or fibre arrangements, fabrics are classified as woven, knitted, twisted and knotted, non-woven or compound fabric. Among them, woven fabric and knitted fabric are the major materials for apparel use (Dai, Choi & Li 2006).

1.7.1. Woven fabrics

Woven fabrics are structures produced by interlacing two sets of threads: the warp which runs in a lengthways direction and the weft which runs in a widthways direction. There are three basic weaves used to produce woven fabrics: plain weave, twill weave and satin weave. Within the structure of these basic weaves are variations. Other weaves are variations and/or combinations of the basic weaves and are classified as complex or novelty weaves. By their very nature, woven fabrics are rigid or semi-rigid in the vertical and horizontal directions with only slightly more flexibility in the bias direction (Gioello 1982).

1.7.2. Knitted fabrics

Knitted fabric is structure that is formed by the intermeshing of loop yarn (Denton & Daniels 2002). There are two types of knitted fabric structure: weft knitted and warp knitted. Weft knitted fabrics is produced by a system of interlocking loops in the weft direction. The loops are in horizontal courses with each course built on top of the other and all the stitches in the course are made by one yarn. Warp knitted fabrics are produced by a system of interlocking loops in the warp direction. Fabric is produced by several parallel yarns that form one stitch for each yarn in each course. Each stitch in a course is made of different yarns (Gioello 1982).

Knitted fabric is the most common fabric structure for the base layer, as it possesses high stretch and recovery, providing greater freedom of movement, shape retention and tailored fit. Knitted fabrics also have relatively uneven surfaces, which make them feel more comfortable than smooth-surfaced woven fabrics of similar fibre compositions.

This effect results from the fact that fabric that has uneven surfaces has less direct contact with the skin (Higgins & Anand, 2003).

Knitted fabric can be structured as multi-layer knitted fabric. Multi-layered fabrics, produced by either warp or weft knitting, have been developed for use in sportswear and active wear. It is possible to knit a simple two-layer construction, which facilitates relatively fast removal of sweat from the skin and in which evaporation remains unhindered by multiple layers of fabric. Such a fabric might have a structure in which the inner layer is produced from a textured synthetic filament yarn which is hydrophobic and has good capillary action while the outer layer is made hydrophilic yarn that absorbs the wicked moisture and then allows it to evaporate (Higgins & Anand 2003).

Regarding different water absorbency of used fibre materials, Long (1999) divided two-layered knitted fabrics into the following four kinds:

- As shown in Figure 1.3(a), water has difficulty being absorbed by the fabric, and so sweat on the skin will diffuse mainly as water vapour through the pores within the fabric and evaporate slowly, which causes the wearer thermal and wetness discomfort.
- As shown in Figure 1.3(b), although sweat is absorbed by the inner layer nearest to the body, it cannot be transferred to the outer layer due to hydrophobicity of the fibres. After the water fills the pores in the inner layer, static air cannot be kept in the pores, so that thermal insulation capacity of the fabric comes down and the fabric feels wet and cool.
- As shown in Figure 1.3(c), sweat absorbed by the inner layer is transferred first to the outer layer, and then evaporates from the outer wet area into the environment. Under the same climate conditions, the rate of evaporation is in direct proportion to the area. As much water remains in the inner layer and the outer wet area is smaller, the rate of evaporation will be lower. In addition, the fabric feels wet and cool.
- As shown in Figure 1.3(d), sweat is hardly absorbed directly by the inner layer, but it can be transferred to the outer layer with the aid of the wicking action of capillary among fibres of the inner layer. The outer layer has good water adsorb ability and produces a larger wet area that can promote quick water evaporation while the inner

layer only plays a conduction role and keeps dry, so that wearing comfort is achieved.

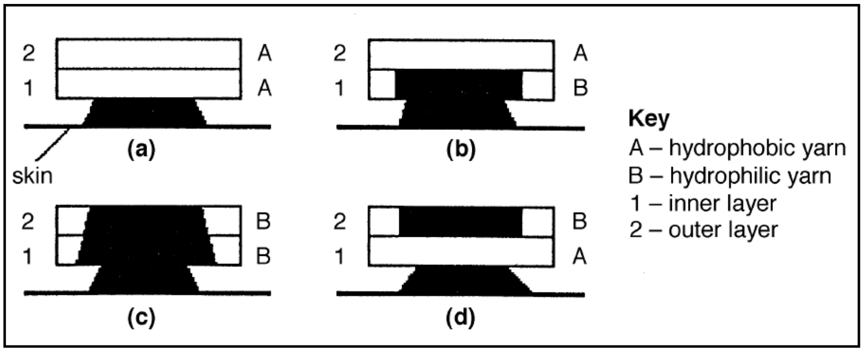


Figure 1.3 Moisture transfer model (Long 1999)

Research into the design of knitted fabric showed that the double layer fabrics are an ideal structure. For the doubled layer fabric, it is recommended that the inner layer, which touches the skin, is made from synthetic materials that have good moisture transfer properties such as polyester, acrylic, nylon or polypropylene. For the outer layer, materials that have good moisture absorption properties such as cotton, wool, viscose or their blends are recommended. The perspiration built up on the surface of the skin will be transferred to the outer layer of the fabric by way of the inner surface and consequently it will be absorbed by the outer surface. When absorptive material is used as inner layer, skin will have continuous contact with a wet layer and this feeling of feeling will irritate the wearer (Ceken 2004).

Higgins and Anand (2003) gave examples of two-layer knitted fabrics:

- Dryline®, produced by Milliken, has a polyester inner layer and a polyamide outer layer. It is commonly used to line waterproof and breathable outerwear.
- In Tactel® and Aquator®, from Dupont, the inner layer is made from normal Tactel fibre (Polyamide) while the outer layer is made from a fine filament variety. The difference in properties between the two layers draws moisture away from the skin.
- DriClime®, by Marmot, is a bi-component tricot made from two 100% polyester yarns. The outer layer comprises thin staple fibre yarn with increased capillary action which helps to pull moisture through fabric.

- Other two-layer structures designed at Bolton Institute for sportswear make use of specific application yarn types on different feeds around a circular interlock machine. One is made in the form of a single pique construction while the second fabric has a pin-tuck construction. Both make use of cotton and polyester yarns.
- One interesting example of sportswear designed for a specific application is the development of Sportwool™ materials. These have been used successfully in a number of sports and sports clothing applications, including football shirts for Manchester United Football Club. The fabric used in the Manchester United football shirt is a two-layered double jersey fabric. The inner layer, worn next to skin, is made from extra fine Merino wool fibres (less than 20 micron). The wool fibre is comfortable, has a good water vapour permeability and transfers heat and moisture from skin to the outer surface which is made from 100% polyester filament yarn. Heat is able to escape and moisture is allowed to evaporate, assisted by wind and body movement.
- A more complex 3x1 weft-knitted fleece fabric has been designed at Bolton Institute in UK. It comprises an absorption and wicking fleece layer next to the skin made from staple fibre polypropylene yarn, a middle wicking and spreading layer made from a CoolMax polyester yarn and an outer layer made from cotton or other cellulose or hydrophilic fibre.

1.7.3. Summary

Knitted fabric is the most suitable fabric structure for next-to-skin sportswear, as it possesses high stretch and recovery, providing greater freedom of movement, shape retention and tailored fit. Knitted fabrics also have relatively uneven surfaces, which make them feel more comfortable than smooth-surfaced woven fabrics of similar fibre compositions and have less direct contact with the skin. Multi-layer knitted fabrics made of different fibres with different water absorption will create base layer fabrics that have good moisture transfer properties and keep the skin dry.

1.8. Garment

1.8.1. Layering and assembling

Garment assemblies are usually composed of several items that are worn as layers one over another. Individual garments may be constructed from more than one layer of material. Additionally, some materials consist of two or more layers held together in some way, constructed as a double layer during the material fabrication operation. The effects that multiple layers of materials and garments have on the properties of garments and on human performance are complex. Several aspects need to be considered, including effects on: (1) maintenance of human thermoneutrality, (2) body movement, and (3) protective performance of garments. (Laing & Sleivert 2002).

The weight of garment layering and assembling also has to be considered. Excess weight of clothing has been shown to be detrimental to performance and results in increased energy expenditure for a given work rate (Laing & Sleivert 2002).

The whole layers need to be considered in producing sportswear; each layer of textile must be compatible with others. Only with all factors working together can perfect performance be achieved. Each sport has its own particular needs (Ishtiaque 2001).

Nielsen (1991), Higgins and Anand (2003) and Patnaik et al. (2006) agreed that a clothing ensemble should be considered as a multi-layer clothing system comprising an inner layer (underwear), middle layer and outer shell layer. A three-layer system is preferable for optimum comfort in sportswear. The use of several layers of clothing is an efficient system for achieving good thermal regulation and moisture management. Some of the layers may be superfluous in a warm environment, but when all are present in cooler environments each layer serves a specific main purpose (Nielsen 1991).

The base layer is usually underwear such as a vest and leggings. This layer provides the primary moisture management by wicking moisture vapour away from the skin. The base layer garment should have close fit in order to act efficiently (Higgins and Anand 2003). The base layer is important for the direct cooling of the skin as well as carrying out a hygiene function (Nielsen, 1991). The inner layer that is designed to be worn next to the skin should have the following characteristics: good thermal conductivity, good moisture management and good tactile properties (Cao et al. 2006).

The middle layer mainly serves insulating functions (Nielsen 1991). The middle layer has to be of light weight and be able to transfer moisture to the next layer and provide good thermal insulation. This layer does not necessarily have to be tight fitting, as the layer of air beneath the garment can help to increase thermal insulation (Higgins & Anand 2003).

The outer layer should be windproof and be able to transfer the moisture to the environment. Depending on the application, it may also be waterproof (Higgins & Anand 2003). The outer layer serves as protection of the human body from the environmental factors or as a practical layer for the storage of tools (Nielsen 1991).

1.8.2. Style

Sportswear is a highly innovative field investing heavily in research and development, pioneering new technologies and concepts, and furthering performance and comfort. Sportswear design changes at a faster speed than other clothing categories. Sportswear designs are influenced by textile innovation, where from a technical point of view, new textiles allow enhanced performance regarding protection as well as athletic achievement and at an aesthetic stage (Bramel 2005).

The introduction of new fibres that enhance performance underwear is the main source of innovation in first-layer garments but they have not essentially influenced their design. Styles most often change around the basic T-shirt shape. The rise of all-in-one suits in competition swimming and running, now spreading to winter sports and high-level athletics, is introducing new shapes and volumes to first-layer garments in general (Bramel 2005).

Outside influences become the source of new styling directions in active sportswear. The fading frontiers between sport and city wear and the large number of luxury and high-end ready-to-wear brands developing sports-oriented ranges are a growing source of new design orientations for performance clothing. The evolution of garment design is influenced both by performance sportswear and ready-to-wear (Bramel 2005).

When ready-to-wear manufacturers develop sports garments, their design approach takes into account an equal measure of style and performance. As first-layer garments have shown, closer-fitting clothing often performs better. Fit thus gains importance in general. Fit and silhouette are often the defining elements of a high-end garment: fabrics and cuts are carefully chosen to enhance the silhouette. In sportswear, however, fabrics and cuts are selected for their performance features. Function is the principal goal of sports garment design. The end silhouette and the balance of proportions are considered less important. This is where high fashion labels gain their aesthetic edge (Bramel 2005).

Garment design styling (sometimes incorrectly referred to as fit) can affect human performance by influencing aerodynamics (aerodynamics being of critical importance to performance when velocities of movement exceed about 5m/s). This has been demonstrated in a number of sports including running, cycling, downhill and cross-country skiing and speed skating, and in the worst case estimates, drag may be reduced by up to 10% through the appropriate use of clothing. Similarly, wetsuits can have a marked effect on changing buoyancy and drag of the swimming body and because of performance benefits, their use is now closely regulated in events such as triathlon (Laing & Sleivert 2002).

1.8.3. Fit

Clothing fit has long been regarded as the single most important element to customers in clothing appearance. The principles of fit are, however, not clearly understood, and the definitions of fit vary from time to time, and depend on the fashion culture, industrial norm and individual perception of fit (Yu 2004).

According to Yu (2004), there are several factors influencing clothing fit:

a. Social message of the ideal body: the satisfaction of fit is affected by a societal message concerning the ideal body. The balance of body proportion and symmetry of body segments are all important.

b. Fashion figure in the industry: the fashion industry's portrayal of an idealised figure, for example, taller and slimmer in proper proportion and balance, is always presented through fashion illustrations, photography and catwalk models.

c. Body cathexis: this is defined as positive and negative feelings toward one's body. Various scales evaluating body cathexis have been used to examine attitudes toward the body.

d. Physical dimension fit of clothing: this is a key element of fit evaluation in numeric form. The clothing size can also significantly affect customer satisfaction.

Sportswear must protect the human body from the environment and, at the same time, support mobile functionality and comfort when worn by the wearer. Measurement of clothing pressure is one method for evaluating activity (mobility) of the cloth under design. It is thus also an important factor for clothing comfort, which is closely related to cloth mobility. Clothing pressure is the pressure applied on the body when wearing a cloth. It varies according to the design, pose of the wearer during the activity, garment material, wearer's body shape and so on. The design of sportswear (for cycling, skating, or swimming) and foundations for body shape correction can sometimes benefit from appropriate clothing pressure (Seo et al. 2007).

Garments worn in sporting activities have different properties and performances attributes according to the activity carried out. For example, in sports like football and basketball where there is intense multi-directional activity, loose-fitting and comfortable clothes are required; in activities such as swimming and cycling where speedy body movements are important, skin-tight or well-fitting clothes are preferred (Ceken 2004).

1.8.4. Construction

The development of advanced second-skin textiles has led to renewed interest in garment construction. Seamless, stitchless and three-dimensional modelling are some of the latest developments in sportswear garment constructions (Bramel 2005).

Sportswear companies first developed seamless styles for fitness and first-layer garments. Seamless knitting requires that engineers and designers work together to develop and fine-tune sizing, fibre choice, composition, and stitching. Leave out one parameter and the garment will not perform as expected (Bramel 2005).

Three-dimensional modelling is a new measuring technique that indicates the precise needs of an athlete in action and helps to associate seamless garments with genuine performance breakthroughs. Three-dimensional modelling, or bodymetrics, implies taking a broader look at how garments fit and why it is important to combine several types of fibres and textiles: laser cuts, bonded seams, multiple fibre composition targeting specific functions and so on. The design of a seamless leotard entails placing compression features, ventilation panels and various trimming or ornamentation at strategically engineered locations to achieve a high-performance sports garment. This implies graduating knit construction to the body and requires in-depth research and development to be effective (Bramel 2005).

The three-dimensional approach to design is ironically relatively new to sportswear. The main difference between city and sports garments has traditionally been that ready-to-wear takes a three-dimensional approach to design (garments are conceived on manikins) whereas sportswear companies conventionally design two-dimensional or flat garments. For example, the collar of a sports jacket lies flat, while it is impossible to design a flat lapel on a tailored city jacket. For an all-in-one swimsuit, designers must work from a three-dimensional model. This physiological approach to design is fundamental to the development of next-generation sportswear (Bramel 2005).

The emergence of stitchless garment construction techniques is introducing new design features to outerwear. The switch to garments that do away with stitching altogether and are entirely heat-sealed is the next step in advanced garment design. The latest generation of high-tech garments is now totally devoid of sewn seams. Bonding is replacing sewing and making close-fitting styles even more streamlined. Laser-cut edges, watertight zippers and trimming can now be compressed into a single indivisible bonded layer. Hems that no longer need to be folded reduce added thicknesses at corners and hems. Designers are combining these new manufacturing techniques with moulded and elasticised panels to create stitchless second skins. Leading wintersport specialists such as Arc'teryx, and surfwear brands Burton Snowboards, RipCurl and O'Neill are opening the way (Bramel 2005).

1.8.5. Summary

Garment assemblies are usually composed of several items that are worn as layers one over another, each layer of textile must be compatible with others and each layer serves a specific main purpose. Sportswear designs are influenced by textiles innovation. From a technical point of view, new textiles allow enhanced performance regarding protection, athletic achievement and aesthetics. Garment design and styling can affect human performance in sport activities. Clothing fit is regarded as the single most important element to customers in clothing appearance but fit in sportswear is not only for appearance but also to support mobile functionality and comfort when worn by the wearer. Seamless, stitchless and three-dimensional modelling are developments in sportswear garment construction.

1.9. Special finishes related to comfort

1.9.1. Moisture management finishes

Moisture management treatment promotes rapid wicking and evaporation and provides high added value to sportswear and casual wear, significantly enhancing the perceived comfort level of the wearer (Holme 2007). Several moisture management finishes have been used to increase moisture absorbency; the fabric is durable to repeated home laundering and improves wetting and wicking action. For example, Resil HJHP is used particularly for increasing moisture absorbency of polyester fabrics and when combined with resil Nanocelle G6, can improve the wicking properties of fabrics of all types (Manickam 2006).

Moisture management finishes are used not only to impart hydrophilicity but also to enhance handle of fabric. A novel moisture management agent, Ultraphil HCT, is based on a silicone microemulsion. Ultraphil HCT imparts hydrophilicity and a very soft handle to cotton, while the quaternary chemical nature of the structure results in very high durability to washing (Holme 2007). A new hydrophilic finish, Sandoperm RPU Liquid is a new thermo-reactive polyurethane for dry fast, very full and extremely soft handle on cellulosic and polyamide fibres. Applied with silicone softeners, Sandoperm RPU Liquid produces a hydrophilic finish, improving the elasticity/shape recovery of knitted goods. The Nano-Dry finish from Nano-Tex LLC is a durable, hydrophilic finish for nylon and polyester. In the latter fibre polyethylene glycol and amino silicone in nano-form are claimed to be applied to sportswear and underwear requiring perspiration absorbency (Holme 2007).

1.9.2. Anti-microbial finishes

As some lifestyles have become more active, sportswear, activewear and casualwear may become more easily contaminated by perspiration leading to bacterial growth and body odours. A number of anti-microbial treatments are now on the market that can kill bacteria and enable garments to smell fresh for longer. An alternative approach is that of b-cyclodextrin which, with a suitable reactive group, could be covalently bound to cotton. It has been shown that body odours become trapped within the hydrophobic internal surfaces of this torus-shaped molecule, eliminating the build-up of body odours. This area is set for growth as the environment purportedly warms up through global warming and if garments are required to be washed less frequently then this decreases environmental pollution (Holme 2007).

To protect against disease-causing bacteria and pathogenic fungi, fibres and fabrics need treatment with anti-microbial agents, because there are no chemically unaltered natural or synthetic fibres that are inherently resistant to these micro-organisms. There are, however, differences in the persistence and retention of these micro-organisms in various types of fibres. Synthetic fibres retain more odour-causing bacteria than do natural fibres. However, natural fibres such as cellulosic fibres are much more susceptible to attack by mildew and rot-producing fungi and algae than are synthetic fibres. Synthetic fibres, however, are not free from these attacks as evidenced by the reports of mildew growth on nylon, poly-vinyl alcohol, and polyurethane-coated fabrics (Bajaj 2002).

For apparel fabrics it is important that the anti-microbial finish leaves the garment comfortable to wear. A very important consideration for anti-microbial finishes applied to apparel fabrics is that such treated fabrics and garments are safe to handle and use. Anti-microbial finishes for apparel should be non-toxic, non-irritating and where handled regularly, the finish must also be non-sensitising (Holme 2007).

1.9.3. Microencapsulated finishes

Microencapsulation is a technique that allows liquid or solid agents such as drugs, proteins, hormones, fertilisers, pesticides, herbicides, dyes, cosmetics and fragrances to be encapsulated by an appropriate barrier wall. Liquid or solid agents that are encapsulated are called core material. Therefore, the core material is isolated from reactive, corrosive and hostile environments and also their releasing behaviour is controlled. The barrier wall can be built using monomers to form polymers or polymers that are polymerised elsewhere, such as liposome, β-cyclodextrin or micro-organism cells. The barrier wall can be classified into two major groups: the first group is a rigid and solid wall and the second group is non-rigid and at liquid phase such as liposome (Gorkhan & Sarisiik 2004).

1.9.3.1. Phase-change materials

Microencapsulation technology was utilised in the early 1980s by the US National Aeronautics and Space Administration (NASA) with the aim of managing the thermal barrier properties of garments, in particular for use in space suits. They encapsulated phase-change materials (PCMs), for example, nonadecane, with the hope of reducing the impact of extreme variations in temperature encountered by astronauts during their missions in space. Ultimately the technology was not taken up within the space program. However, the potential was recognised and after further development the work was licensed by the inventor, the Triangle Research and Development Co, to Outlast Technologies, in Boulder, Colorado. Outlast has exploited the technology in textile fibres and fabric coatings and PCM capsules are now applied to all manner of materials particularly outdoor wear (parkas, vests, thermals, snowsuits and trousers) and in the house in blankets, doonah, mattresses and pillowcases. As well as being designed to combat cold, textiles containing PCMs also help to combat overheating, so overall the effect can be described as thermoregulation (Nelson 2002).

1.9.3.2. Fragrance finishes

The addition of fragrances to textiles has been carried out for many years in the form of fabric conditioners in the wash and during tumble-drying; all are designed to lend a fresh aroma to the textile. However, no matter the quality of the technology used to impart the fragrance, the effect is relatively short-lived. Numerous attempts have been made at adding fragrances directly to fibre and fabrics but all fail to survive one or two wash cycles. Only through microencapsulation are fragrances able to remain on a garment during a significant part of its lifetime. Microencapsulation of essential oil flavours has led to many novelty applications, particularly for children’s garments, but it has also allowed exposure at home and in the work place to the beneficial effects of aromatherapy (Nelson 2002).

Aromatherapy utilises the controlled release of an aroma or fragrance to promote feelings of comfort and wellbeing among consumers. Among the many applications for aromatherapy, a number of fragrances such as camomile, lavender, lemon, peppermint, jasmine and rose can provide a broad spectrum of advantages when applied to performance apparel. L J Specialities (Holmewood, UK) has pointed out that an uplifting/head-clearing fragrance-like microencapsulated peppermint could be used for active sportswear, while lavender on bedding has been shown in customer wearer trials to relax customers and encourage sleep. Peppermint is also claimed to have muscle-easing properties, another advantage for active sportswear end uses. Microencapsulated fragrances that encourage clear thinking/confidence building could be applied to suiting for formal wear (Holme 2007).

1.9.3.3. Polychromic and thermochromic microcapsules

Colour-changing technology is now being seen in textiles, such as product labelling and medical and security applications. In addition, there is continued interest in novelty textiles for purposes such as swimwear and T-shirts. There are two major types of colour-changing systems: thermochromatic, which alters colour in response to temperature, and photochromatic, which alters colour in response to UV light. Both forms of colour-change material are produced in an encapsulated form as microencapsulation helps to protect these sensitive chemicals from the external environment. Today, manufacturers are able to make dyes that change colour at specific temperatures for a given application; for example, colour changes can be initiated from the heat generated in response to human contact (Nelson 2002).

1.9.4 Summary

Finishes or treatments are utilised in textiles to improve their properties or to provide new properties that are not available in their original state. Finishes that are used in sportswear are moisture management, anti-microbial and microencapsulated finishes (phase-change materials, fragrance and polychromic and thermochromic materials).

CHAPTER 2

PURPOSE OF THE STUDY

This chapter discusses the objective of the present study, research questions to be addressed, research hypothesis and limitation of the study.

2.1 Objective of the study

The objective of the present study is to produce winter active sportswear fabrics using natural and synthetic fibres that will provide good comfort properties. In order to establish the optimum usage of natural fibres in sportswear, natural and synthetic fibres will be blended in different ratios. The possible blending will be carried out in intimate fibres blending, yarns blending and construction blending. The yarns will be knitted into fabrics. The thermophysiological and skin sensorial comfort properties of these fabrics will then be measured.

The two specific objectives of the present study are:

1. To measure the thermophysiological and sensorial comfort properties of knitted fabrics made from natural and synthetic blended yarns intended for winter active sportswear.
2. To gain insight into the relationship between thermophysiological and sensorial comfort and fibre composition, construction of knitted fabric designed for winter active sportswear.

2.2 Research questions

The study will focus on the selection of natural and synthetic fibres, blend ratios, yarns specifications, fabrics construction and fabrics parameters. Study will be carried out to compare the thermophysiological and skin sensorial comfort of the resulting knitted fabrics with that of existing commercial fabrics in this field.

The research questions to be addressed are:

1. What are the required fibre and fabric properties for winter performance sportswear?
2. What is the range of synthetic and natural fibre that can be used for winter performance sportswear?

3. What range of fibre blend ratios can be used?
4. What is the range of fabric construction best suitable for performance sportswear?
5. What is the most effective method of testing and evaluating fabric performance?
6. Does the resulting fabric, yarn and fibre composition provide better performance when compared to existing commercial fabric?

2.3. Research hypothesis

Good wear comfort related to the liquid moisture is the ability of fabric to transport sweat from the human body to the environment so that the wearer will feel dry. In this case, according to background research, the fabric should be a moisture-management fabric.

Good wear comfort related to the cold environment is the ability of fabric to maintain body heat. Since there are several layers of apparel worn in cold environments, and as this research focused on the base layer, the most important apparel component is that the fabric as base layer can transport the moisture from the body to the environment. The feeling of warmth certainly has to be considered too.

Good wear comfort related to sensorial comfort is fabric not prickling or being too stiff. Fabric should have good stretch and recovery to ensure that clothing does not restrict body movement and performance.

Hypothesis

- To create moisture management fabric, two types of fibre with different reactions to water are needed. One fibre is hydrophilic and the other is hydrophobic. Hydrophobic fibre will be used next to the skin and the hydrophilic fibre will be used in outer surface of fabric near the environment or near the next layer. Liquid moisture will be transferred through the hydrophobic fibre and the hydrophilic fibre will absorb it so the skin will dry. Fibre with high surface energy is considered hydrophilic and fibre with low surface energy is considered hydrophobic.
- To get a warm feeling, wool fibre will be used. But since wool has lower surface energy, wool will act as top surface, hydrophobic fibre. Polyester or bamboo fibre is used for the bottom surface since they have higher surface energy than wool, and will act as hydrophilic fibre.

- To reduce friction, fine wool fibre will be used.

2.4. Limitations of the study

The limitations of this research include:

1. The fabrics intended for winter active sportswear in this research were limited to the base layer.
2. Testing was limited to objective testing on a laboratory scale and textiles were tested as fabric layers.
3. The intimate fibre blending was not possible to achieve exactly so was done as best as practically possible.

CHAPTER 3
RESEARCH DESIGN

This chapter discusses the methodology and methods used for the present work. The aim was to create a research design to achieve objectives and answer the research question stated in the previous chapter.

3.1. Methodology

To achieve the objectives of the study, the following methodology has been adopted (Figure 3.1)

- Conducting market research

Market research was carried out to observe the recent trend in commercial base layer winter active sportswear. The market research focused on the fibre types that are used in the base layer garments.

- Selecting garments representative of the current trend

Garments that represent the current trend in commercial base layer winter active sportswear were selected for the current study.

- Analysing the commercial sample fabrics

The analysis of commercial sample fabrics was carried out to find out their physical and structural properties. The results of this analysis can be used as a starting point for experimental fabric production.

- Selecting fibre

The fibres to be used in the experimental sample fabric production were selected. The selected fibres are polyester, wool and bamboo. Polyester was selected because it is the most common fibre used in sportswear, while wool was selected because wool fibre has grown in use in sportswear. Bamboo was selected because bamboo is a relatively new fibre that offers properties suitable for base layer sportswear. Bamboo is also labelled as a green and eco-friendly fibre.

- Selecting yarn

Polyester, wool and bamboo yarns were selected based on their yarn count. The experimental fabrics would be made of fibre blends. Since the fibre blends were not in the intimate blend form but the blend from several yarn ends from different fibre, the yarn count held an important position that would influence the blend ratio. The yarns from different fibres were selected according to the blend ratio that would be used so that the entire blend yarn count has a similar yarn count as close as possible.

- Selecting fabric construction

The selected fabric to be produced was knitted fabric. Knitted fabric is the most common fabric structure for the base layer, as it possesses high stretch and recovery, providing greater freedom of movement, shape retention and tailored fit. Knitted fabrics also have relatively uneven surfaces, which make them feel more comfortable than smooth-surfaced woven fabric of similar fibre compositions. This effect results from the fact that the fabric which has uneven surfaces has less direct contact with the skin (Higgins & Anand 2003).

- Conducting the preliminary experiment

A preliminary experiment was carried out to examine liquid moisture transfer performance of knitted fabrics made of single fibre yarns that would be used in production of the experimental sample fabrics. Liquid moisture performance is an important property for the base layer since the base layer has to transfer moisture from the skin to the next layer or the environment.

In the preliminary experiment, several fabrics were produced from single-fibre (non-blended) yarn. The fabrics were produced from the same yarn count with different cover factors. Then the fabrics were scoured and prepared for liquid moisture transfer properties test. The test was carried out to find the relationship between liquid moisture transfer performances and the cover factor.

In this preliminary experiment, only two fibres were used, wool and bamboo, because wool has the lowest fibre surface energy (hydrophobic) and bamboo has the highest fibre surface energy (hydrophilic), while polyester has fibre surface energy that is slightly higher than wool. Beside that, as bamboo is a relatively new fibre, there is not much information about its properties, hence that the preliminary experiment was needed to investigate bamboo performance.

- Producing experimental sample fabrics

Experimental sample fabrics were produced as single jersey fabrics following the knitting plan that has been developed so that the fabrics have similar cover factors and weight.

- Scouring and preparing experimental sample fabrics

Experimental sample fabrics were scoured to remove dirt and oil from the production process and were prepared for testing.

- Conducting experimental sample fabrics physical and structural tests

The physical and structural properties selected for testing were weight/m^2, thickness, stitch density (course/cm and wales/cm), porosity and optical porosity.

- Conducting commercial and experimental sample fabrics comfort properties test

The comfort properties selected for testing were liquid moisture transfer and fabric classification relevant to this property; thermal conductivity, warm/cool feeling, stiffness and number of contact points.

- Analysing test results of commercial and experimental sample fabrics comfort properties

The results were analysed whether the commercial and experimental sample fabrics have comfort properties that are suitable for base layer winter active sportswear.

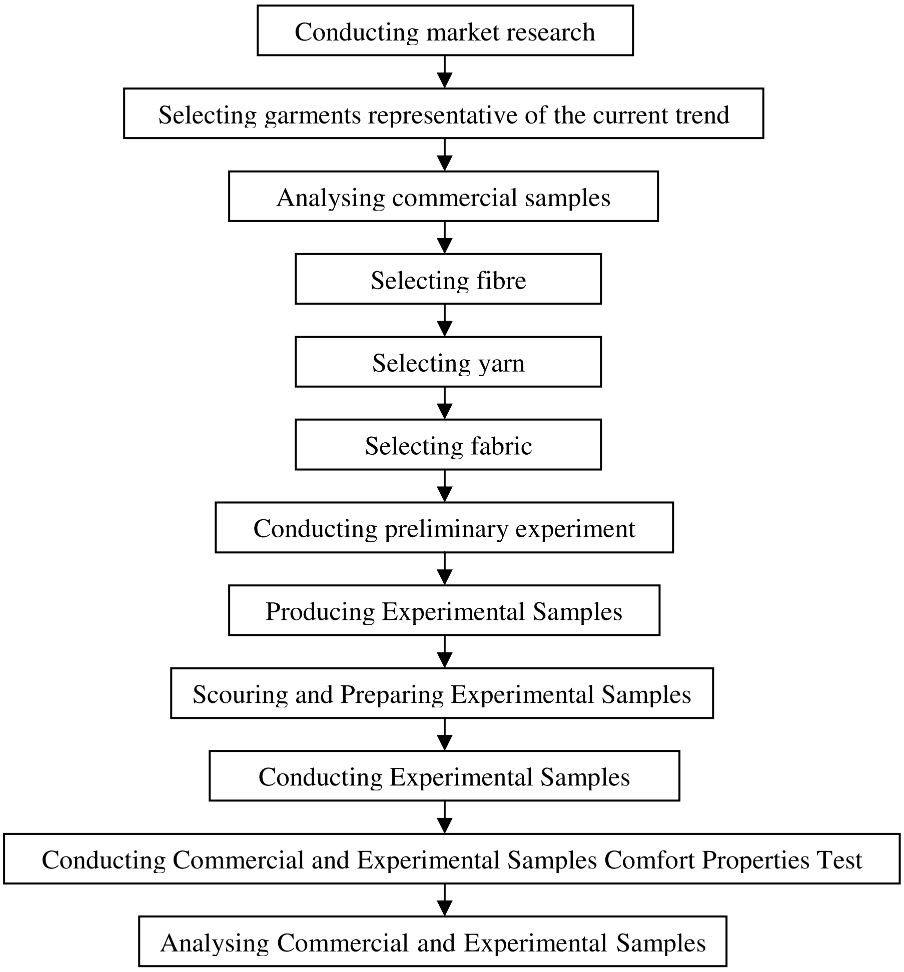


Figure 3.1.Methodology

3.2. Methods

3.2.1. Materials and equipment used

Materials of the following specifications were used in the present study.

3.2.1.1. Commercial sample fabrics

Five commercial sample fabrics were selected for this study (Table 3.1). Their selection was based on the current trend in commercial base layer winter active sportswear market.

Table.3.1 Details of commercial sample fabrics

No	Sample fabric code	Source type	Fabric construction	Fibre content
1	FGNE	Garment	Single jersey	Nylon, Elastane
2	MGW	Garment	Single jersey	Wool
3	MBW	Garment	Single jersey	Wool
4	MRWB	Fabric	Double layer, interlock	Wool, Bamboo
5	MGWP	Fabric	Double layer, interlock	Wool, Polyester

3.2.1.2. Fibres and yarns

The study selected 100% polyester, 100% wool and 100% bamboo yarns. The selection was based on their yarn count to achieve different blend ratios but at the same time to retain a yarn count similar or as close as possible. Fibre and yarn details that were used in this study are presented in table 3.2 and the blend yarn count and ratio are presented in table 3.3.

Table 3.2.Fibre and yarn details

Fibre composition, 100%	**Fibre diameter** (Micron)	**Yarn count (Tex)**	**Yarn type**
Wool	18.5	20	Worsted
Wool	20.5	27.8	Worsted
Wool	19.5	16.7	Worsted
Polyester	n/a	11.1	Continuous Filament
Bamboo	n/a	18.3	Ring spun

Table 3.3.Blended yarn counts and their ratios

Fibre	**Blend ratio**	**Yarn ends**	**Blended yarn (Tex)**
Polyester	100	4P@11.1	44.40
Wool/Polyester	43:57	1W@16.7/2P	38.90
Wool/Polyester	48:52	1W@20/2P	42.20
Wool/Polyester	71:29	1W@27.8/1P	38.90
Wool	100	2W@20	40.00
Wool/Bamboo	35:65	1W@20/2B	56.60
Wool/Bamboo	52:48	1W@20/1B	38.30
Wool/Bamboo	60:40	1W@27.8/1B	46.10
Bamboo	100	2B	36.60

The resultant (blended) yarn count was calculated by adding the yarn counts of each yarn comprising the final blend. For example, wool/polyester 43:57, one end of 16.7 Tex wool yarn and two ends of 11.1 Tex polyester yarn were added so they formed blended yarn of the resultant count of (16.7+ (2x 11.1)) = 38.9 Tex. The blend ratio was arrived at from the following calculations: for wool fibre = 16.7/38.9 x 100% = 43%, and for polyester fibre = 22.2/38.9 x 100% = 57%, so that the resultant blend ratio of wool/polyester is 43:57.

3.2.1.3. Sample manufacturing methods and equipment used

A Fibre Analysis Knitter (FAK) circular knitting machine of 3.5 inches diameter was used for manufacturing the specimens. Blending was done by knitting two or more yarn ends from different fibres into one yarn feeder and knitting with a plating technique (Figure 3.2). By changing the stitch cam on the quality wheel the rate of yarn feed to needles was controlled. Since sample fabrics were produced from different yarn counts and different numbers of yarn ends; the amount of yarn fed in one machine revolution was adjusted in order to produce fabrics with similar cover factors, and weights per square meter.

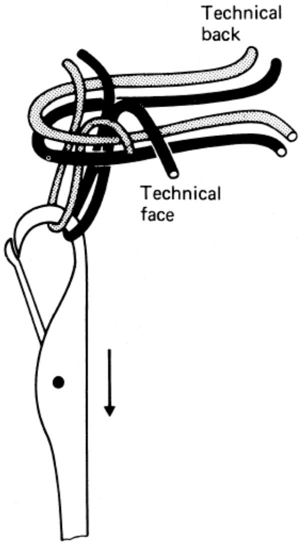


Figure 3.2.Plating Technique (Spencer 2001)

The fabrics were scoured to remove dirt and to make the yarn relax. The samples were scoured at 40ºC for 30 minutes using synthetic detergent, followed by rinsing for the same time period. After the scouring process was completed, the samples were tumble dried at 45ºC for about 60 minutes. Then the samples were ironed to make them flat.

3.2.1.4 Sample fabrics coding

Commercial and experimental sample fabrics were given a code to make the sample fabrics easier to recognise and differentiate from one another. For commercial samples, the sample coding is as follows: two first letters are the abbreviation of their brand name and the letter/s following it, is/are the abbreviation of their fibre content. For experimental samples, the sample coding is as follows: the first letter is the abbreviation of the first fibre and the number following the letter is the first fibre content percentage; the second letter is the abbreviation of the second fibre and the number following the letter is the second fibre content percentage. The samples' codes and their meaning are given in table 3.4.

Table 3.4.Sample fabric coding

No	Sample code	Meaning
	Commercial	
1	MBW	MB = brand; W = wool
2	MGW	MG = brand; W = wool
3	MRWB	MR = brand; W = wool; B = bamboo
4	MGWP	MG = brand; W = wool; P = polyester
5	FGNE	FG = brand; N = nylon; E = elastane
	Experimental	
6	P100	P100 = polyester 100%
7	W43P57	W43 = wool 43%; P57 = polyester 57%
8	W48P52	W48 = wool 48%; P52 = polyester 52%
9	W71P29	W71 = wool 71%; P29 = polyester 29%
10	W100	W100 = wool 100%
11	W35B65	W35 = wool 35%; B65 = bamboo 65%
12	W52B48	W52 = wool 52%; B48 = bamboo 48%
13	W60B40	W60 = wool 60%; B40 = bamboo 40%
14	B100	B100 = bamboo 100 %

3.2.1.5. Laboratory equipment used for data collection and analysis of results

Laboratory equipment used in this study presented in table 3.5.

Table 3.5.Equipment

No	Process	Equipment
1	Fabric Production	FIBRE ANALYSIS KNITTER (FAK) 3.5 inch circular Knitting Machine (Single Jersey)
2	Fabric Scouring	HOOVER ZODIAL Washing Machine; HOOVER APOLLO Drying Machine; PHILIPS Iron
3	Fabric Testing	
	Structural and physical	
	Mass per unit area	SARTORIUS BP100 Measuring balance
	Thickness	Thickness Tester
	Wales and courses length unit	MOTIC Microscope with mounted camera
	Optical porosity	MOTIC Microscope with mounted camera; IMAGE TOOL
	Thermophysiological comfort testing	
	Liquid moisture transport	MOISTURE MANAGEMENT TESTER
	Thermal conductivity	KAWABATA EVALUATION SYSTEM F7-THERMO LABO II
	Warm/cool feeling	KAWABATA EVALUATION SYSTEM F7-THERMO LABO II
	Sensorial comfort testing	
	Stiffness	SHIRLEY Stiffness Tester
	Number of contact point	ERNST-BENZ Laboratory padding mangle: DELL Scanner; IMAGE TOOL

3.2.2. Test methods

3.2.2.1. Determination of fabric structural and physical properties

Fabric structural and physical properties were tested since these properties would influence fabric comfort properties. In this study, fabric weight (mass per unit area), thickness, wale and course per unit length, porosity, optical porosity, loop length and cover factors are the structural and physical fabric properties that were tested.

Before each test commenced, the fabrics had to be conditioned to eliminate the influence of the atmospheric moisture content as the physical properties of fibres can be affected by their moisture content. In general, the fibres that absorb the greatest amount of moisture are those whose properties change the most. The three main types of properties that are affected are: dimensional, mechanical and electrical (Saville 2004).

During conditioning, sample fabrics were brought to equilibrium with an atmosphere of a specified temperature and relative humidity. Moisture equilibrium is the condition attained when two successive weighing, at an interval of 15 minutes of the material or sample freely exposed to the atmosphere in an air conditioned laboratory, show a change mass of no more than 0.1% of the last mass recorded (AS 2001.1–1995).

Fabric samples were preconditioned to ensure subsequent conditioning in the standard atmosphere commenced from a dry state. After that fabric samples were exposed in as open a manner as possible to the standard atmosphere in the controlled laboratory until moisture equilibrium had been attained (AS 2001.1–1995).

3.2.2.1.1. Mass per unit area

Five specimens of 100 mm x 100 mm from the fabrics sample were conditioned and tested in a standard atmosphere. Each of specimens was weighed by measuring balance. The mass per unit area was calculated as the mean mass per unit area of the five specimens (AS 2001.2.13–1987).

Mass per unit area was calculated using the following formula:

$$M_{ua} = \frac{m}{a} \tag{3.1}$$

Where

M_{ua} = the mass per unit area of the fabric after conditioning in the standard atmosphere of testing, g/m^2;

a = the area of the specimen, m^2

m = the mass of the specimen, g

3.2.2.1.2. Thickness

The thickness of a fabric is one of its basic properties giving information on its warmth, heaviness or stiffness in use (Saville 2004). The thickness of fabric samples was measured as the distance between the reference plate and parallel presser foot (AS 2001.2.15–1989).

Test specimens were conditioned and tested in the standard atmosphere. After that the thickness tester was prepared. After the presser foot was lifted, the fabric sample was positioned on the thickness tester reference plate, and then the presser foot was gently lowered to apply pressure to the fabric sample. The indicator reading was recorded (AS 2001.2.15–1989).

3.2.2.1.3. Wales and courses per unit length (stitch density)

The number of wales and courses in an accurately measured length were counted along a line at right angles to the course or wale being considered (AS 2001.2.6–2001). After sample fabrics were conditioned, each was laid on a horizontal space and the minimum tension required was supplied to keep the fabric flat. The number of wales and courses was counted using a low-power microscope. Determination was made at the point not closer than one tenth of the width of fabric to the edge of the fabric being tested. Five counts in each direction were made; positions evenly spaced along or across the fabric were selected; selvedge was avoided and no count in either direction included the same wales and courses was performed (AS 2001.2.6–2001).

3.2.2.1.4. Porosity

Porosity was determined by measuring the total volume of a fabric and calculating the total volume of fibre in the sample. The difference between these two values is considered as air space and when calculated as a percentage of the total volume, it gives the porosity (Skinkle 1940).

Porosity was calculated based on the following formula: (Skinkle 1940)

$$P = \frac{100(AT - \frac{W}{D})}{AT} \qquad (3.2)$$

Where;

P = porosity, %

A = area of the sample, m^2

W = weight of the sample, g

T = thickness of the sample, cm

D = density of fiber, g/cm^3

3.2.2.1.5. Optical porosity

Optical porosity is expressed as transmittance (%) of visible light through fabric (Hatch et al. 1990). A microscopic image of the sample was presented by Motic stereo microscope. The microscope was coupled with a digital camera. Motic Image software was used to capture and process the image. Image Tool software was used to determine optical porosity of obtained images.

Principle

Optical porosity is represented by voids between yarns in the fabric. The light from microscope is captured through the voids and is converted into white pixels while the yarn that blocked the light is converted into black pixels.

Microscopic image capture procedure

- Motic Image Plus 2.0 software was launched.
- The specimen underwent the microscope stage.
- The bottom lamp was turned on to provide light.
- The image was displayed on the screen.
- The microscope was set to obtain a proper image.
- The image was captured.
- The image file was saved.
- Three images from three specimens were captured.

Optical porosity determination procedure

- Image Tool software was launched.
- The image file was opened.
- The image was converted into a grey scale image.
- The grey scale image was thresholded by clicking the threshold button in the software window.
- The black and white pixels in the image were counted.

Optical porosity was determined based on the formula:

$$Optical porosity = \frac{whitepixel}{whitepixel + blackpixel} x100\% \qquad (3.3)$$

3.2.2.1.6. Loop length

To determine loop length, results from course and wales per unit length were used. The yarn diameter was calculated based on the yarn count used.

Yarn diameter was calculated based on the formula (Karaguzel 2004):

$$d = 2\sqrt{\frac{4T}{\pi\rho 10^5}} \tag{3.4}$$

Where;

d = diameter, cm

T = yarn density, Tex

ρ = fiber density, g/cm^3

Loop length was determined based on the formula (Peirce 1947):

$$l = \frac{2}{c} + \frac{1}{w} + 5.94d \tag{3.5}$$

Where;

l = length of yarn in one loop, cm

c = number of courses per cm

w = number of wales per cm

d = diameter of the yarn, cm

3.2.2.1.7 Cover factor

Cover factor is a factor that indicates the relative tightness or looseness of the plain weft knitted structure and is used in a similar manner to that of the cover factor in the weaving industry. The cover factor is defined as the ratio of the area covered by the yarn in one loop to the area occupied by that loop (Spencer 2001).

In the present study, the cover factor was determined through the yarn count that was used to produce the fabric and calculated loop length (3.2.2.1.6).

The cover factor was determined based on the formula (Gravas & Langenhove 2006):

$$CF = \frac{\sqrt{Tex}}{l} \tag{3.6}$$

Where

CF = cover factor,

Tex = the yarn linear density

ℓ = the loop length; in the current study loop length is presented in mm

3.2.2.2. Determination of thermophysiological comfort properties of the fabric

3.2.2.2.1. Liquid moisture transport

The Moisture Management Tester instrument was used to test the liquid solution transfer and distribution in knitted fabric samples. The principle utilised by the MMT (Li & Wong 2006) is based on the fact that when moisture travels through a fabric, the contact of electrical resistance of the fabric will change. The fabric is in contact with the sensor rings, which determine the liquid content and the liquid moisture transfer behaviour on the top and bottom surfaces of the fabric. On the basis of the measured voltage charges, the variation of water content with time on the fabric's top and bottom can be quantitatively measured.

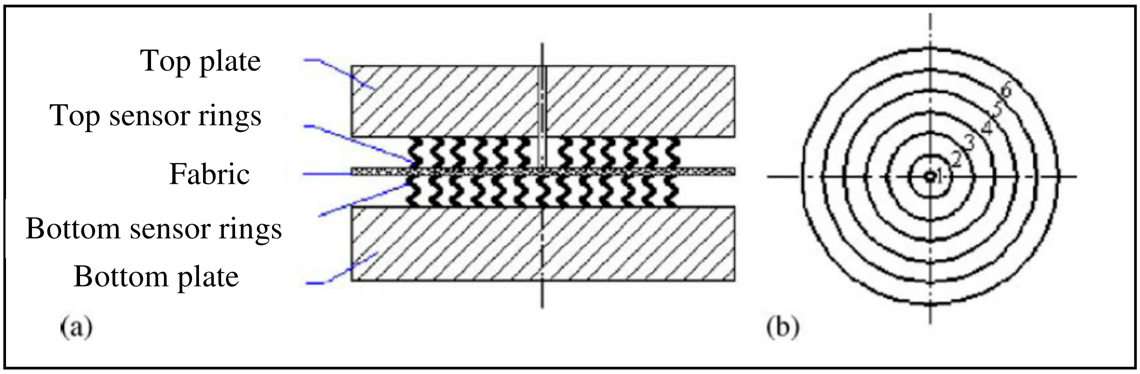


Figure 3.3 Sketch of MMT sensors: (a) sensor structure; (b) measuring rings (Yao et al. 2006)

During testing, each fabric specimen, the size of 80 x 80 mm, was placed flat between the top and bottom sensors and a predetermined quantity (0.15 g) of the testing solution was pumped onto the upper surface of the fabric to simulate a drop of liquid sweat. The signal for electrical resistance of the fabric samples was processed by the MMT software. All fabrics were tested under the same laboratory conditions. The upper surface of the fabric is considered the surface closest to the skin of the human body and the bottom surface of the fabric is the closest to the neighbouring environment. The parameters (indices) measured were:

Wetting Time, *WTt* (top surface) and *WTb* (bottom surface), is the time in which top and bottom surfaces of the fabric just start to get wet respectively after the test commences.

Absorption Rate, *ARt* (top surface) and *ARb* (bottom surface), is the average moisture absorption ability of the fabric’s top and bottom surface during the rise of water content, respectively.

Maximum Wetted Radius, MWRt (top surface) and *MWRb* (bottom surface), is defined as maximum wetted ring radius at the top and bottom surfaces.

Spreading Speed, SSt (top surface) and SSb (bottom surface), is the accumulative spreading speed from the centre of the fabric sample to the maximum wetted radius.

Accumulative One-Way Transport Index, (AOTI) represents the difference of the accumulative moisture content between the two surfaces of the fabric and determines to a large extend whether the fabric has good moisture management properties. In terms of comfort, it means that the higher the one-way transport capacity, the quicker and easier the liquid sweat can be transferred from next to the skin to the outer surface of the fabric, thus keeping the skin dry.

Overall Moisture Management Capability, (OMMC) indicates the overall capability of the fabric to manage the transport of liquid moisture. The larger the OMMC is, the higher the overall moisture management capability of the fabric.

Using the above indices, the test sample can be evaluated for its liquid moisture management properties. Sometimes, however, the values of the indices are difficult to interpret. To address this, the indices can be graded and converted from value to grade based on a five-grade scale (1–5). The five grades of indices represent: 1 – poor, 2 – fair, 3 – good, 4 – very good, 5 – excellent. Table 3.6 shows the grading of all indices.

Table 3.6.Grading of all MMT indices (Yao et al. 2006)

Index		Grade				
		1	2	3	4	5
Wetting time (s)	Top	⩾120 No wetting	20–119 Slow	5–19 Medium	3–5 Fast	<3 Very fast
	Bottom	⩾120 No wetting	20–119 Slow	5–19 Medium	3–5 Fast	<3 Very fast
Absorption rate (%/s)	Top	0–10 Very slow	10–30 Slow	30–50 Medium	50–100 Fast	>100 Very fast
	Bottom	0–10 Very slow	10–30 Slow	30–50 Medium	50–100 Fast	>100 Very fast
Max wetted radius (mm)	Top	0–7 No wetting	7–12 Small	12–17 Medium	17–22 Large	>22 Very large
	Bottom	0–7 No wetting	7–12 Small	12–17 Medium	17–22 Large	>22 Very large
Spreading speed (mm/s)	Top	0–1 Very slow	1–2 Slow	2–3 Medium	3–4 Fast	>4 Very fast
	Bottom	0–1 Very slow	1–2 Slow	2–3 Medium	3–4 Fast	>4 Very fast
One-way transport capacity (*R*)		<−50 Poor	−50 to 100 Fair	100–200 Good	200–400 Very good	>400 Excellent
Overall moisture management capability (OMMC)		0–0.2 Poor	0.2–0.4 Fair	0.4–0.6 Good	0.6–0.8 Very good	>0.8 Excellent

In order to give a direct overall evaluation and result for the liquid moisture management properties, the tested fabrics were classified into seven categories, types 1 – 7 (Table 3.7), based on the grades and values of indices. Figure 3.3 shows the flow chart of the criteria and the procedure for the fabric classification method (Yao et al. 2006).

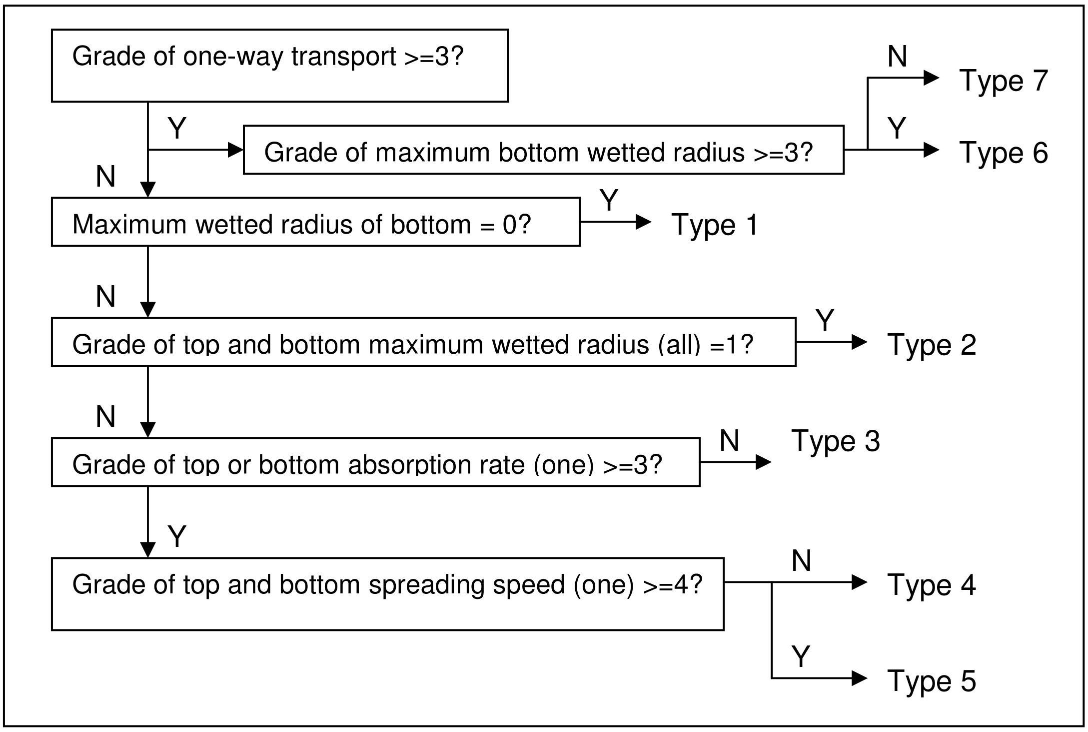


Figure 3.4.Flow chart of MMT fabric classification method (Yao et al. 2006)

Table 3.7.Fabric classification into seven categories (Yao et al. 2006)

Type no.	Type name	Properties
1	Waterproof fabric	Very slow absorption Slow spreading No one-way transport, no penetration
2	Water-repellent fabric	No wetting No absorption No spreading Poor one-way transport without external forces
3	Slow absorbing and slow-drying fabric	Slow absorption Slow spreading Poor one-way transport
4	Fast-absorbing and slow-drying fabric	Medium to fast wetting Medium to fast absorption Small spreading area Slow spreading Poor one-way transport
5	Fast-absorbing and quick-drying fabric	Medium to fast wetting Medium to fast absorption Large spreading area Fast spreading Poor one-way transport
6	Water-penetration fabric	Small-spreading area Excellent one-way transport
7	Moisture-management fabric	Medium to fast wetting Medium to fast absorption Large spread area at bottom surface Fast spreading at bottom surface Good to excellent one-way transport

3.2.2.2.2. Thermal conductivity

KES F7 Thermolabo was used to determine the fabric's thermal conductivity. The KES F7 Thermolabo is illustrated in Figure 3.5. After water circulated through the water box, the sample of 50 x 50 mm was sandwiched between the BT Box (hot plate) and water box (cold plate). The BT Box pressure was set to 6 g/cm^2.The temperature of both plates was controlled. After reaching constant value, the heat flow loss of BT was read by the panel meter and the thermal conductivity was determined based on the formula:

$$K = \frac{W.D}{A.\Delta T} \tag{3.7}$$

Where:

D = Thickness of sample, cm

A = Area of BT heat sample, cm^2

ΔT = Temperature difference sample, ^oC

W = Heat flow loss, W

K = Thermal Conductivity, W/cm ^oC

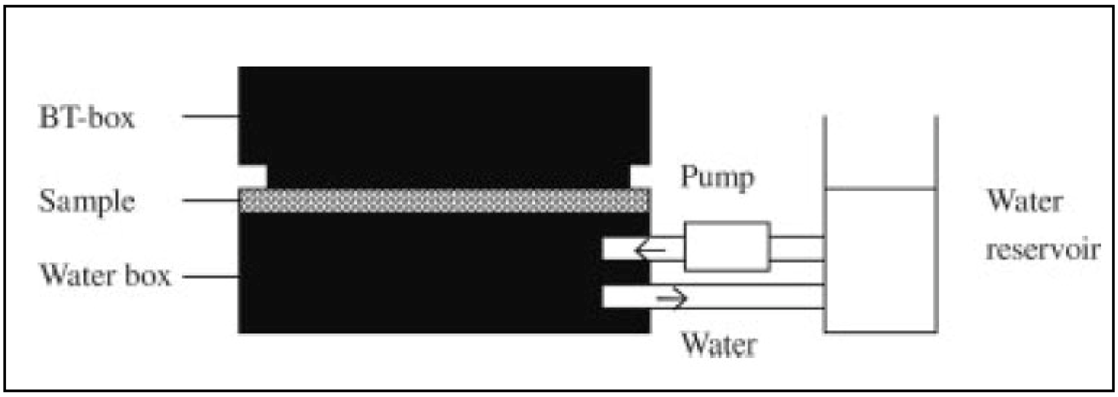


Figure 3.5.Scheme of KES F7 Thermolabo to measure thermal conductivity (Wu et al. 2007)

3.2.2.2.3. Warm/cool feeling

Kawabata Evaluation System F7-Thermo Labo II was used to determine the warm or cool feeling touch of the fabric. Warm/cool feeling is represented by *Qmax*. The greater Qmax value is equivalent to a cool sensation, the smaller value to warm.

Figure 3.6 shows the principle used by Kawabata's Thermolabo device to measure the warm/cool sensation of fabrics. When a preheated hot plate (as a simulator of human skin) is placed on a fabric sample, a heat flux versus time curve is generated. Maximum heat flow (*Qmax*) is measured for a fraction of a second after the hot plate contacts the fabric, a time that approximates the warm/cool feeling experienced when fabric is placed on skin. The *Qmax* value depends on the heat capacity and conductivity of the fabric and on the area of contact established between the skin and fabric surface. Contact area is the most important determinant of how warm or cool a fabric feels to an individual (Barker 2002).

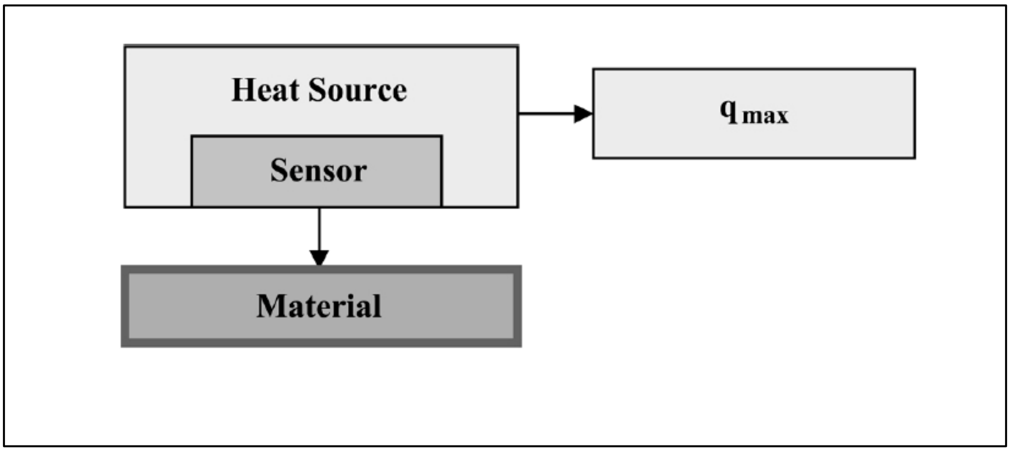


Figure 3.6.Warm/cool feeling measuring device (Barker 2002)

3.2.2.3 Determination of fabric sensorial comfort properties

3.2.2.3.1. Stiffness

The Shirley stiffness test was utilised to measure the bending stiffness of a fabric by allowing a narrow strip of the fabric to bend to a fixed angle under its own weight. The length of the fabric required to bend to this angle is measured, and is known as the bending length. The higher the bending length, the stiffer the fabric.

The test specimens were each 25 mm wide x 200mm long; three of them were cut parallel to the warp and three cut parallel to the weft, so that no two warp specimens contained the same warp threads, and no two weft specimens contained the same weft threads. The specimens should not be creased and those that tended to twist were flattened (AS 2001.2.9–1977).

Before the test the specimens were preconditioned then conditioned for 24 hours. If a specimen was found to be twisted, its midpoint was aligned with the two index lines. Four readings were taken from each specimen, one face up and one face down on the first end, and then the same for the second end. The mean bending length for warp and weft was calculated.

The bending length, *C*, was calculated. The mean bending length, in millimetres, for lengthwise and width wise directions were calculated separately, using the following formula (AS 2001.2.9-1977):

$$C = 10s \qquad (3.8)$$

Where

C = mean bending length, mm

s = scale reading

3.2.2.3.2. Number of contact points

The number of contact points was determined based on the Hohenstein Institute method (Bartels & Umbach 2001) but not all steps were followed, only the principle, adjusted with the available equipment.

To obtain the number of contact points in the first step the specimen was dyed on its surface using the ERNST-BENZ Laboratory padding machine by putting the specimens into dye solution on the top of the machine. As the pair of rollers in the machine rotated, the specimen followed the rotation. Since pressure was applied on the rollers, in the time the specimen passed between the rollers, the dye solution that absorbed into the specimen was pressed but there were still dye remains on the fabric. Afterwards the specimen was placed on one sheet of paper with the back the specimen facing the paper. Then a roller was placed on top of the specimen and rolled by hand with minimal pressure, so that a negative of the fabric was generated on the paper. After the dye on the paper dried, the negative on the paper was marked with pen to a size of 35 mm x 35 mm square.

The marked paper negative was scanned on a DELL scanner. An image taken was analysed by the IMAGE TOOL system to count its dots. The dots of dye on the print were considered as contact points of the textile with the skin.

3.2.3. Statistical analysis of result

The following statistical analyses were performed using MINITAB version 15.

1. Descriptive statistics were used to summarise and describe the difference of properties of sample fabrics intended for base layer winter active sportswear.
2. One-way analysis of variance (ANOVA) was performed to determine whether the properties of the sample fabrics differed significantly from each other.
3. Pearson’s correlation analysis was conducted to test for a significant relationship between each piece of data.
4. Linear regressions were used to analyse the relationship between two variables.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter discusses the outcome of the present work according to the experiments carried out. The chapter includes results covering the structural and physical properties of fabrics, their sensorial comfort properties and thermophysiological comfort properties.

4.1. Preliminary experiment sample

4.1.1. Wool-knitted fabrics

The preliminary experiment was conducted by producing 11 single jersey fabrics with 11 different cover factors. The sample fabrics were made of 20 Tex wool yarn. The structural and physical properties and liquid moisture transfer performance of the sample fabrics were determined. The purpose of the preliminary experiment was to observe the liquid moisture transfer performance of wool-knitted fabrics and to discover whether the cover factor of the sample fabrics influenced the performance or not.

4.1.1.1 Structural and physical properties

The test results of the structural and physical properties of 11 100% wool-knitted fabrics with different cover factors are given in Table 4.1.

Table 4.1.Structural and physical properties of 100% wool-knitted fabrics

Fabrics	Weight (g/m^2) *n = 5	Thickness (mm) *n = 5	Wales/cm *n = 5	Courses/cm *n = 5	Porosity (%)	Optical Porosity (%) *n = 5	Loop length (mm)	Cover factor
1	82.0	0.40	9	10	84.47	35.23	3.94	1.14
2	88.4	0.41	10	11	83.51	30.78	3.64	1.23
3	102.4	0.42	11	13	81.53	24.32	3.27	1.37
4	107.0	0.42	12	13	80.70	21.12	3.20	1.40
5	122.6	0.44	13	14	78.79	17.51	3.02	1.48
6	131.8	0.44	14	15	77.51	15.36	2.87	1.56
7	135.8	0.45	15	16	76.93	11.72	2.74	1.63
8	138.6	0.44	15	17	76.30	10.95	2.67	1.68
9	145.4	0.45	15	18	75.74	10.95	2.60	1.72
10	151.4	0.46	16	18	74.90	8.56	2.56	1.75
11	156.2	0.46	16	19	74.33	7.62	2.50	1.79

*n = number of samples

Pearson correlations between the cover factor and structural and physical properties were determined (Table 4.2).

Table 4.2.Pearson correlations of cover factor and structural and physical properties

Variables of wool fabrics	**Pearson correlations**
CF, weight	0.994
CF, thickness	0.970
CF, wales/cm	0.991
CF, course/cm	0.995
CF, porosity	-0.996
CF, optical porosity	-0.990
CF, loop length	-0.991

It can be seen that all correlations between the cover factor and physical and structural properties of the fabric has values that are closer to 1 or -1, which indicated that the variables are linearly related. As the cover factor increased, fabric weight, thickness, wales/cm and course/cm also increased; by contrast, as the cover factor increased, fabric porosity, optical porosity and loop length decreased (Figures 4.1–4.7).

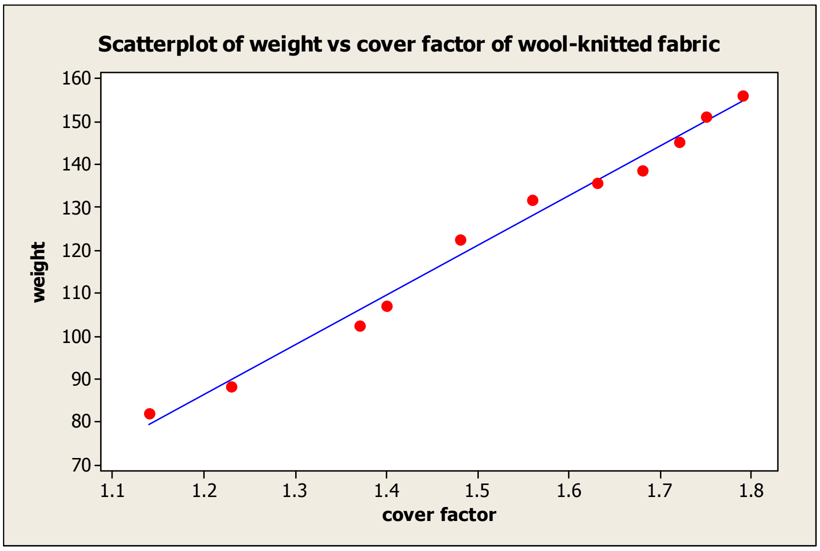


Figure 4.1.Weight versus cover factor in 100% wool-knitted fabrics

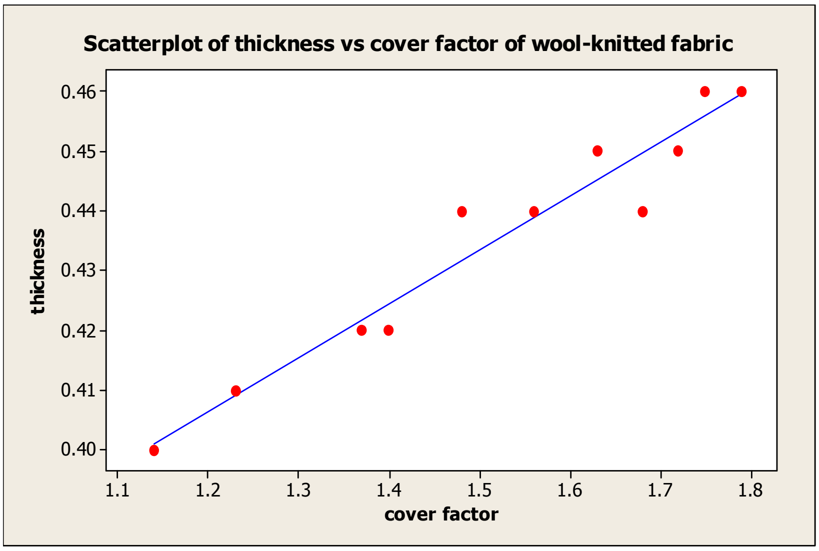


Figure 4.2.Thickness versus cover factor in 100% wool-knitted fabrics

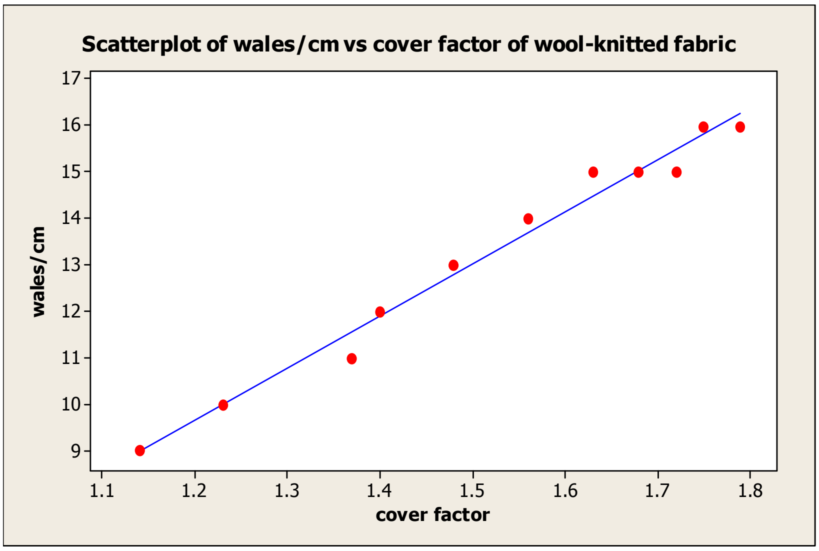


Figure 4.3.Wales/cm versus cover factor in 100% wool-knitted fabrics

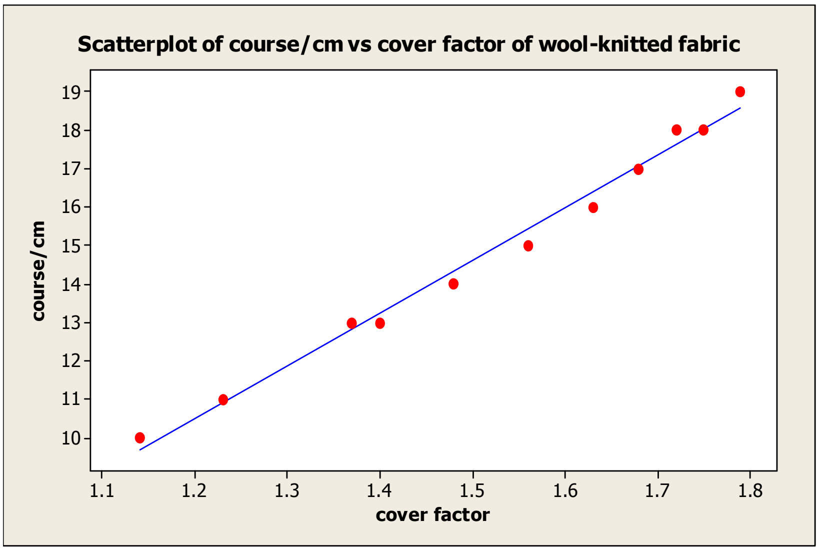


Figure 4.4.Course/cm versus cover factor in 100% wool-knitted fabrics

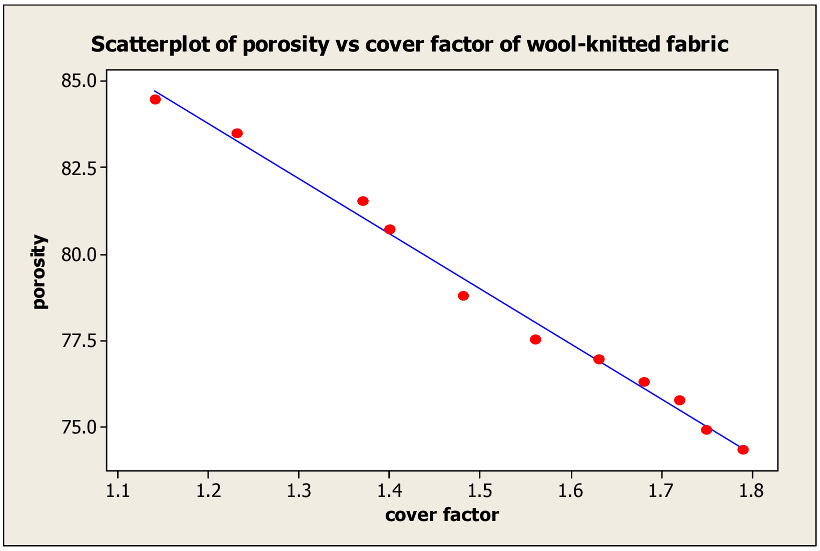


Figure 4.5.Porosity versus cover factor in 100% wool-knitted fabrics

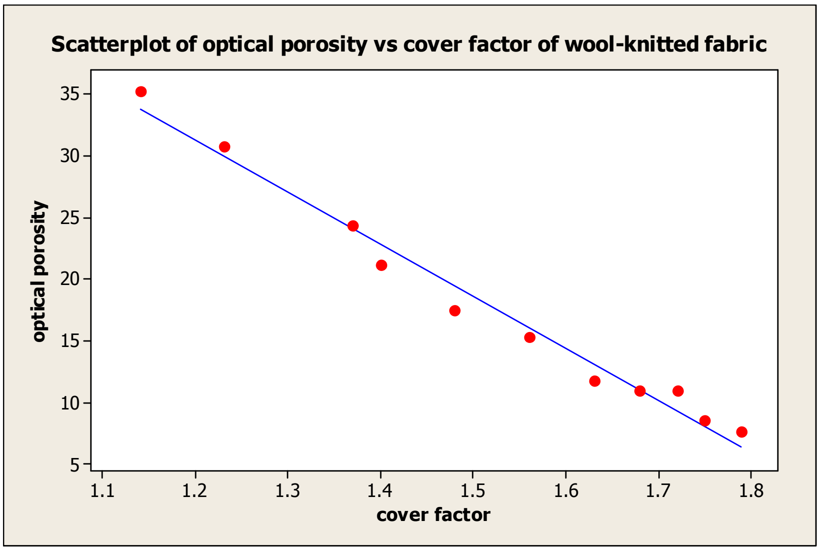


Figure 4.6.Optical porosity versus cover factor in 100% wool-knitted fabrics

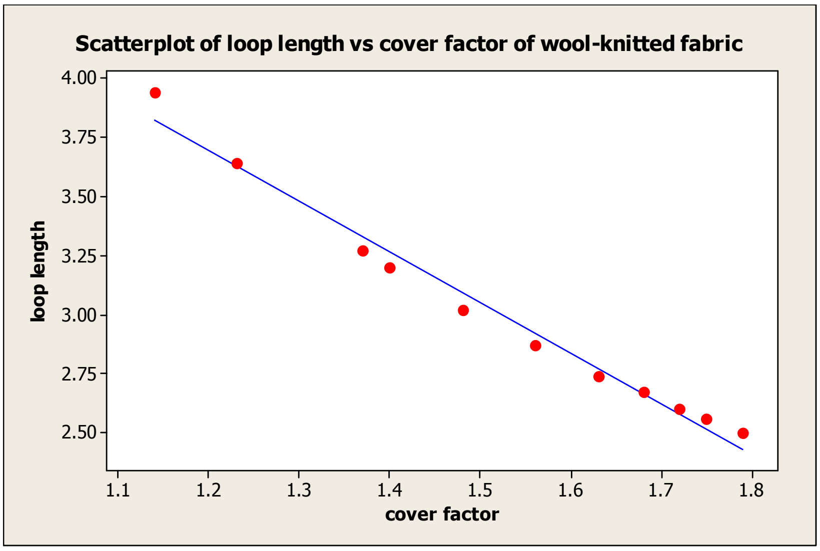


Figure 4.7.Loop length versus cover factor in 100% wool-knitted fabrics

Since the cover factor is the function of loop length and yarn count (Tex)(equation 3.6 chapter 3), it can be seen from Figure 4.7 that it was influenced by loop length. As the yarn count used for producing sample fabrics remained constant, it can be seen that the cover factor influenced the fabric weight, course/cm and wale/cm. Thus the fabric weight is a function of loop length and yarn count, while loop length is a function of course/cm and wales/cm. The cover factor was also influenced by fabric porosity and optical porosity (openness). As the cover factor increased, the fabric openness decreased.

4.1.1.2 Liquid moisture transfer properties

Liquid moisture transfer test results of wool-knitted fabrics in value are given in Table 4.3. The results in the values are difficult to interpret, so that the results are converted into grades (Table 4.4). The grade ranges from 1 to 5 (poor to excellent) (Yao et al. 2006).

Table 4.3.MMT results of 100% wool-knitted fabrics in value

Cover factor	WTt	WTb	ARt	ARb	MWRt	MWRb	SSt	SSb	AOTI	OMMC
1.14	119.95	44.12	0.00	5.11	0.00	5.00	0.00	0.34	1023.37	0.50
1.23	7.37	44.52	119.69	3.74	5.00	6.67	0.67	0.25	987.31	0.50
1.37	7.23	4.41	109.05	12.25	6.67	18.33	1.30	4.41	2041.10	0.70
1.40	119.95	2.04	0.00	69.96	0.00	10.00	0.00	4.60	1432.68	0.92
1.48	119.95	3.75	0.00	63.46	0.00	5.00	0.00	1.58	1375.78	0.70
1.56	119.95	3.77	0.00	73.20	0.00	5.00	0.00	1.42	1307.28	0.72
1.63	119.95	4.15	0.00	65.03	0.00	5.00	0.00	1.58	1316.64	0.71
1.68	119.95	5.61	0.00	81.68	0.00	5.00	0.00	0.95	1277.53	0.71
1.72	119.95	6.52	0.00	88.88	0.00	5.00	0.00	0.80	1252.78	0.71
1.75	119.95	9.21	0.00	99.47	0.00	5.00	0.00	0.68	1188.96	0.73
1.79	47.27	49.69	159.44	131.02	3.33	3.33	0.32	0.25	175.46	0.49

Table 4.4.MMT results of 100% wool-knitted fabrics in grade

Cover factor	WTt	WTb	ARt	ARb	MWRt	MWRb	SSt	SSb	AOTI	OMMC
1.14	1.0	3.0	1.0	1.0	1.0	1.0	1.0	1.0	5.0	3.0
1.23	3.5	2.5	4.5	1.0	1.0	1.0	1.0	1.0	5.0	3.0
1.37	3.5	5.0	4.5	1.5	1.0	3.0	1.0	5.0	5.0	4.5
1.40	1.0	5.0	1.0	4.0	1.0	2.0	1.0	5.0	5.0	5.0
1.48	1.0	4.0	1.0	4.0	1.0	1.0	1.0	1.5	5.0	4.0
1.56	1.0	5.0	1.0	4.0	1.0	1.0	1.0	2.0	5.0	4.0
1.63	1.0	4.0	1.0	4.0	1.0	1.0	1.0	1.5	5.0	4.0
1.68	1.0	3.5	1.0	4.0	1.0	1.0	1.0	1.0	5.0	4.0
1.72	1.0	3.5	1.0	4.0	1.0	1.0	1.0	1.0	5.0	4.0
1.75	1.0	3.0	1.0	5.0	1.0	1.0	1.0	1.0	5.0	4.5
1.79	3.0	2.5	5.0	5.0	1.0	1.0	1.0	1.0	4.5	4.0

Almost all of the bottom indices of the fabrics have a higher rating than the top indices (Table 4.4), which means that the moisture does not remain at the top of the fabric surface near the skin, but is transported to the bottom of the fabric surface.

Almost all of the fabrics have low grade in top wetting time, but at the same time they have a medium to very fast range of bottom wetting time and almost all have higher WTb than WTt. This indicates that the bottom surfaces of the fabrics start to get wet faster than the top surface. The solution penetrates the fabric almost immediately as it drops onto the top surface. The fabrics have a low grade of top surface wetting time, which indicates that it takes time for the top surface to get wet. This allows us to conclude that the top fabric surface will stay dry in the time period of the test.

Almost all of the fabrics are very slow in top absorption rate but have a fast to very fast range of bottom absorption rate and almost all of the fabrics have higher ARb than ARt. This indicates that the bottom surface of the fabrics has greater ability to absorb moisture than the top surface of the fabrics. As the bottom surface absorbs more moisture than the top surface, the top surface remains drier than the bottom surface.

The maximum wetted radius for top and bottom surfaces are almost the same; all the fabrics have a low grade of maximum wetted radius. This indicates that the solution is not spread in a big radius. If the water is concentrated in a small area, the top surface will get wet, but since the WTb is higher than the WTt and the ARb is higher than the ARt, the water is transported from the top to the bottom surface and the top surface will remain dry.

All the fabrics have a very slow-spreading speed on the top surface, but have a very slow to very fast range of spreading speed on the bottom surface.

All fabrics have an excellent one-way transport accumulative index. This indicates that the difference of the accumulative moisture content between the two surfaces of the fabric is high. This means that the moisture content of the bottom surface is higher than the moisture content of the top surface.

All the fabrics have good to excellent grades of OMMC. This indicates that they have a high capability of managing the transport of liquid moisture, which is determined by the higher ARb grade than ARt grade, higher grade of AOTI and higher SSb than SSt. Thus is it is possible to conclude that the 100% wool fabrics of variable cover factors are highly suitable for base layer active sportswear.

An excellent one-way transport index of 100% wool-knitted fabrics shows that wool has good transport ability. This result agrees with Higgins and Anand's view (2003). The good transport ability of wool is due to its complex structure where every follicle of wool is made up of a hydrophobic (water-hating) exterior shaft and a hydrophilic (water-loving) inner core. This gives wool the unique ability to wick perspiration (sweat) away from the body.

In order to give a direct overall evaluation and result for the liquid moisture management properties, each fabric is classified into fabric type, based on the grades and values of indices (Table 4.5) (Yao et al. 2006). All 100% wool-knitted fabrics were classified as water-penetration fabrics. The key properties of water-penetration fabrics are small-spreading area and excellent one-way liquid transport.

Table 4.5.Fabric classification results of 100% wool-knitted fabric

Fabrics	Cover factor	Fabric classification
1	1.14	Water penetration fabric
2	1.23	Water penetration fabric
3	1.37	Water penetration fabric
4	1.40	Water penetration fabric
5	1.48	Water penetration fabric
6	1.56	Water penetration fabric
7	1.63	Water penetration fabric
8	1.68	Water penetration fabric
9	1.72	Water penetration fabric
10	1.75	Water penetration fabric
11	1.79	Water penetration fabric

4.1.1.3. Relationship between cover factor and moisture management properties of 100% wool-knitted fabrics

To find out the relationship between the cover factor and the moisture management properties of 100% wool-knitted fabrics, scatterplots with regression lines of MMT indices and the cover factors were prepared (Figures 4.8–4.17). It can be seen from the scatterplots that the cover factor has not influenced MMT indices. The scatterplots did not indicate a relationship between the variables, except for ARb. It can be seen that as the cover factor increases the value of ARb also increases. It may be due to wool's ability to absorb a large amount of water vapour.

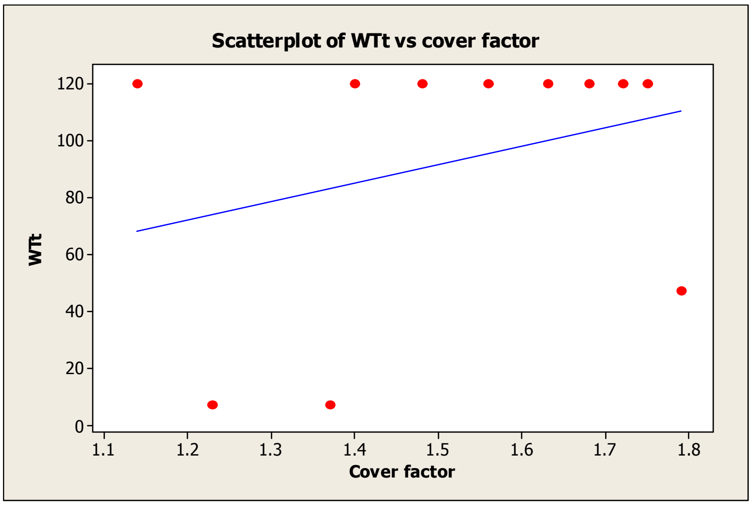


Figure 4.8.Top wetting time versus cover factor in 100% wool-knitted fabrics

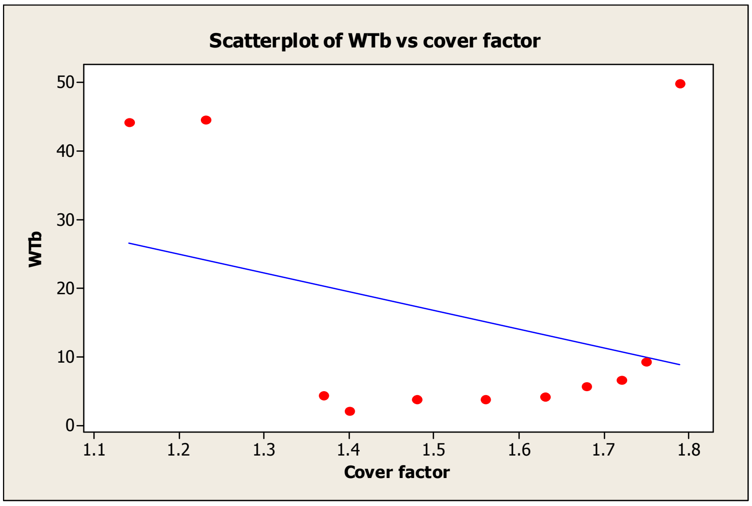


Figure 4.9.Bottom wetting time versus cover factor in 100% wool-knitted fabrics

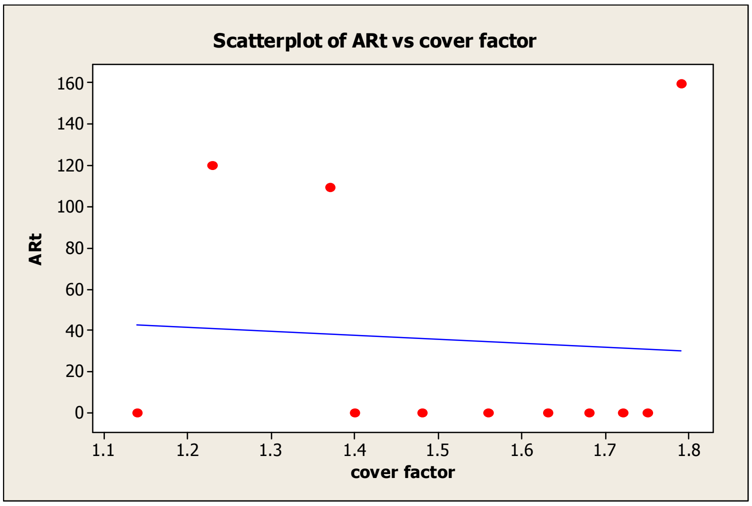


Figure 4.10.Top absorption rate versus cover factor in 100% wool-knitted fabrics

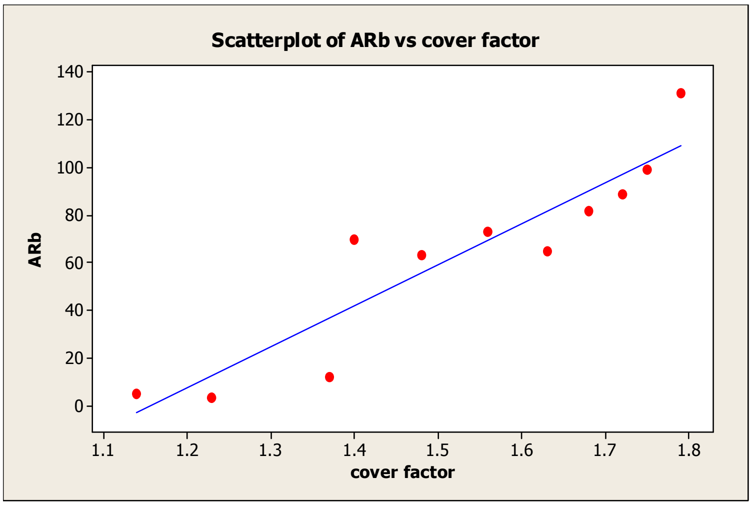


Figure 4.11.Bottom absorption rate versus cover factor in 100% wool-knitted fabrics

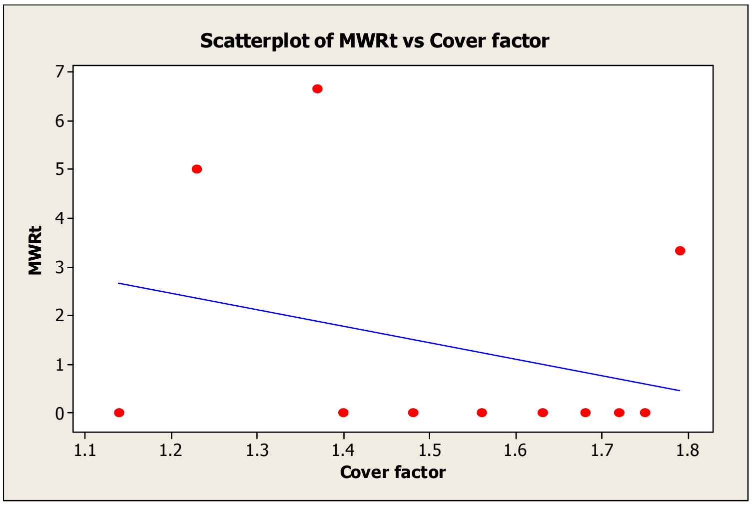


Figure 4.12.Top maximum wetted radius versus cover factor in 100% wool-knitted fabrics

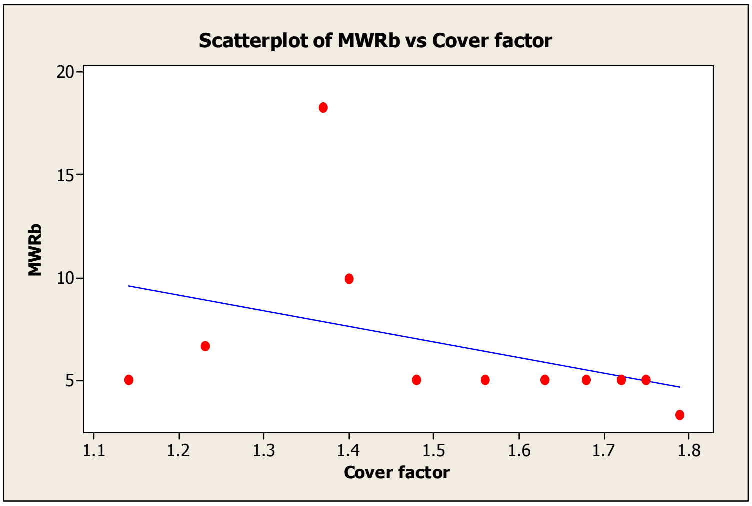


Figure 4.13.Bottom maximum wetted radius versus cover factor in 100% wool-knitted fabrics

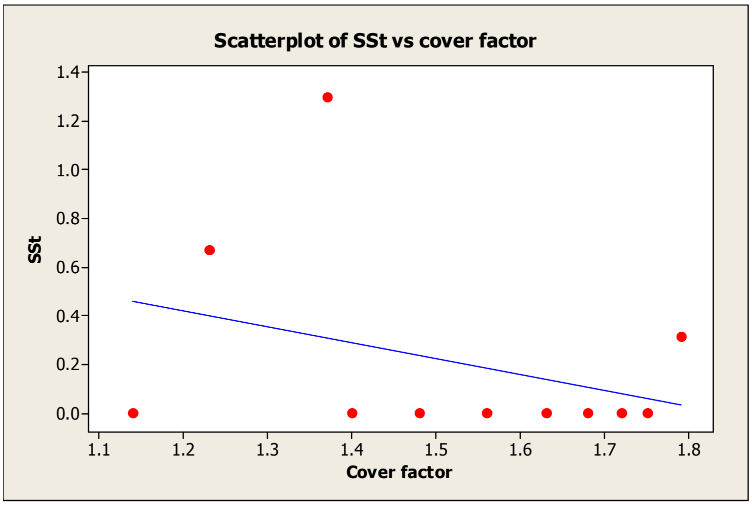


Figure 4.14.Top spreading speed versus cover factor in 100% wool-knitted fabrics

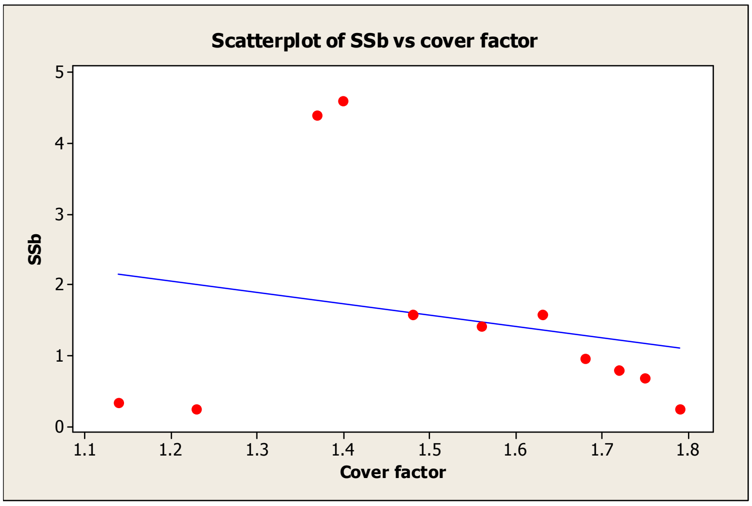


Figure 4.15.Bottom spreading speed versus cover factor in 100% wool-knitted fabrics

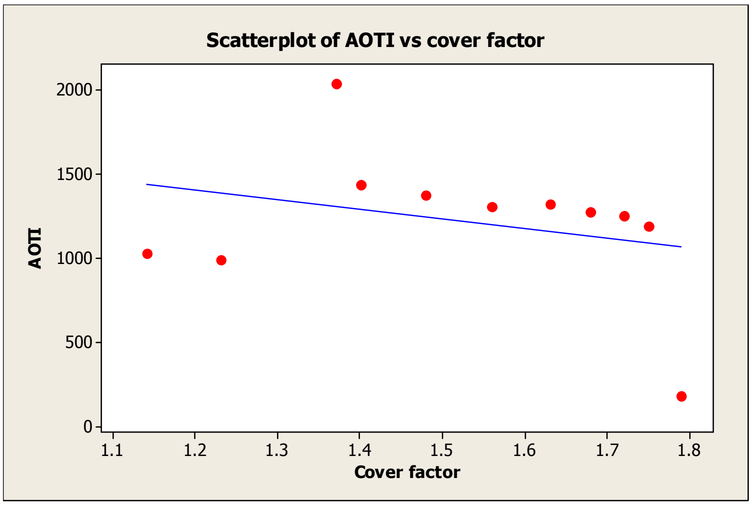


Figure 4.16.Accumulative one-way transport index versus cover factor in 100% wool-knitted fabrics

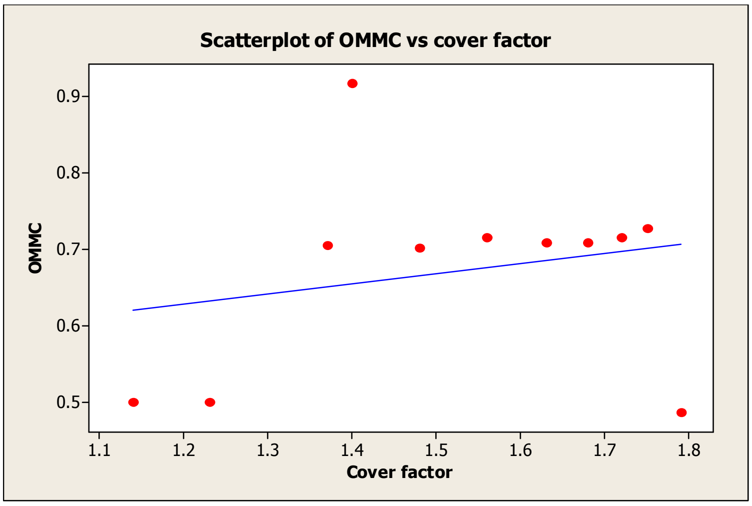


Figure 4.17.Overall moisture management capacity versus cover factor in 100% wool-knitted fabrics

Pearson correlations between the cover factor and moisture management properties indices are given in Table 4.6. It can be seen that almost all correlations between the cover factor and the indices are not linearly related since the Pearson correlations are not close to +1 or -1. This indicates that for 20 Tex 100% wool single jersey fabrics, with a cover factor from 1.14 to 1.79, the cover factor did not influence the overall moisture management fabric properties.

Table 4.6.Pearson correlations between cover factor and MMT indices in 100% wool-knitted fabrics

Variables	**Pearson correlations**
CF, WTt	0.298
CF, WTb	-0.306
CF, ARt	-0.068
CF, ARb	0.921
CF, MWRt	-0.299
CF, MWRb	-0.391
CF, SSt	-0.340
CF, SSb	-0.225
CF, AOWTI	-0.283
CF, OMMC	0.223

Pearson correlations between structural properties and moisture management properties indices are given in Table 4.7. It can be seen that almost all correlations between physical and structural fabric properties and the indices are not linearly related since the Pearson correlations are not close to +1 or -1. This indicates for 20 Tex 100% wool single jersey fabrics that their physical and structural properties did not influence their moisture management performance.

Table 4.7.Pearson correlations between structural properties and MMT indices of 100% wool-knitted fabrics

Wool		**Weight**	**Thickness**	**Porosity**	**Optical porosity**
Liquid Moisture Transfer					
	WTt	0.335	0.294	-0.345	-0.342
	WTb	-0.281	-0.291	0.304	0.392
	ARt	-0.089	-0.066	0.104	0.123
	ARb	0.932	0.894	-0.934	-0.921
	MWRt	-0.340	-0.300	0.349	0.339
	MWRb	-0.450	-0.431	0.441	0.373
	SSt	-0.386	-0.346	0.391	0.368
	SSb	-0.274	-0.263	0.254	0.150
	AOTI	-0.323	-0.294	0.305	0.222
	OMMC	0.196	0.185	-0.223	-0.319

4.1.2 Bamboo-knitted fabrics

To observe the liquid moisture transfer performance of 100% single jersey bamboo-knitted fabrics and to discover whether the cover factor of the sample fabrics influences the performance 13 single jersey fabrics made of 36.66 Tex yarn, different cover factors were produced and their structural and physical properties and liquid moisture transfer performance were determined.

4.1.2.1 Structural and physical properties

The test results of structural and physical properties of 13 100% bamboo-knitted fabrics with different cover factors are given in Table 4.8.

Table 4.8.Structural and physical properties of 100% bamboo-knitted fabrics

Fabric	Yarn count (Tex)	Average weight (g/m^2) *n=5	Average thickness (mm) *n=5	Average wales/ cm *n=5	Average courses/ cm *n=5	Average optical porosity (%) *n=3	Porosity (%)	Actual loop length (mm)	Cover factor
B1	36.66	228.60	0.69	11.4	14	10.20	58.37	3.73	1.62
B2	36.66	209.40	0.68	11	13	13.26	61.33	3.88	1.56
B3	36.66	196.80	0.67	10.4	12	13.84	63.55	4.05	1.49
B4	36.66	195.20	0.67	10	11	14.45	63.38	4.25	1.42
B5	36.66	175.20	0.65	10	10	16.71	66.30	4.43	1.37
B6	36.66	160.20	0.63	10	9	18.31	68.36	4.66	1.30
B7	36.66	159.00	0.63	9	9	18.79	68.28	4.77	1.27
B8	36.66	149.00	0.61	9	7.4	19.82	69.37	5.21	1.16
B9	36.66	138.60	0.57	9	7	20.74	69.59	5.40	1.12
B10	36.66	133.20	0.57	9	6.4	21.52	70.66	5.62	1.08
B11	36.66	130.20	0.56	9	6	21.99	71.01	5.88	1.03
B12	36.66	125.40	0.54	8	5.4	22.30	70.99	6.32	0.96
B13	36.66	120.40	0.54	8	5	23.19	71.97	6.68	0.91

The Pearson correlations between the cover factor and structural and physical properties of bamboo-knitted fabrics are given in Table 4.9. It can be seen that all correlations coefficients between the cover factor and physical and structural fabric properties have values that are closer to 1 or -1. This indicates that the variables are linearly related. As the cover factor increased, fabric weight, thickness, wales/cm and course/cm also increased. By contrast, as the cover factor increased, fabric porosity, optical porosity and loop length decreased (Figures 4.18–4.24).

Table 4.9.Pearson correlations of cover factor and structural and physical properties of 100% bamboo-knitted fabrics

Variables of bamboo-knitted fabrics	**Pearson correlations**
CF, weight	0.983
CF, thickness	0.984
CF, wales/cm	0.964
CF, course/cm	0.995
CF, porosity	-0.958
CF, optical porisity	-0.981
CF, loop length	-0.987

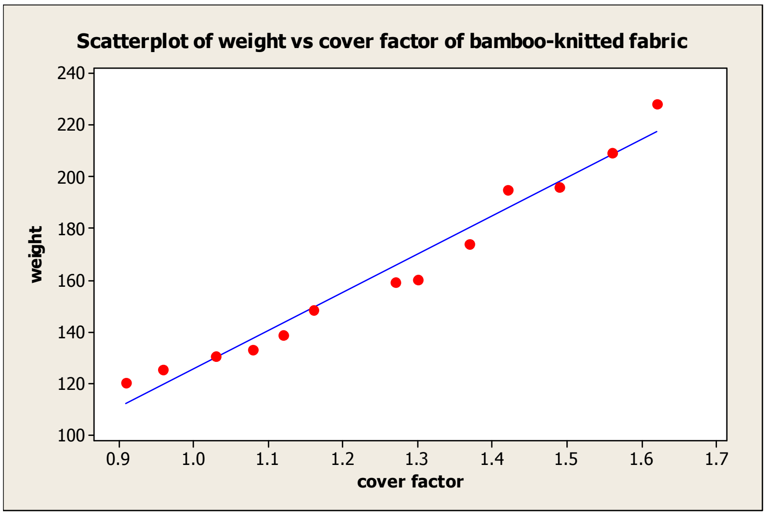


Figure 4.18.Weight versus cover factor in 100% bamboo-knitted fabrics

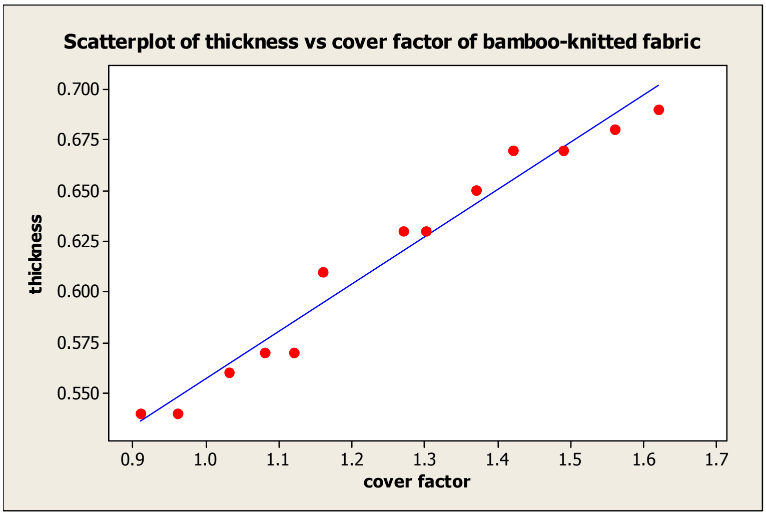


Figure 4.19.Thickness versus cover factor in 100% bamboo-knitted fabrics

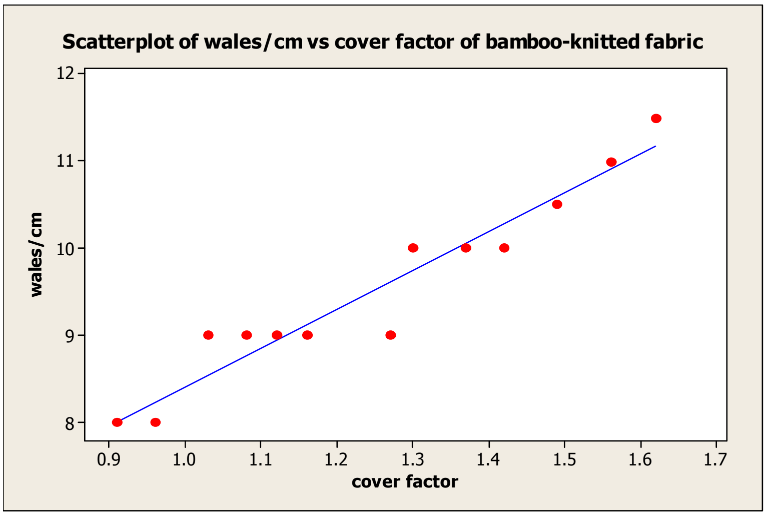


Figure 4.20.Wales/cm versus cover factor in 100% bamboo-knitted fabrics

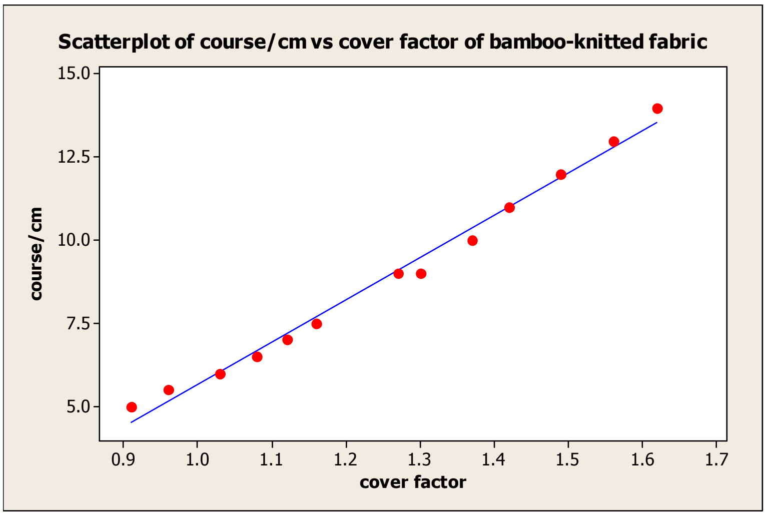


Figure 4.21.Course/cm versus cover factor in 100% bamboo-knitted fabrics

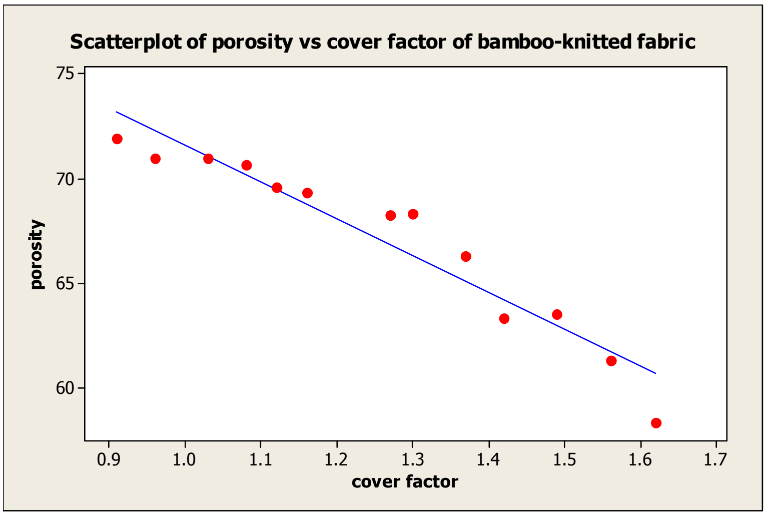


Figure 4.22.Porosity versus cover factor in 100% bamboo-knitted fabrics

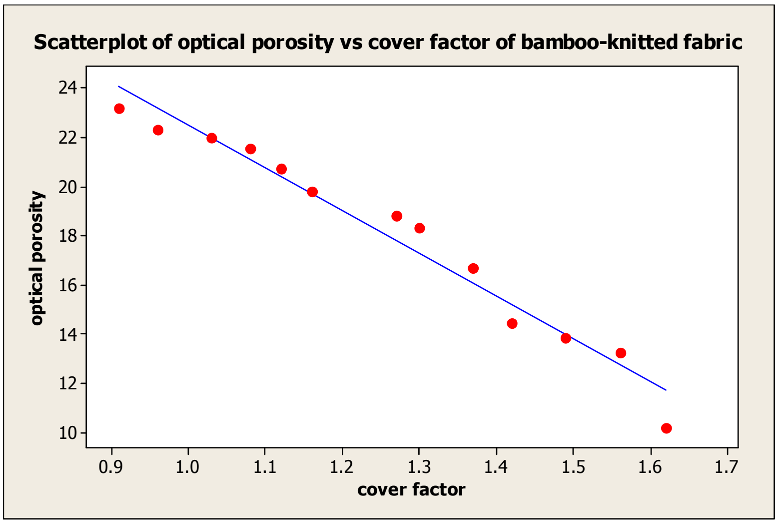


Figure 4.23.Optical porosity versus cover factor in 100% bamboo-knitted fabrics

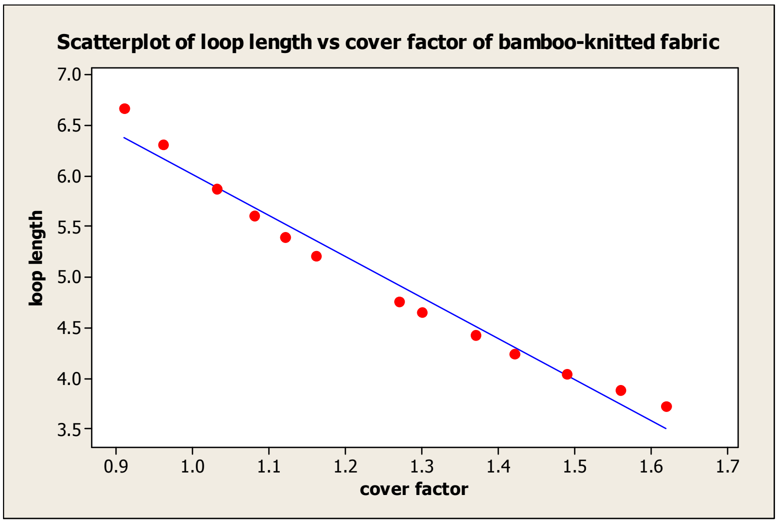


Figure 4.24.Loop length versus cover factor in 100% bamboo-knitted fabrics

Since the cover factor is the function of loop length and the yarn count (Tex), it can be seen from Figure 4.24 that the cover factor was influenced by the loop length. As the yarn count used for producing sample fabrics was the same count, it can be seen that the cover factor also influenced the fabric weight, courses/cm and wales/cm. Fabric weight is a function of loop length and yarn count, while loop length is a function of courses/cm and wales/cm. The cover factor also influenced the porosity and optical porosity (openness) of the fabric; as the cover factor increased, the openness decreased.

4.1.2.2 Liquid moisture transfer properties

Liquid moisture transfer test results of 100% bamboo-knitted fabrics in value are given in Table 4.10. Since results in value are difficult to interpret, the results were converted into grades (Table 4.11). The grades range from 1 to 5 (poor to excellent) (Yao et al. 2006).

Table 4.10.MMT results of 100% bamboo-knitted fabrics in value

	Cover factor	WTt (sec)	WTb (sec)	ARt (%/sec)	ARb (%/sec)	MWRt (mm)	MWRb (mm)	SSt (mm/sec)	SSb (mm/sec)	AOTI (%)	OMMC
B1	1.62	4.062	4.380	54.098	51.113	15.000	15.000	2.347	2.217	-52.484	0.220
B2	1.56	3.510	3.979	53.392	45.119	15.000	15.000	2.566	2.389	-48.344	0.217
B3	1.49	2.592	2.913	36.323	32.421	10.000	10.000	1.666	1.569	-29.614	0.150
B4	1.42	3.344	3.745	55.605	47.737	16.667	15.000	2.785	2.541	-71.891	0.233
B5	1.37	3.182	3.349	56.171	50.299	16.667	15.000	2.973	2.747	-59.792	0.258
B6	1.30	2.943	3.214	56.900	50.856	20.000	16.667	3.262	2.911	-73.314	0.273
B7	1.27	2.734	2.896	57.867	52.856	20.000	20.000	3.731	3.584	-59.789	0.334
B8	1.16	2.760	2.838	59.088	52.777	20.000	20.000	3.874	3.820	-64.221	0.354
B9	1.12	2.651	2.818	58.605	53.175	20.000	20.000	4.037	3.889	-58.771	0.362
B10	1.08	2.307	2.411	58.451	52.289	20.000	20.000	4.641	4.456	-55.961	0.370
B11	1.03	2.203	2.464	59.226	53.204	23.333	20.000	5.027	4.620	-56.448	0.370
B12	0.96	2.281	2.151	62.143	54.782	25.000	25.000	5.645	5.538	-56.984	0.375
B13	0.91	2.177	2.307	62.107	55.506	23.333	25.000	5.729	5.639	-58.692	0.376

Table 4.11.MMT results of 100% bamboo-knitted fabrics in grade

Fabrics	Cover factor	WTt	WTb	ARt	ARb	MWRt	MWRb	SSt	SSb	AOTI	OMMC
B1	1.62	4.0	3.5	3.5	3.5	3.0	3.0	3.0	2.5	1.0	1.5
B2	1.56	4.0	4.0	3.5	3.0	3.0	3.0	3.0	3.0	1.5	1.5
B3	1.49	4.5	4.0	3.5	3.5	3.0	3.0	3.0	3.0	1.0	2.0
B4	1.42	4.5	4.0	3.5	3.5	3.0	3.0	3.0	3.0	1.0	1.5
B5	1.37	4.5	4.5	3.5	3.5	3.0	3.0	3.5	3.0	1.0	2.0
B6	1.30	4.5	4.5	3.5	3.5	4.0	3.0	4.0	3.5	1.0	2.0
B7	1.27	5.0	5.0	3.5	3.5	4.0	4.0	4.0	4.0	1.0	2.0
B8	1.16	5.0	5.0	3.5	3.5	4.0	4.0	4.5	4.5	1.0	2.5
B9	1.12	5.0	5.0	3.5	3.5	4.0	4.0	5.0	4.5	1.0	2.5
B10	1.08	5.0	5.0	3.5	3.5	4.0	4.0	5.0	5.0	1.0	2.5
B11	1.03	5.0	5.0	3.5	3.5	5.0	4.0	5.0	5.0	1.0	2.5
B12	0.96	5.0	5.0	3.5	3.5	5.0	5.0	5.0	5.0	1.0	2.5
B13	0.91	5.0	5.0	3.5	3.5	5.0	5.0	5.0	5.0	1.0	2.5

Fabrics B1, B2 and B4 have poor liquid management capacity grade and a poor accumulative one-way transport index, but these fabrics have a medium spreading speed rate and fast wetting time. Fabrics B3, B5 to B7 have a fair liquid management capacity grade and poor accumulative one-way transport index, but these fabrics have a medium to fast spreading speed rate and fast to very fast wetting time. Fabrics B8 to B13 have a medium liquid management capacity grade and poor accumulative one-way transport index, but these fabrics have a fast to very fast spreading speed rate and very fast wetting time.

Fabrics B1 to B5 are classified as fast-absorbing and slow-drying fabrics as their spreading speed is less than 4 grades or a fast-spreading speed. Fabrics B6 to B13 are classified as fast-absorbing and quick-drying fabrics as their spreading speed is 4 grades or more or has a very fast spreading speed.

Most of the fabrics have a shorter top wetting time than bottom wetting time and all of the fabrics demonstrate higher absorption ability on the top surface than on the bottom. All fabrics have a negative accumulative one-way transport index, indicating that water solution content on the top surface is higher than on the bottom surface.

One hundred per cent bamboo-knitted fabrics had good to excellent wetting time in both surfaces due to the high attraction between the liquid and the fibre surface (known as the fibre surface energy). The fibre surface energy of bamboo fibre and cotton fibre can be regarded as the same (Shen et al 2004). Cotton fibre can be classified as cellulose fibre and its surface energy can be found in Table 4.12 (TFT CSIRO,2008)

Table 4.12.Fibre surface energy (TFT CSIRO,2008)

Fibre	**Surface energy(mJm^2)**
Aramid	-30
Carbon	40–50
Cellulose	200
Polyacrylonitrile	44
Polyamide	46
Polyester	43
Polyethylene	~22
Polypropylene	29
Polyvinylchloride	37
Wool	29

In order to give a direct overall evaluation and result for the liquid moisture management properties, each of the fabrics is classified into fabric type, based on the grades and values of indices (Table 4.13) (Yao et al. 2006).

One hundred per cent bamboo-knitted fabrics with a cover factor range from 0.91 to 1.30 were classified as fast-absorbing and quick-drying fabrics. The key properties of fast-absorbing and quick-drying fabrics are medium to fast wetting, medium to fast absorption, large spreading area, fast spreading and poor one-way transport.

One hundred per cent bamboo-knitted fabrics with a cover factor range from 1.37 to 1.62 were classified as fast-absorbing and quick-drying fabrics. The key properties of fast-absorbing and quick-drying fabrics are medium to fast wetting, medium to fast absorption, small spreading area, slow spreading and poor one-way transport.

In 100% bamboo-knitted fabrics (Table 4.13), it can be seen that the cover factor also influenced fabric classification. For low cover factor, the fabric classification is fast-absorbing and quick-drying fabric. This is probably due to the fabric's open structure, high porosity and high optical porosity so that it is easy for water to spread with relatively high spreading speed. For high cover factor, the fabric classification is fast-absorbing and slow-drying fabric. This is probably due to the fabric's close structure, low porosity and low optical porosity so that it is not easy for water to spread (spreading speed is relatively low).

It can be seen that the difference between slow-drying and quick-drying fabrics is in their water spreading area and spreading speed. Slow-drying fabric has a small spreading area and slow spreading speed while quick-drying fabric has a large spreading area and fast spreading speed.

Table 4.13.Fabric classification results of 100% bamboo-knitted fabric

Fabrics	Cover factor	Fabric classification
B1	1.62	fast-absorbing and slow-drying fabric
B2	1.56	fast-absorbing and slow-drying fabric
B3	1.49	fast-absorbing and slow-drying fabric
B4	1.42	fast-absorbing and slow-drying fabric
B5	1.37	fast-absorbing and slow-drying fabric
B6	1.30	fast-absorbing and quick-drying fabric
B7	1.27	fast-absorbing and quick-drying fabric
B8	1.16	fast-absorbing and quick-drying fabric
B9	1.12	fast-absorbing and quick-drying fabric
B10	1.08	fast-absorbing and quick-drying fabric
B11	1.03	fast-absorbing and quick-drying fabric
B12	0.96	fast-absorbing and quick-drying fabric
B13	0.91	fast-absorbing and quick-drying fabric

Compare 100% bamboo-knitted fabrics to 100% wool-knitted fabrics. All 100% wool-knitted fabrics were classified as water-penetration fabrics. The key properties of water-penetration fabrics are: small spreading area and excellent one-way liquid transport. It can be concluded that in terms of fabric drying speed, 100% wool-knitted fabrics have a slow drying speed since they have a small spreading area and relatively low spreading speed (Table 4.4).

4.1.2.3 Relationship between the cover factor and the moisture management properties of 100% bamboo-knitted fabrics

To find the possible relationship between the cover factor and moisture management properties of bamboo-knitted fabrics, scatterplots with regression lines of MMT indices and the cover factor were prepared (Figures 4.25–4.34).

The scatterplots of the cover factor versus top wetting time and the cover factor versus bottom wetting time reflect that the relationships between the cover factor and the top wetting time (WTt) and the bottom wetting time (WTb) were relatively similar. The top and bottom wetting times increased as the cover factor increased.

In regards to the maximum wetted radius, the relationships between the cover factor versus top maximum wetted radius can be seen from scatterplots of the cover factor versus MWRt and the cover factor versus MWRb. The top maximum wetted radius (MWRt) and the MWRb decreased with the increase of the cover factor.

The scatterplot the cover factor versus ARt depicts the relationship between the cover factor and top absorption rate. The rate of absorption of the top surface decreased as the cover factor increased. The same occurrence can be observed in the scatterplot of the cover factor versus ARb; as the cover factor increased, the bottom surface absorption rate decreased.

The scatterplot of the cover factor versus the top spreading speed and of the cover factor versus the bottom spreading speed indicates that the relationships between the cover factor and the top spreading speed and the bottom spreading speed was relatively similar. The top and bottom spreading speeds decreased as the cover factor increased.

The relationship between the cover factor and the rest of the indexes (AOTI and OMMC) can be seen in the last two scatterplots (Figures 4.33–4.34). The accumulative one-way transport index was not influenced by the cover factor since the Pearson correlation of AOTI and the cover factor is not linearly related. Overall moisture management capacity decreased as the cover factor increased.

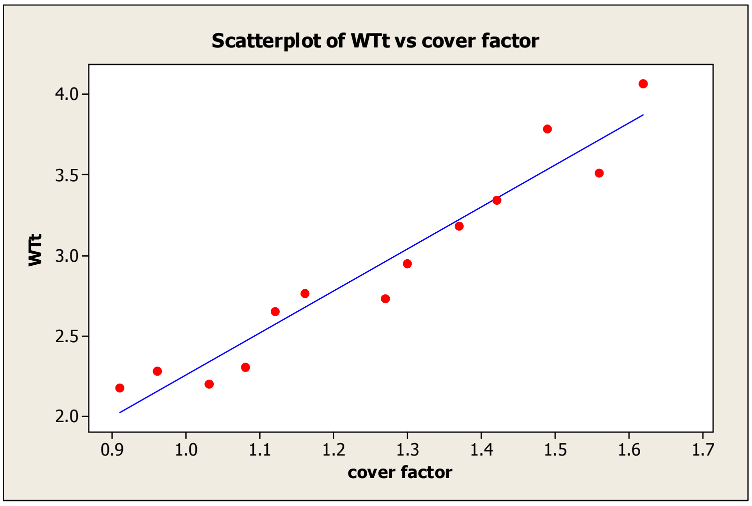


Figure 4.25.Top wetting time versus cover factor in 100% bamboo-knitted fabrics

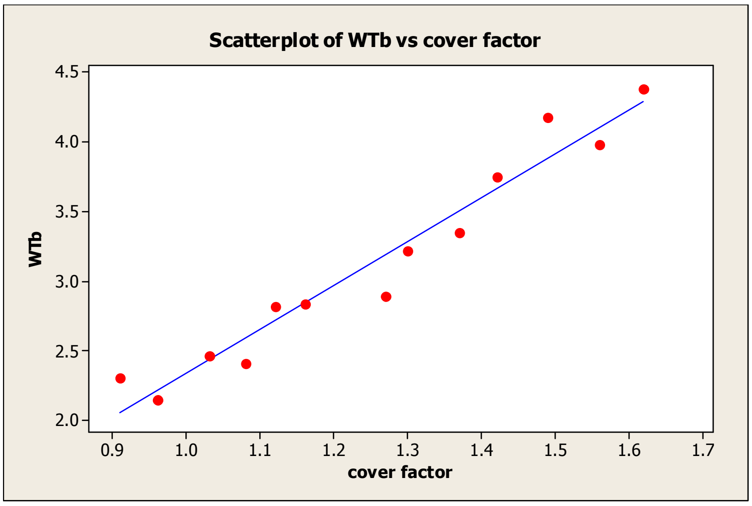


Figure 4.26.Bottom wetting time versus cover factor in 100% bamboo-knitted fabrics

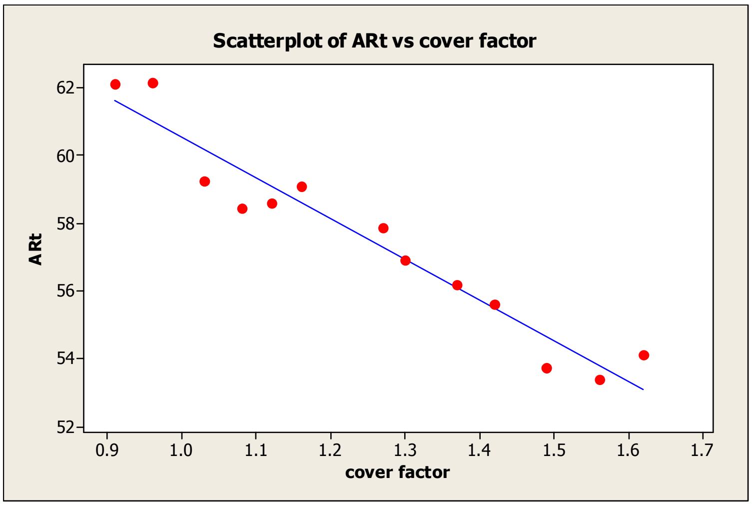


Figure 4.27.Top absorption rate versus cover factor in 100% bamboo-knitted fabrics

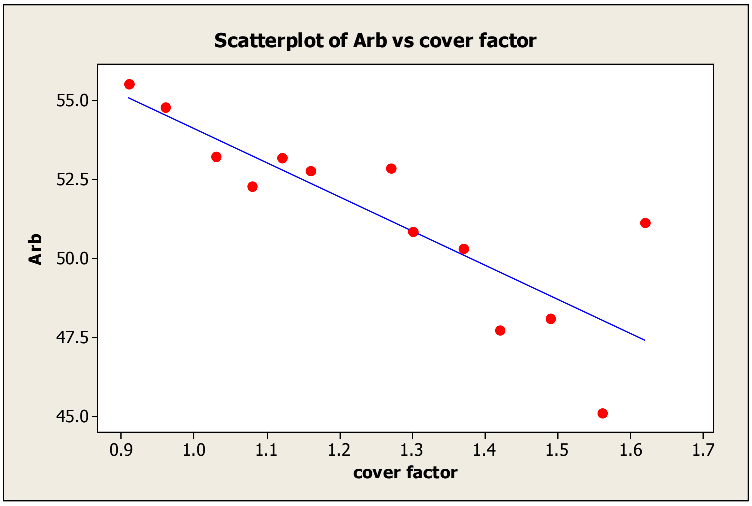


Figure 4.28.Bottom absorption rate versus cover factor in 100% bamboo-knitted fabrics

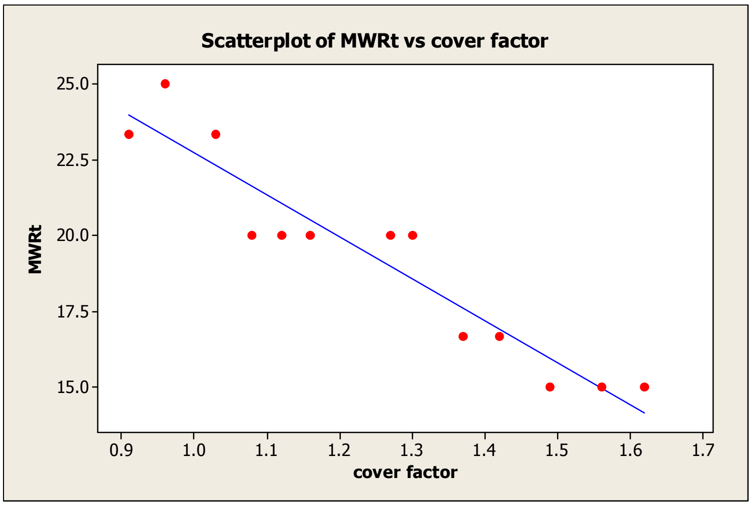


Figure 4.29.Top maximum wetted radius versus cover factor in 100% bamboo-knitted fabrics

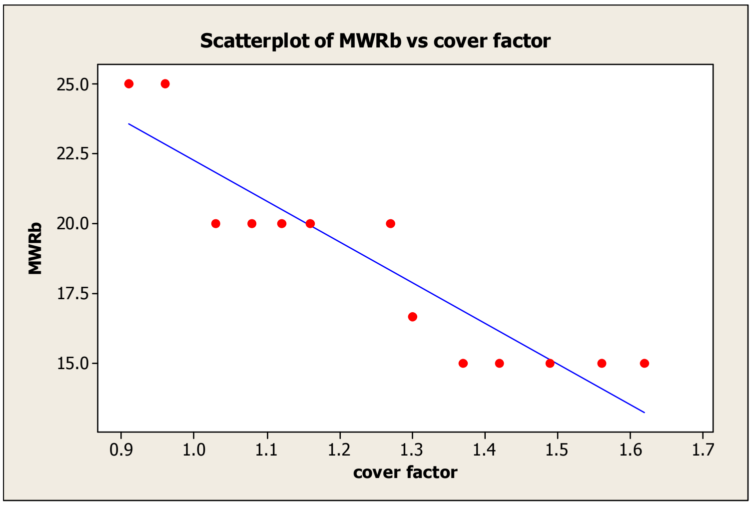


Figure 4.30.Bottom maximum wetted radius versus cover factor in 100% bamboo-knitted fabrics

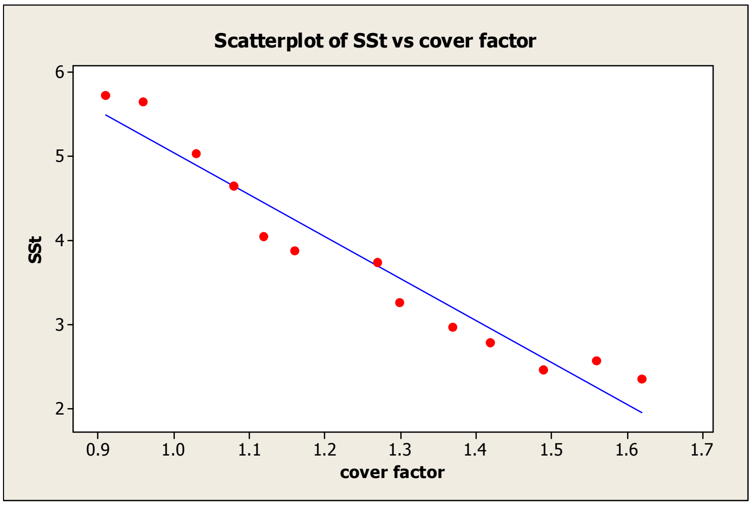


Figure 4.31.Top spreading speed versus cover factor in 100% bamboo-knitted fabrics

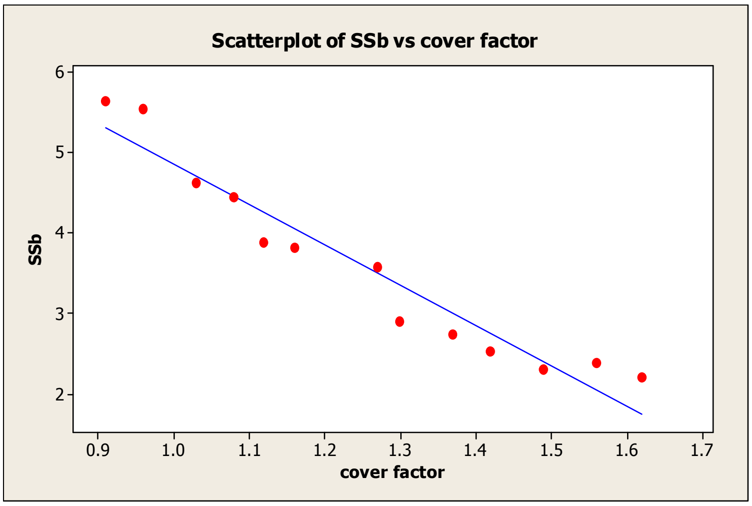


Figure 4.32.Bottom spreading speed versus cover factor in 100% bamboo-knitted fabrics

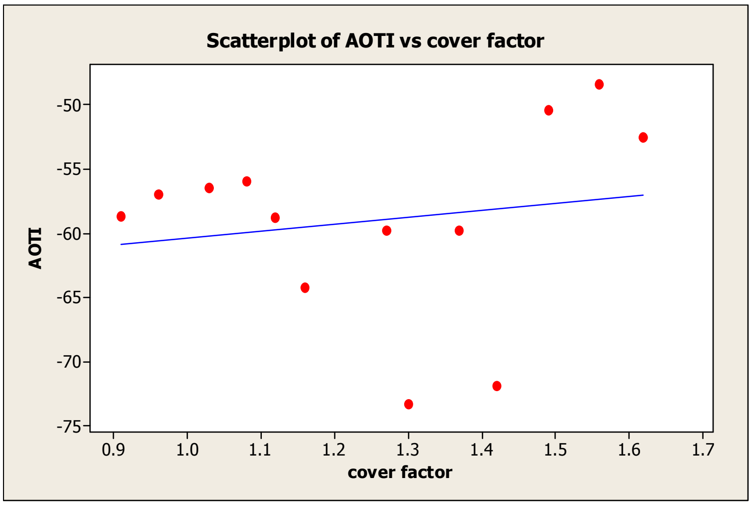
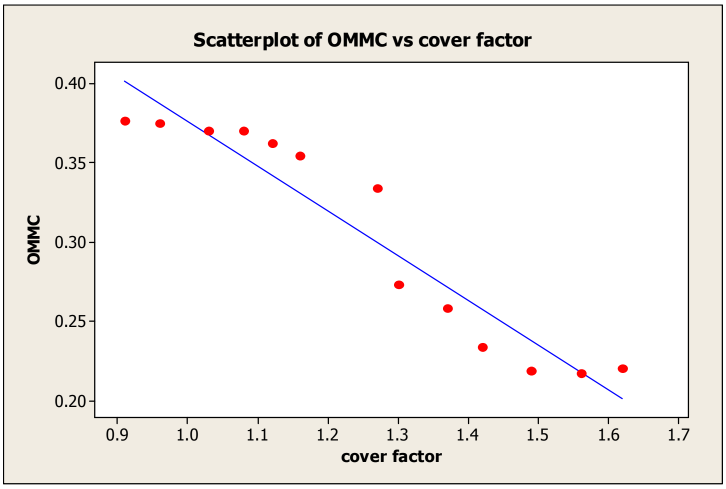


Figure 4.33.Accumulative one-way transport index versus cover factor in 100% bamboo-knitted fabrics



4.34. Overall moisture management capacity versus cover factor in 100% bamboo-knitted fabrics

Pearson correlations between the cover factor and moisture management properties indices are given in Table 4.14. It can be seen that almost all correlations between the cover factor and the indices are linearly related since the Pearson correlations are close to +1 or -1. This indicates that for 100% bamboo single jersey fabrics, with a cover factor from 0.91 to 1.62, the cover factor influenced the overall moisture management fabric properties.

It is also means that regression analysis can be used to determine the relationship between the cover factor and the indices, except for the cover factor and the accumulative one-way transfer index (AOTI) where the correlations were not significant.

Table 4.14.Pearson correlations of cover factor versus MMT indices of 100% bamboo-knitted fabrics

No	**Predictors, responses**	**Pearson correlations**
1	*CF, WTt*	0.967*
2	*CF, WTb*	0.974*
3	*CF, ARt*	-0.967*
4	*CF, ARb*	-0.840*
5	*CF, MWRt*	-0.947*
6	*CF, MWRb*	-0.920*
7	*CF, SSt*	-0.971*
8	*CF, SSb*	-0.965*
9	*CF, AOTI*	0.168
10	*CF, OMMC*	-0.954*

* Linearly related

Pearson correlations between structural properties and moisture management properties indices are given in Table 4.15. It can be seen that almost all of the correlations between the physical and structural properties and the indices are linearly related since the Pearson correlations are close to +1 or -1. This indicated that for 36.66 Tex 100% bamboo single jersey fabrics physical and structural properties influence the fabric moisture management result.

Table 4.15.Pearson correlations between structural properties and MMT indices of 100% bamboo-knitted fabrics

Bamboo		Weight	Thickness	Porosity	Optical porosity
Liquid Moisture Transfer					
	WTt	0.899	0.860	-0.903	-0.893
	WTb	0.929	0.895	-0.927	-0.919
	ARt	-0.620	-0.634	0.584	0.640
	ARb	-0.603	-0.625	0.565	0.615
	MWRt	-0.855	-0.869	0.824	0.864
	MWRb	-0.836	-0.881	0.786	0.845
	SSt	-0.909	-0.954	0.863	0.916
	SSb	-0.903	-0.952	0.854	0.909
	AOTI	0.290	0.193	-0.317	-0.304
	OMMC	-0.907	-0.907	0.875	0.913

4.1.3 Preliminary experiment analysis

From the preliminary experiment, using two different types of fibres and several cover factors in each fabric, the results are as follows:

- The moisture liquid transfer performance of 100% wool-knitted fabrics was not influenced by the cover factor.
- The moisture liquid transfer performance of 100% wool-knitted fabrics was not influenced by physical and structural properties.
- The moisture liquid transfer performance of 100% bamboo-knitted fabrics was influenced by the cover factor. The overall moisture management capacity of 100% bamboo-knitted fabrics decreased as the cover factor increased (Pearson correlation: 0.954, Table 4.14 and Figure 4.34).
- The moisture liquid transfer performance of 100% bamboo-knitted fabrics was influenced by physical and structural properties. As the fabric weight and thickness increased (Pearson correlation: -0.907), the overall moisture management capacity of 100% bamboo-knitted fabrics decreased and as the fabric porosity and optical porosity increased, the overall moisture management capacity of 100% bamboo-knitted fabrics also increased (Pearson correlations: 0.875 and 0.913) (Table 4.15).
- The moisture liquid transfer performance and fabric classification of 100% wool-knitted fabrics are different from those of 100% bamboo-knitted fabrics. All 100% wool-knitted fabrics were classified as water-penetration fabrics. One hundred per cent bamboo-knitted fabrics with a cover factor range from 0.91 to 1.30 were classified as a fast-absorbing and quick-drying fabric. One hundred per cent bamboo-

knitted fabrics with a cover factor range from 1.37 to 1.62 were classified as fast-absorbing and slow-drying fabrics.

The results of the preliminary experiment produced important information that could be used in the final experiment:

- The cover factor was influenced by loop length.
- Since the cover factor is the function of loop length and yarn count (Tex), fabric cover factor was influenced by loop length. For wool-knitted fabrics Pearson correlations were -0.991 (Table 4.2) and for bamboo-knitted fabrics Pearson correlations were -0.987 (Table 4.9). The relationships between the cover factor and loop length are as the cover factor increased, the loop length decreased (Figure 4.7 and Figure 4.24).
- The cover factor influenced the liquid moisture performance of the fabric, depending on the fibre used, so that in the final experiment, the cover factor of the experimental fabrics should be similar or as close as possible to prevent the influence of the cover factor.
- Physical and structural properties influenced the liquid moisture performance of fabrics, depending on the fibre used.

4.2. Commercial and experimental samples

Five commercial samples were selected and nine experimental samples were produced. All the samples were tested to find out their physical, structural and comfort properties. The comfort properties of fabrics were measured for thermophysiological comfort properties and sensorial comfort properties.

4.2.1. Structural and physical properties

The test results of structural and physical properties of five commercial samples of base layer winter active sportswear are given in Table 4.16. Fabric MRWB has the highest weight and is also the thickest among all commercial samples. Fabric MGW is the thinnest fabric.

Table 4.16.Structural and physical properties of commercial samples

No	Fabric	Fibre	Blend ratio	Construction	Weight (g/m2)	Optical porosity (%)	Thickness (mm)
1	MBW	Wool	100	single jersey	151.80	11.78	0.54
2	MGW	Wool	100	single jersey	165.60	12.37	0.43
3	MRWB	Wool; Bamboo	52:48	two layer, interlock	253.00	9.27	0.90
4	MGWP	Wool; Polyester	60:40	two layer interlock	161.80	13.05	0.82
5	FGNE	Nylon; Elastane	92:8	single jersey	214.20	3.65	0.80

The test results of structural and physical properties of nine experimental fabrics intended for base layer winter active sportswear are given in Table 4.17. The fabrics were tested after being scoured. All the fabrics have a single jersey structure. Since the fabrics were produced especially for the present research, the weight, thickness and cover factor were controlled within a certain range to avoid weight, thickness and cover factor effects on the final results.

Table 4.17.Structural and physical properties of experimental fabrics

No	Fabric	Fibre	Yarn count Tex	Blend ratio	Weight (g/m^2)	Thickness (mm)	Porosity (%)	Optical porosity (%)	Loop length mm	Cover factor
1	P100	Polyester	44.40	100	220.00	0.77	79.24	5.01	3.44	1.93
2	W43P57	Wool; Polyester	38.90	43:57	222.60	0.75	78.14	7.89	3.38	1.85
3	W48P52	Wool; Polyester	42.20	48:52	236.80	0.75	76.76	6.37	3.46	1.88
4	W71P29	Wool; Polyester	38.90	61:29	225.80	0.72	73.84	6.08	3.54	1.76
5	W100	Wool	40.00	100	204.40	0.72	78.37	6.39	3.61	1.75
6	W35B65	Wool; Bamboo	56.60	35:65	270.20	0.83	67.01	8.47	4.39	1.71
7	W52B48	Wool; Bamboo	38.30	52:48	210.00	0.74	73.56	13.91	3.72	1.67
8	W60B40	Wool; Bamboo	46.10	60:40	236.80	0.75	71.76	9.91	3.90	1.74
9	B100	Bamboo	36.60	100	220.00	0.69	60.26	11.84	3.68	1.65

One-way ANOVA was conducted to find out the differences between the samples. For sample weight, there was sufficient evidence at the 5% level of significance to conclude that at least one sample weight is different from other weight samples. The same result occurred in sample thickness, where there was sufficient evidence at the 5% level of significance to conclude that at least one of sample thickness was different from the other.

The results of ANOVA show that experimental samples exhibit a difference in weight and thickness, even though the sample production was controlled to produce similar weight and thickness. The difference within the sample is probably due to the sample fabric W35B65 being made of 56.6 Tex yarn, the thickest of all yarn counts. Since the machine parameter that can be controlled in fabric production is loop length that influences the cover factor, fabric W35B65 is relatively heavier and has the highest thickness of all fabrics.

4.2.2. Thermophysiological comfort properties

Thermophysiological properties of commercial and experimental samples were measured for the following properties: liquid moisture transfer, fabric classification in terms of moisture management properties, thermal conductivity and warm/cool feeling generated by them.

4.2.2.1 Liquid moisture transfer properties

Liquid moisture transfer test results of commercial and experimental samples in value are given in Table 4.18, while liquid moisture transfer test results of commercial experimental samples in grade are given in Table 4.19.

Table 4.18.MMT results in value of commercial and experimental samples

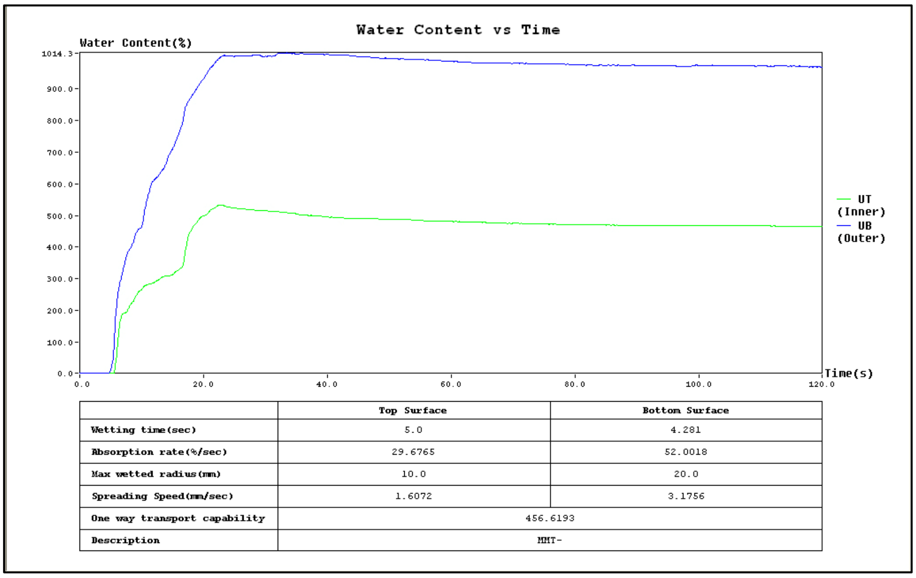
No	Fabric	WTt (sec)	WTb (sec)	ARt (%/sec)	ARb (%/sec)	MWRt (mm)	MWRb (mm)	SSt (mm/sec)	SSb (mm/sec)	AOTI (%)	OMMC
1	FGNE	9.72	103.35	290.05	45.06	5.00	0.83	0.54	0.04	-962.44	0.04
2	MBW	119.95	6.05	0.00	66.77	0.00	5.00	0.00	0.81	1084.42	0.66
3	MGW	17.43	8.15	39.58	80.17	18.00	18.00	0.95	1.10	232.94	0.51
4	MGWP	4.04	3.44	52.99	57.30	20.00	21.00	3.68	4.09	125.98	0.57
5	MRWB	6.39	4.22	39.30	50.64	13.00	15.00	1.60	2.37	313.64	0.63
6	P100	5.65	5.21	35.68	53.31	14.00	16.00	1.72	2.31	328.51	0.64
7	W43P57	24.15	7.35	24.97	54.40	16.00	17.00	0.78	1.36	620.55	0.65
8	W48P52	8.62	15.56	73.46	82.28	14.00	14.00	1.21	1.29	-118.83	0.26
9	W71P29	7.16	89.88	216.56	102.05	5.00	3.00	0.69	0.04	-591.28	0.12
10	W100	119.95	6.57	0.00	69.92	0.00	5.00	0.00	0.77	1052.22	0.67
11	W60B40	4.42	2.89	36.16	49.42	18.33	20.83	3.65	4.41	242.22	0.69
12	W52B48	4.31	4.25	106.86	65.23	17.00	20.00	3.22	4.49	427.76	0.89
13	W35B65	3.56	3.34	36.92	47.57	15.00	15.00	2.71	2.74	171.78	0.50
14	B100	4.09	4.29	49.34	49.23	15.00	15.00	2.31	2.21	-45.06	0.22

Table 4.19.MMT results in grade of commercial and experimental sample fabrics

No	Fabric	WTt	WTb	ARt	ARb	MWRt	MWRb	SSt	SSb	AOTI	OMMC
1	FGNE	3.5	1.0	5.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
2	MBW	1.0	3.5	1.0	4.0	1.0	1.0	1.0	1.0	5.0	4.0
3	MGW	2.5	3.5	3.0	4.0	4.0	4.0	1.0	1.5	3.5	3.0
4	MGWP	4.0	4.5	3.5	3.5	4.0	4.0	4.5	5.0	2.5	3.5
5	MRWB	3.5	4.0	3.0	3.5	3.0	3.0	2.0	3.0	4.0	3.5
6	P100	3.5	3.5	3.0	3.5	3.0	3.0	2.0	2.5	4.0	3.5
7	W43P57	2.5	3.5	2.5	4.0	3.0	3.0	1.0	1.5	5.0	3.5
8	W48P52	3.5	3.0	4.0	3.5	3.0	3.0	1.0	2.0	1.0	1.0
9	W71P29	3.5	2.0	5.0	3.0	1.0	1.0	1.0	1.0	1.0	1.0
10	W100	1.0	3.5	1.0	4.0	1.0	1.0	1.0	1.0	5.0	4.0
11	W60B40	3.5	5.0	2.0	3.5	3.0	4.0	3.5	5.0	5.0	5.0
12	W52B48	4.0	5.0	2.5	3.5	3.0	4.0	3.5	5.0	5.0	5.0
13	W35B65	4.3	4.5	3.0	3.5	3.0	3.0	3.3	3.0	3.3	3.0
14	B100	4.0	4.0	3.5	3.5	3.0	3.0	3.0	2.5	1.5	1.5

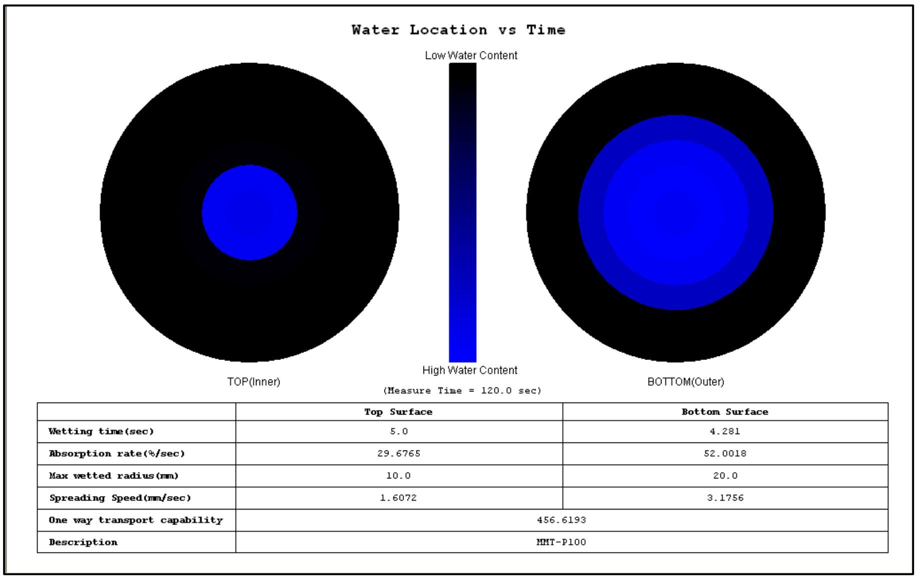
The water content at the samples' top surface (inner or next to the skin) and bottom surface (outer or next to the environment) at the testing presented in the diagram of water content versus time (Figures 4.35, 4.37,4.39, 4.41, 4.43, 4.45, 4.47, 4.49, 4.61). Water content at the bottom surface is represented by a blue line and water content at the top surface is represented by a green line. Separate diagrams were generated for the water content versus time of each different sample fabric and the diagrams depict different behaviour of water in different samples.

In sample fabrics P100, W43P57, W35B65, W52B48, W60B40, MGW, MRWB and MGWP the water content of the outer surface is higher than those of on the inner surface. This indicates that water from the inner surface has been transported to the outer surface and the inner surface is drier than the outer surface. As the outer surface has higher water content, the water of the outer surface spreads into the larger area with a relatively high spreading speed compared to that of the inner surface. How large the water spread is in the sample can be seen in the diagram of water location versus time (Figures 4.36, 4.38, 4.40, 4.42, 4.44, 4.46, 4.48, 4.60 4.62). This spread correlates with the maximum wetted radius index.



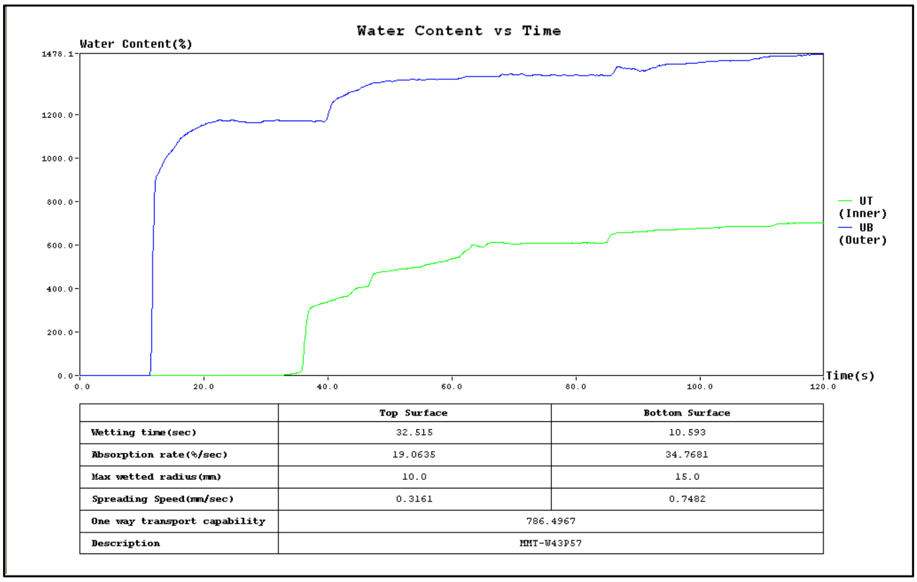
	Top Surface	Bottom Surface
Wetting time(sec)	5.0	4.281
Absorption rate(%/sec)	29.6765	52.0018
Max wetted radius(mm)	10.0	20.0
Spreading Speed(mm/sec)	1.6072	3.1756
One way transport capability	456.6193	
Description	MMT-	

Figure 4.35.Water content vs time of P100



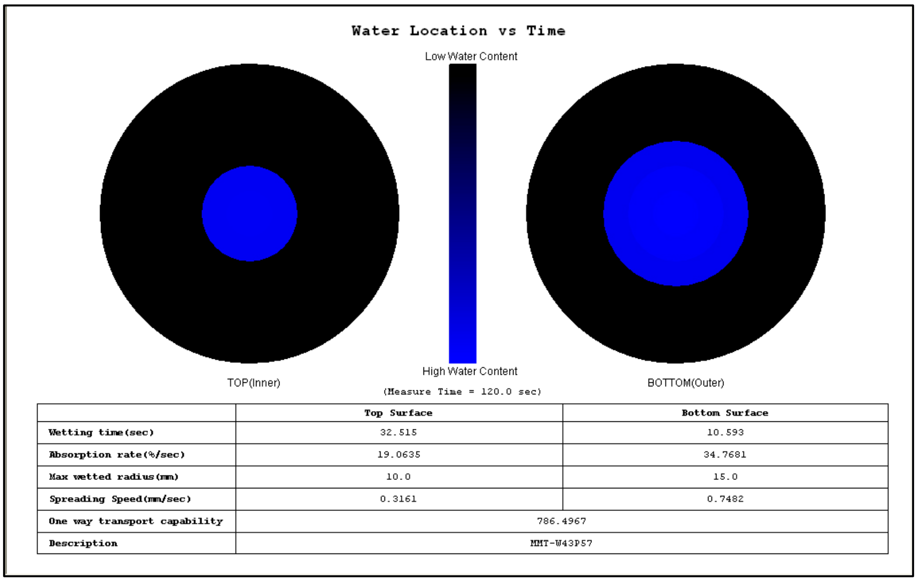
	Top Surface	Bottom Surface
Wetting time(sec)	5.0	4.281
Absorption rate(%/sec)	29.6765	52.0018
Max wetted radius(mm)	10.0	20.0
Spreading Speed(mm/sec)	1.6072	3.1756
One way transport capability	456.6193	
Description	MMT-P100	

Figure 4.36.Water location vs time of P100



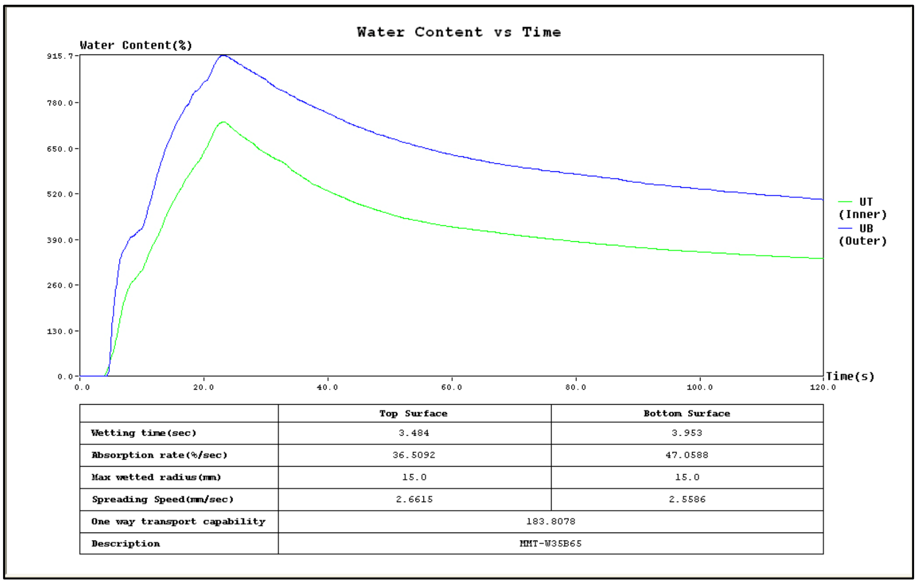
	Top Surface	Bottom Surface
Wetting time(sec)	32.515	10.593
Absorption rate(%/sec)	19.0635	34.7681
Max wetted radius(mm)	10.0	15.0
Spreading Speed(mm/sec)	0.3161	0.7482
One way transport capability	786.4967	
Description	MMT-W43P57	

Figure 4.37.Water content vs time of W43P57



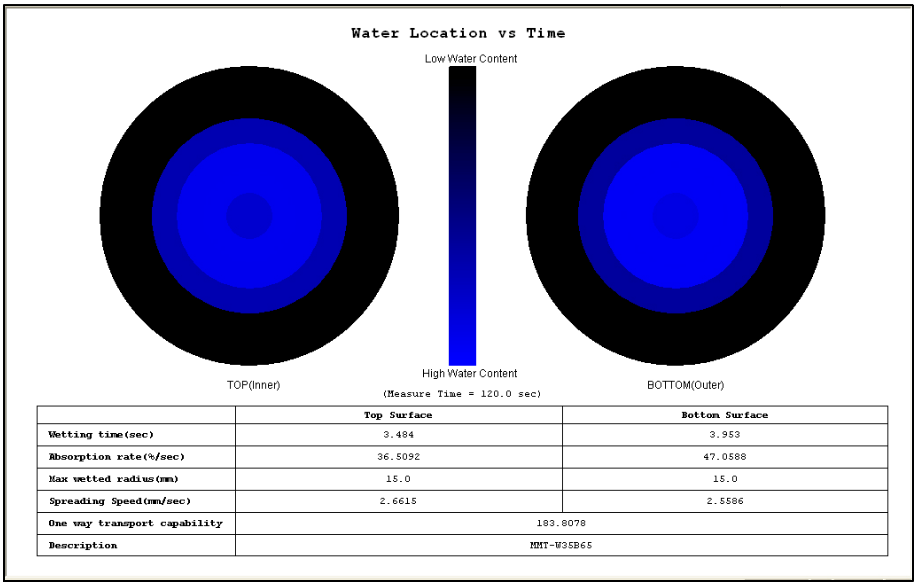
	Top Surface	Bottom Surface
Wetting time(sec)	32.515	10.593
Absorption rate(%/sec)	19.0635	34.7681
Max wetted radius(mm)	10.0	15.0
Spreading Speed(mm/sec)	0.3161	0.7482
One way transport capability	786.4967	
Description	MMT-W43P57	

Figure 4.38.Water location vs time of W43P57



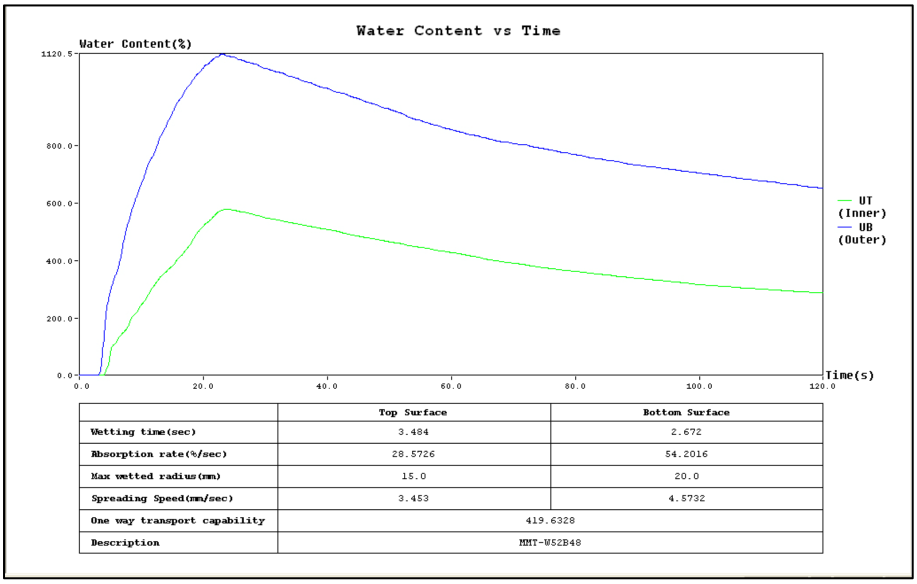
	Top Surface	Bottom Surface
Wetting time(sec)	3.484	3.953
Absorption rate(%/sec)	36.5092	47.0588
Max wetted radius(mm)	15.0	15.0
Spreading Speed(mm/sec)	2.6615	2.5586
One way transport capability	183.8078	
Description	MMT-W35B65	

Figure 4.39.Water content vs time of W35B65



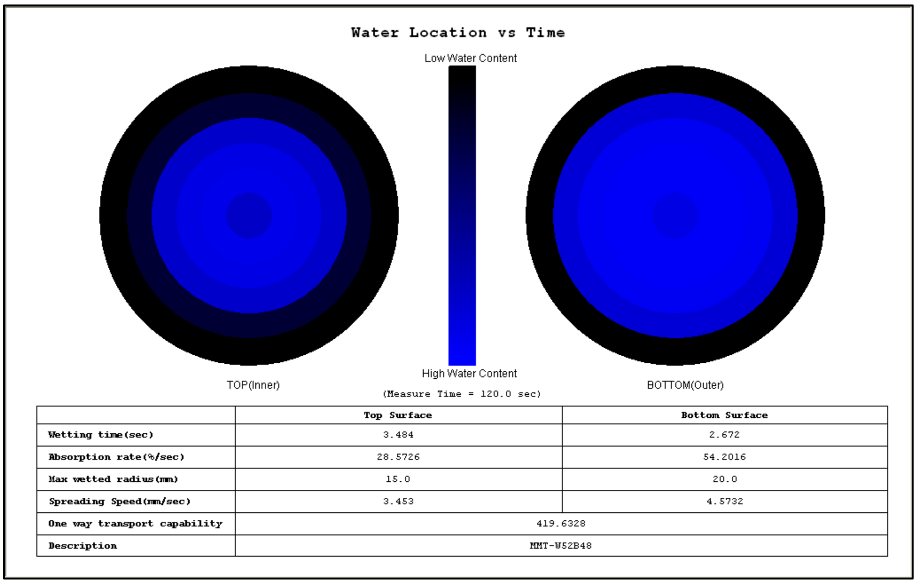
	Top Surface	Bottom Surface
Wetting time(sec)	3.484	3.953
Absorption rate(%/sec)	36.5092	47.0588
Max wetted radius(mm)	15.0	15.0
Spreading Speed(mm/sec)	2.6615	2.5586
One way transport capability	183.8078	
Description	MMT-W35B65	

Figure 4.40.Water location vs time of W35B65



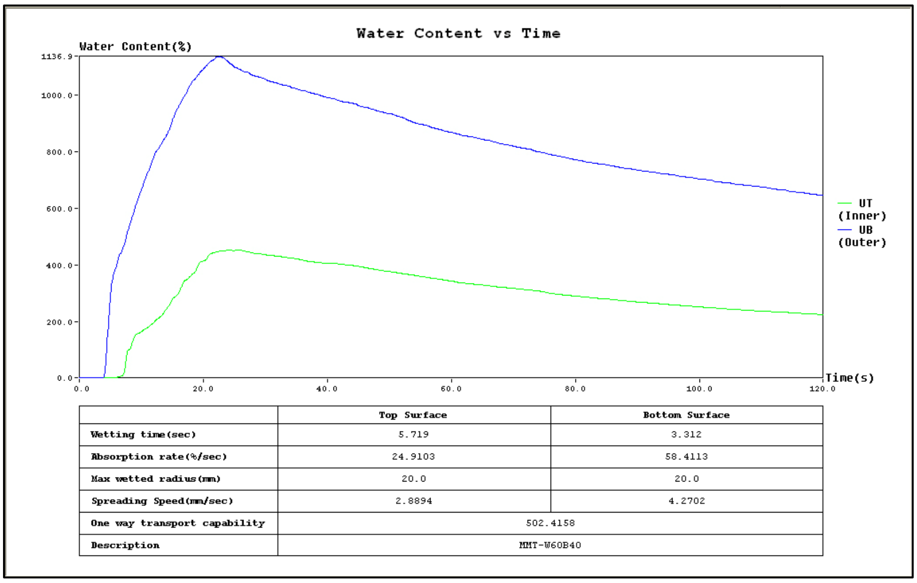
	Top Surface	Bottom Surface
Wetting time(sec)	3.484	2.672
Absorption rate(%/sec)	28.5726	54.2016
Max wetted radius(mm)	15.0	20.0
Spreading Speed(mm/sec)	3.453	4.5732
One way transport capability	419.6328	
Description	MMT-W52B48	

Figure 4.41.Water content vs time of W52B48



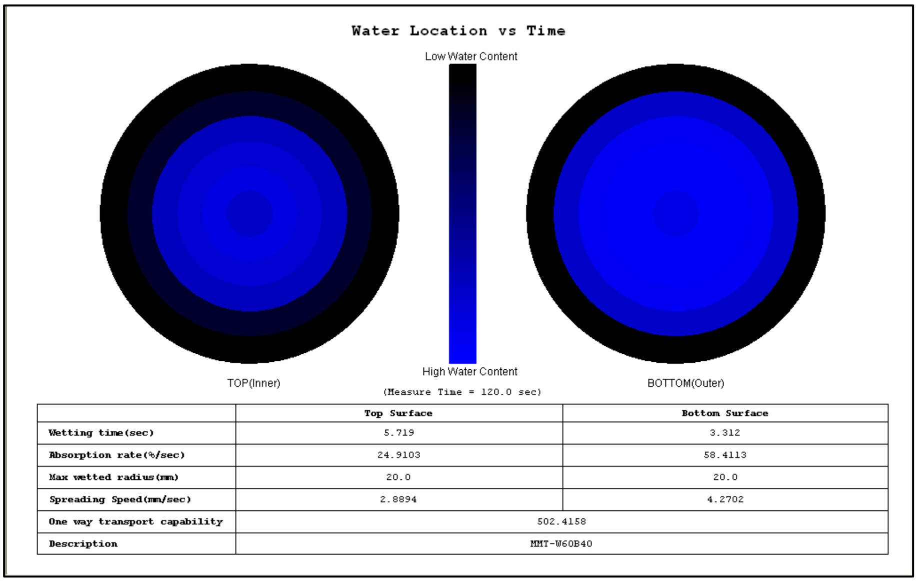
	Top Surface	Bottom Surface
Wetting time(sec)	3.484	2.672
Absorption rate(%/sec)	28.5726	54.2016
Max wetted radius(mm)	15.0	20.0
Spreading Speed(mm/sec)	3.453	4.5732
One way transport capability	419.6328	
Description	MMT-W52B48	

Figure 4.42.Water location vs time of W52B48



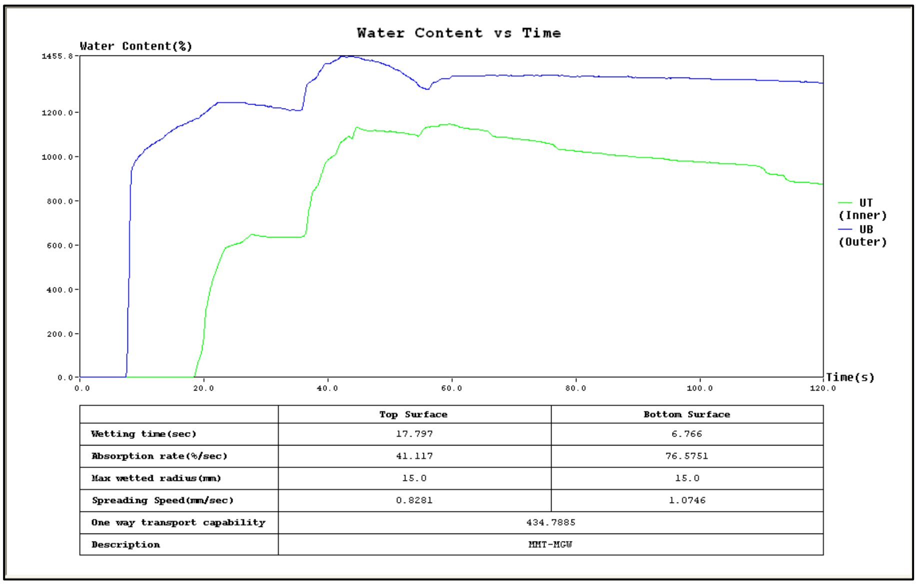
	Top Surface	Bottom Surface
Wetting time(sec)	5.719	3.312
Absorption rate(%/sec)	24.9103	58.4113
Max wetted radius(mm)	20.0	20.0
Spreading Speed(mm/sec)	2.8894	4.2702
One way transport capability	502.4158	
Description	MMT-W60B40	

Figure 4.43.Water content vs time of W60B40



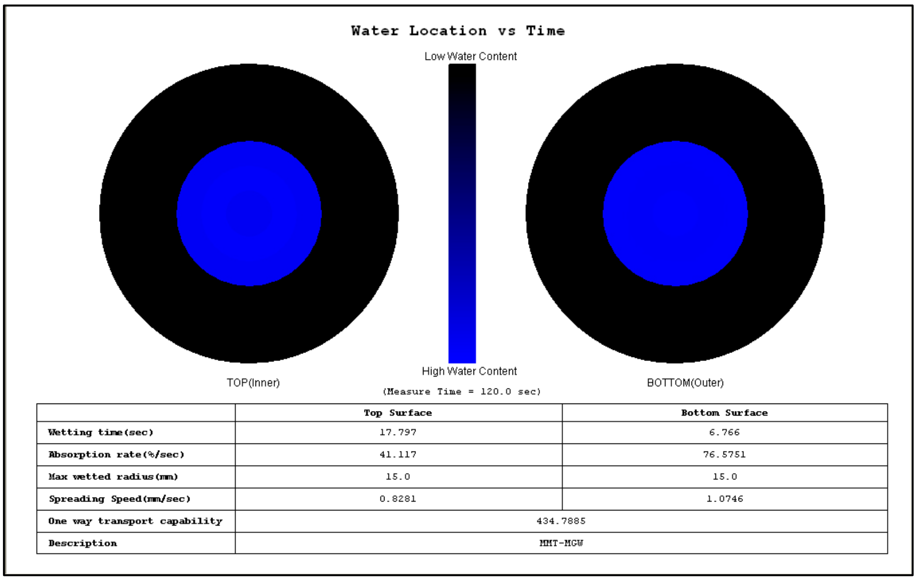
	Top Surface	Bottom Surface
Wetting time(sec)	5.719	3.312
Absorption rate(%/sec)	24.9103	58.4113
Max wetted radius(mm)	20.0	20.0
Spreading Speed(mm/sec)	2.8894	4.2702
One way transport capability	502.4158	
Description	MMT-W60B40	

Figure 4.44.Water location vs time of W60B40



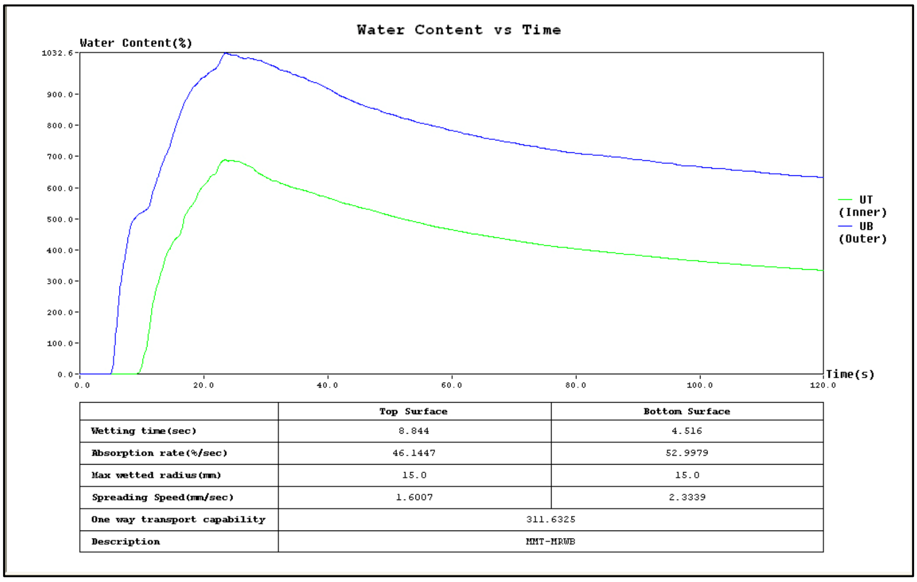
	Top Surface	Bottom Surface
Wetting time(sec)	17.797	6.766
Absorption rate(%/sec)	41.117	76.5751
Max wetted radius(mm)	15.0	15.0
Spreading Speed(mm/sec)	0.8281	1.0746
One way transport capability	434.7885	
Description	MMT-MGW	

Figure 4.45.Water content vs time of MGW



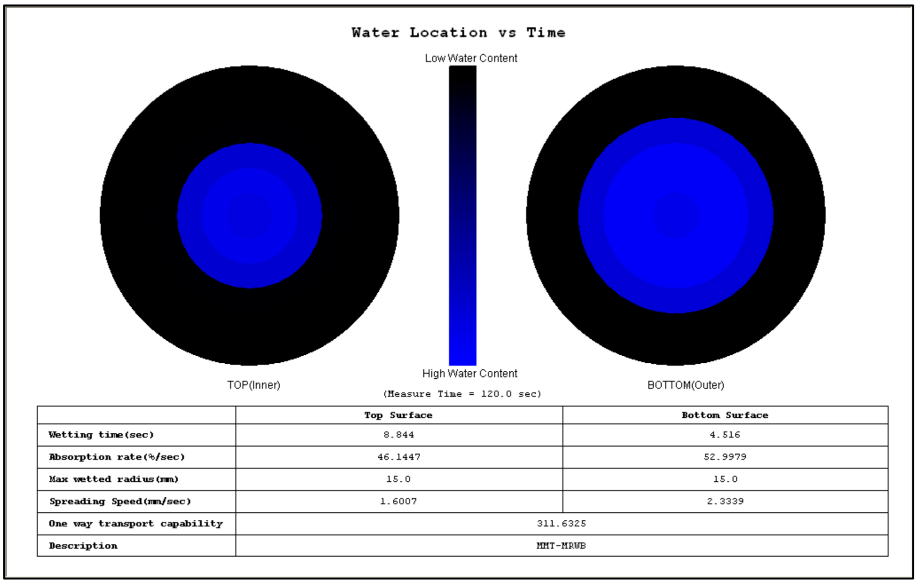
	Top Surface	Bottom Surface
Wetting time(sec)	17.797	6.766
Absorption rate(%/sec)	41.117	76.5751
Max wetted radius(mm)	15.0	15.0
Spreading Speed(mm/sec)	0.8281	1.0746
One way transport capability	434.7885	
Description	MMT-MGW	

Figure 4.46.Water location vs time of MGW



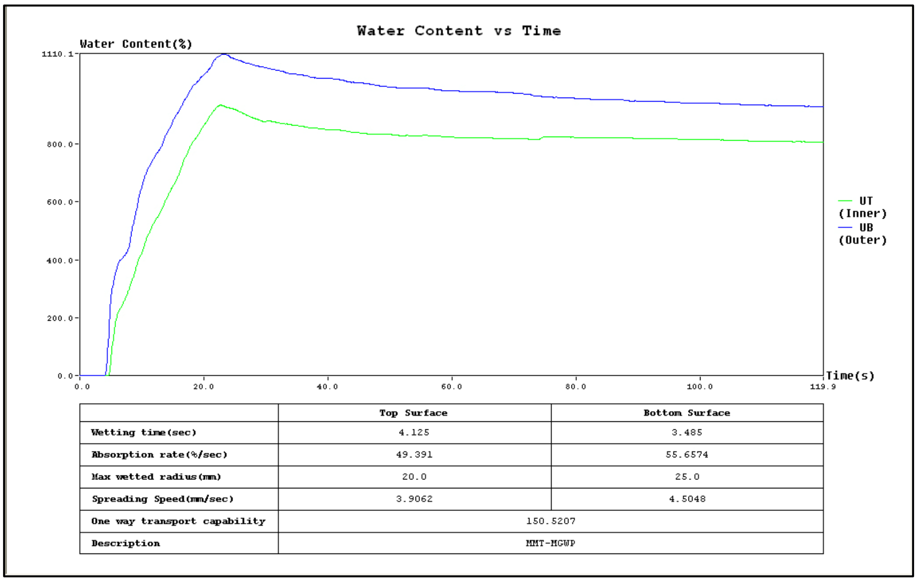
	Top Surface	Bottom Surface
Wetting time(sec)	8.844	4.516
Absorption rate(%/sec)	46.1447	52.9979
Max wetted radius(mm)	15.0	15.0
Spreading Speed(mm/sec)	1.6007	2.3339
One way transport capability	311.6325	
Description	MMT-MRWB	

Figure 4.47.Water content vs time of MRWB



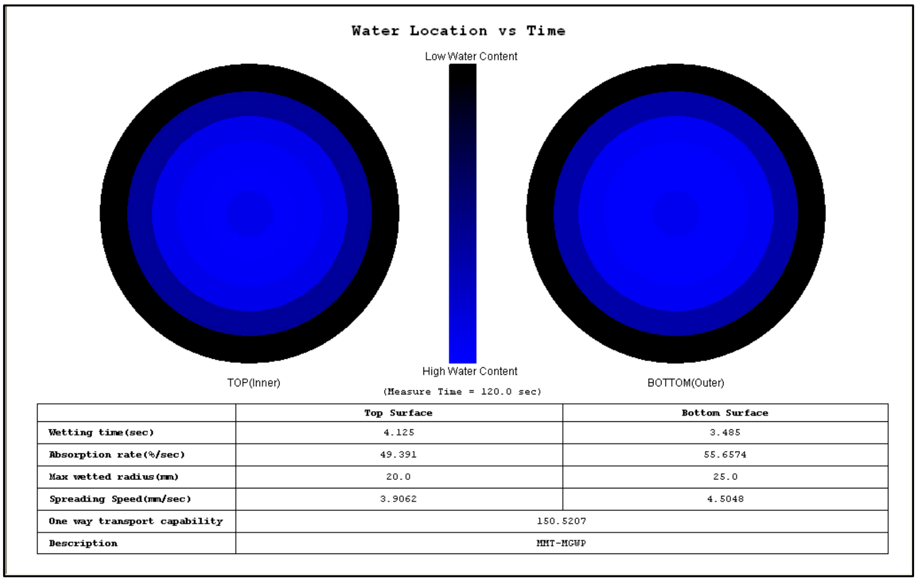
	Top Surface	Bottom Surface
Wetting time(sec)	8.844	4.516
Absorption rate(%/sec)	46.1447	52.9979
Max wetted radius(mm)	15.0	15.0
Spreading Speed(mm/sec)	1.6007	2.3339
One way transport capability	311.6325	
Description	MMT-MRWB	

Figure 4.48.Water location vs time of MRWB



	Top Surface	Bottom Surface
Wetting time(sec)	4.125	3.485
Absorption rate(%/sec)	49.391	55.6574
Max wetted radius(mm)	20.0	25.0
Spreading Speed(mm/sec)	3.9062	4.5048
One way transport capability	150.5207	
Description	MMT-MGWP	

Figure 4.49.Water content vs time of MGWP

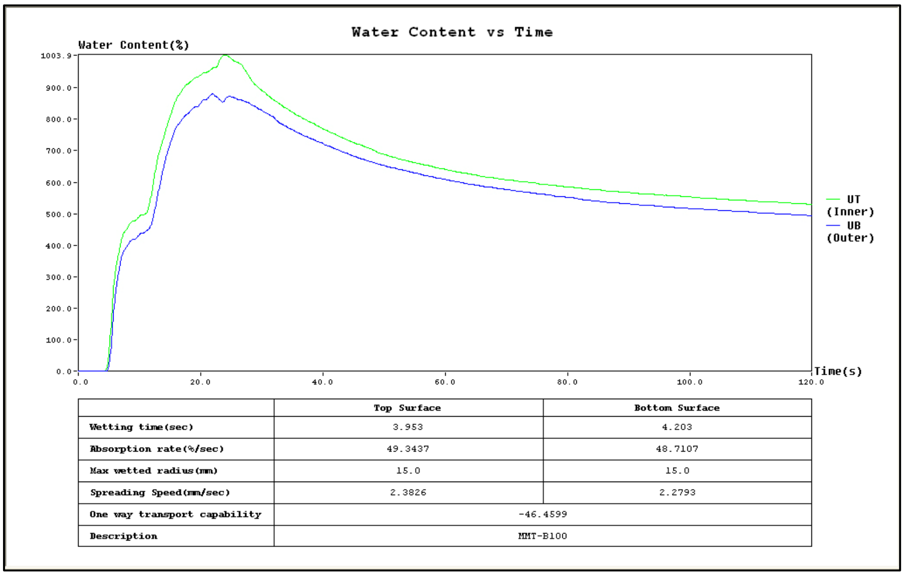


	Top Surface	Bottom Surface
Wetting time(sec)	4.125	3.485
Absorption rate(%/sec)	49.391	55.6574
Max wetted radius(mm)	20.0	25.0
Spreading Speed(mm/sec)	3.9062	4.5048
One way transport capability	150.5207	
Description	MMT-MGWP	

Figure 4.50.Water location vs time of MGWP

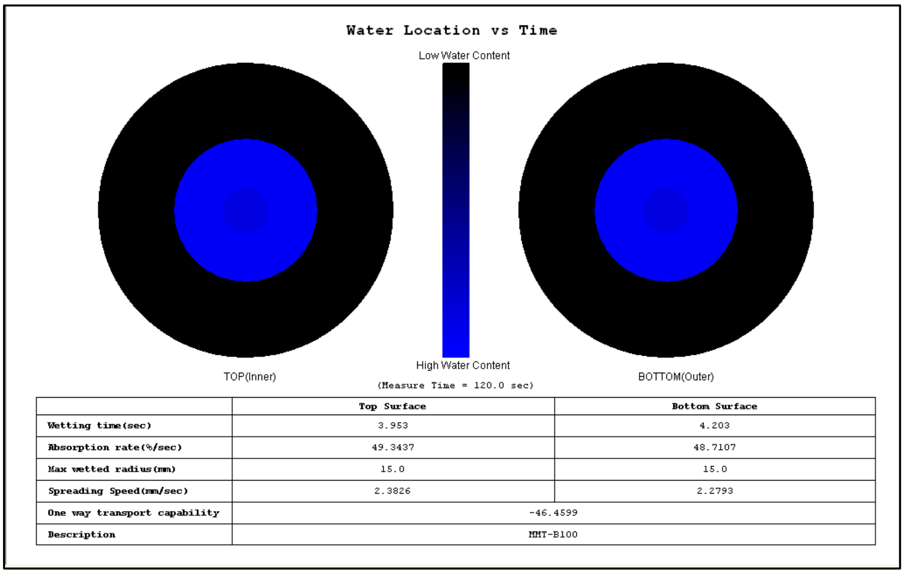
In the sample fabrics B100 and W48P52, the water content of inner surfaces is higher than those of outer surfaces. This indicates that water from the inner surface has been transported to the outer surface; however, there is still more water content at the inner surface compared to the outer surface, so that the inner surface remains wetter than the outer surface. The water solution wet the same area in the top and bottom surfaces with the spreading speed of water at the inner surface slightly higher than that of the outer surface.

Comparing the behaviour of the water solution in samples, it can be seen that the behaviour of the water solution in the sample fabrics P100, W43P57, W35B65, W52B48, W60B40, MGW, MRWB and MGWP is opposite to that of the water solution of sample fabrics B100 and W48P52.



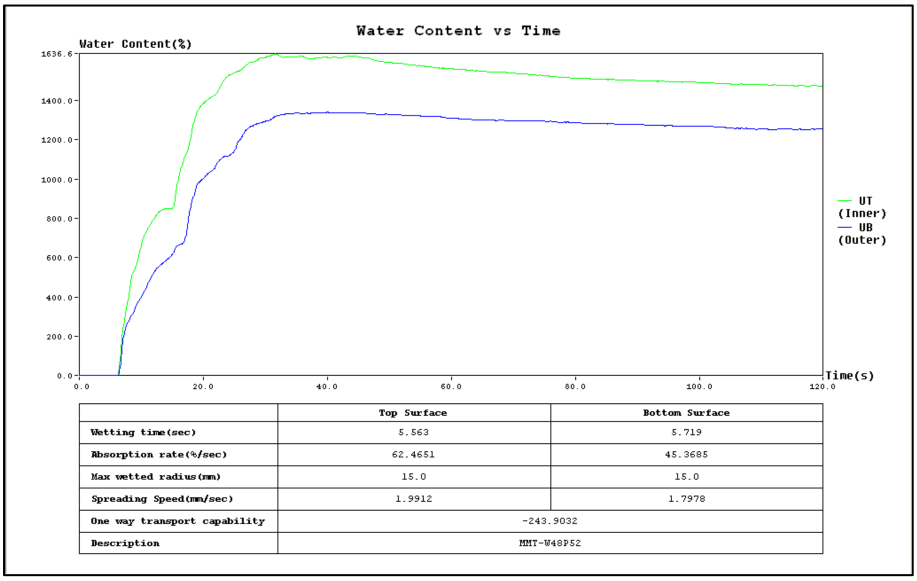
	Top Surface	Bottom Surface
Wetting time(sec)	3.953	4.203
Absorption rate(%/sec)	49.3437	48.7107
Max wetted radius(mm)	15.0	15.0
Spreading Speed(mm/sec)	2.3826	2.2793
One way transport capability	-46.4599	
Description	MMT-B100	

Figure 4.51.Water content vs time of B100



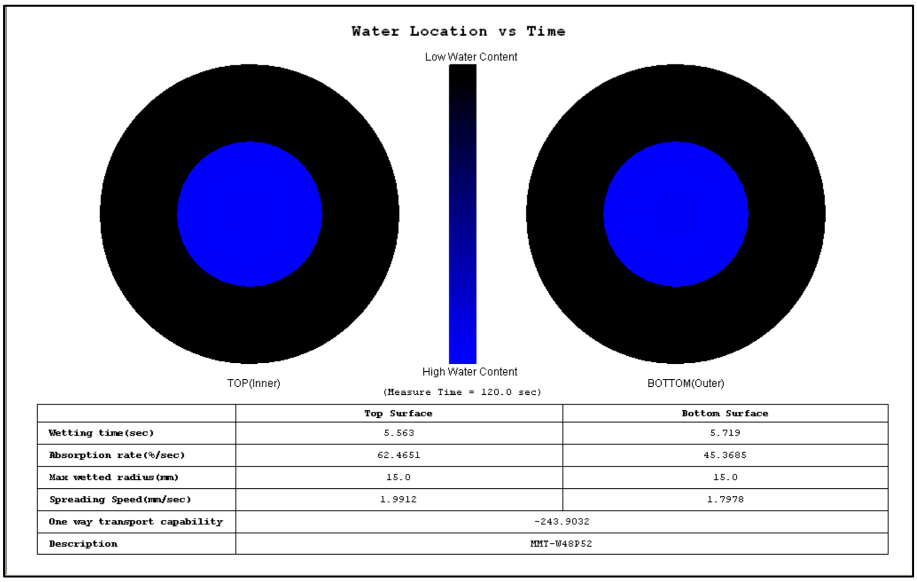
	Top Surface	Bottom Surface
Wetting time(sec)	3.953	4.203
Absorption rate(%/sec)	49.3437	48.7107
Max wetted radius(mm)	15.0	15.0
Spreading Speed(mm/sec)	2.3826	2.2793
One way transport capability	-46.4599	
Description	MMT-B100	

Figure 4.52.Water location vs time of B100



	Top Surface	Bottom Surface
Wetting time(sec)	5.563	5.719
Absorption rate(%/sec)	62.4651	45.3685
Max wetted radius(mm)	15.0	15.0
Spreading Speed(mm/sec)	1.9912	1.7978
One way transport capability	-243.9032	
Description	MMT-W48P52	

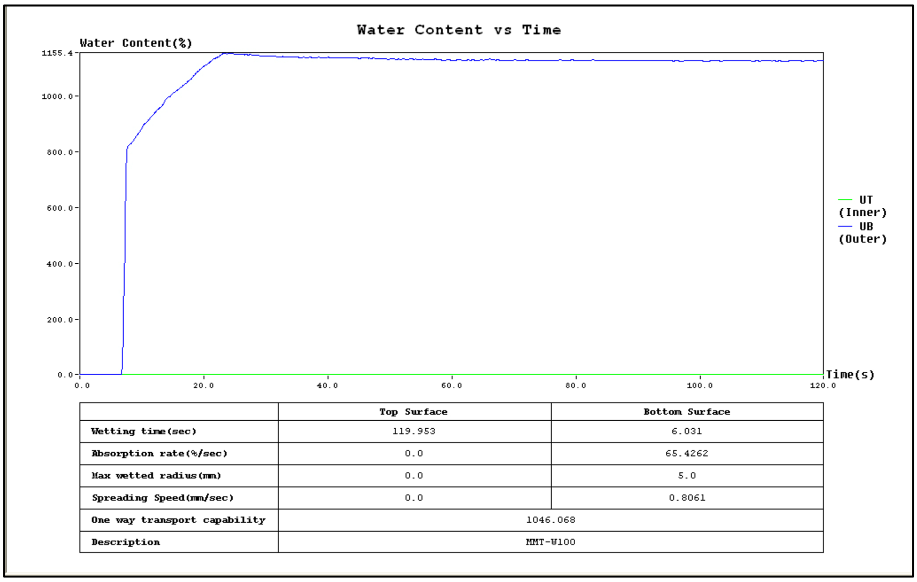
Figure 4.53.Water content vs time of W48P52



	Top Surface	Bottom Surface
Wetting time(sec)	5.563	5.719
Absorption rate(%/sec)	62.4651	45.3685
Max wetted radius(mm)	15.0	15.0
Spreading Speed(mm/sec)	1.9912	1.7978
One way transport capability	-243.9032	
Description	MMT-W48P52	

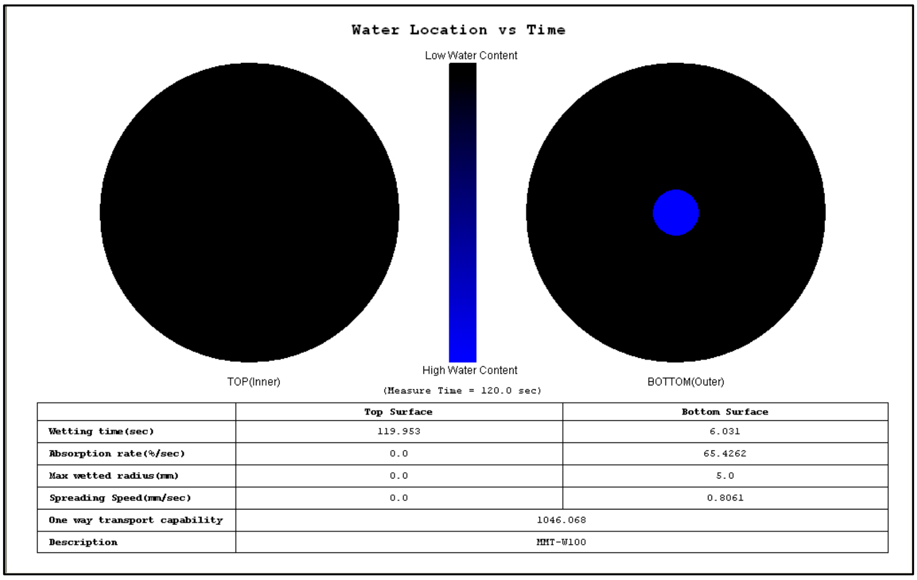
Figure 4.54.Water location vs time of W48P52

In sample fabrics W100 and MBW, the water content at the outer surface is higher than that at the inner surface, but the water content at the inner surface did not increase with time and stayed at zero (Figure 4.55) This indicates that the inner surface stayed dry for the length of the testing time (Figure 4.56), and the water solution was transported to the outer surface as soon as it dropped on the inner surface. On the outer surface, the water content rose quickly at 6 seconds and continued until it reached the peak at 20 seconds (when the pumping time finished). The water content at the outer surface did not decrease but stayed steadily at the peak until the end of the testing time. However, it had a very slow spreading speed and did not spread into the larger area.



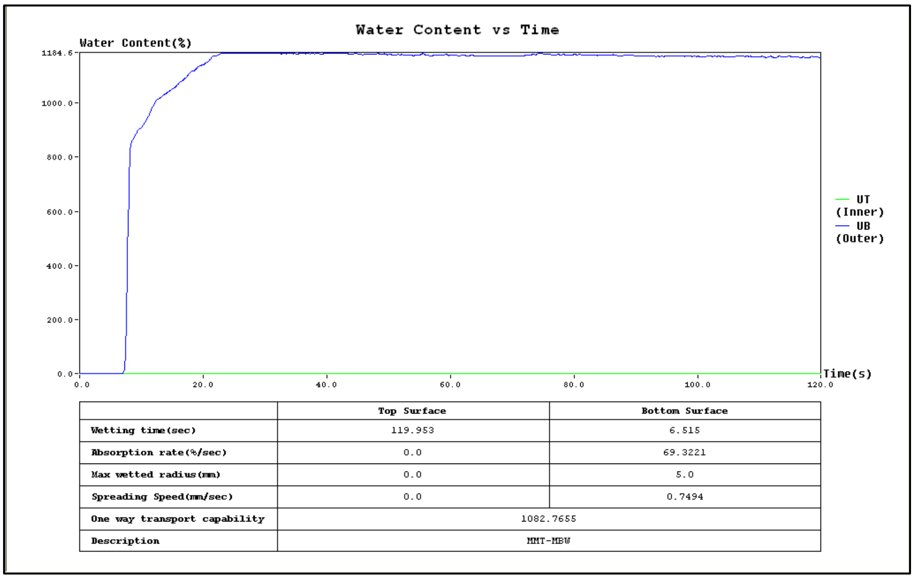
	Top Surface	Bottom Surface
Wetting time(sec)	119.953	6.031
Absorption rate(%/sec)	0.0	65.4262
Max wetted radius(mm)	0.0	5.0
Spreading Speed(mm/sec)	0.0	0.8061
One way transport capability	1046.068	
Description	MMT-W100	

Figure 4.55.Water content vs time of W100



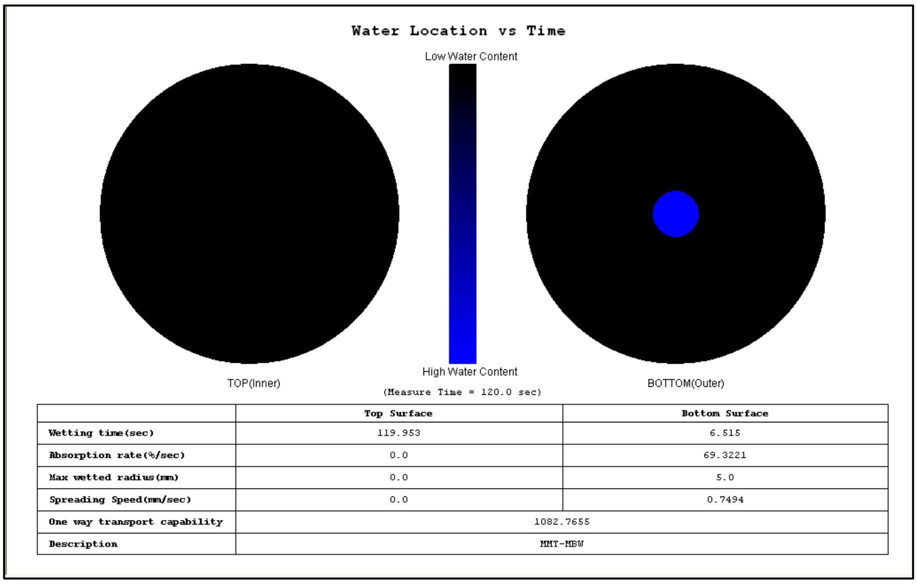
	Top Surface	Bottom Surface
Wetting time(sec)	119.953	6.031
Absorption rate(%/sec)	0.0	65.4262
Max wetted radius(mm)	0.0	5.0
Spreading Speed(mm/sec)	0.0	0.8061
One way transport capability	1046.068	
Description	MMT-W100	

Figure 4.56.Water location vs time of W100



	Top Surface	Bottom Surface
Wetting time(sec)	119.953	6.515
Absorption rate(%/sec)	0.0	69.3221
Max wetted radius(mm)	0.0	5.0
Spreading Speed(mm/sec)	0.0	0.7494
One way transport capability	1082.7655	
Description	MMT-MBW	

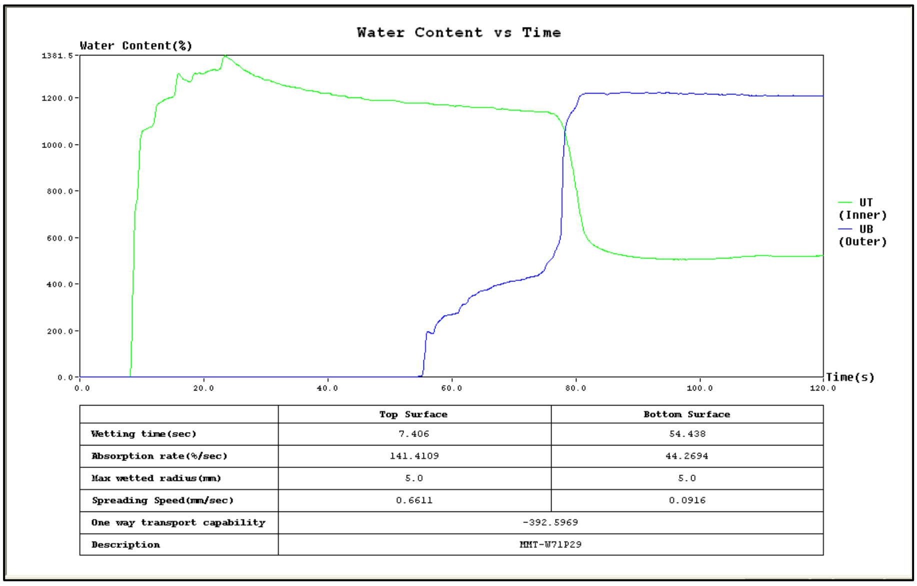
Figure 4.57.Water content vs time of MBW



	Top Surface	Bottom Surface
Wetting time(sec)	119.953	6.515
Absorption rate(%/sec)	0.0	69.3221
Max wetted radius(mm)	0.0	5.0
Spreading Speed(mm/sec)	0.0	0.7494
One way transport capability	1082.7655	
Description	MMT-MBW	

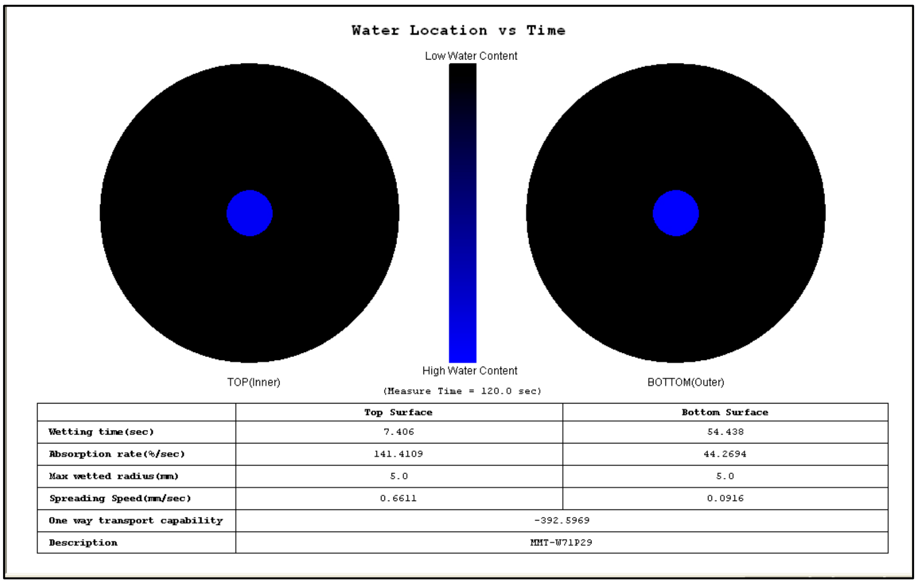
Figure 4.58.Water location vs time of MBW

In sample fabric W71P29, from the beginning of the test until approximately the middle of testing time, the water content of the inner surface was higher than that of the outer surface. After that the water content of the inner surface decreased and the water content of the outer surface increased. The absorption rate of the inner surface is higher than that of the outer layer and the water did not spread into a large area; this indicates that the spreading speed was slow.



	Top Surface	Bottom Surface
Wetting time(sec)	7.406	54.438
Absorption rate(%/sec)	141.4109	44.2694
Max wetted radius(mm)	5.0	5.0
Spreading Speed(mm/sec)	0.6611	0.0916
One way transport capability	-392.5969	
Description	MMT-W71P29	

Figure 4.59.Water content vs time of W71P29

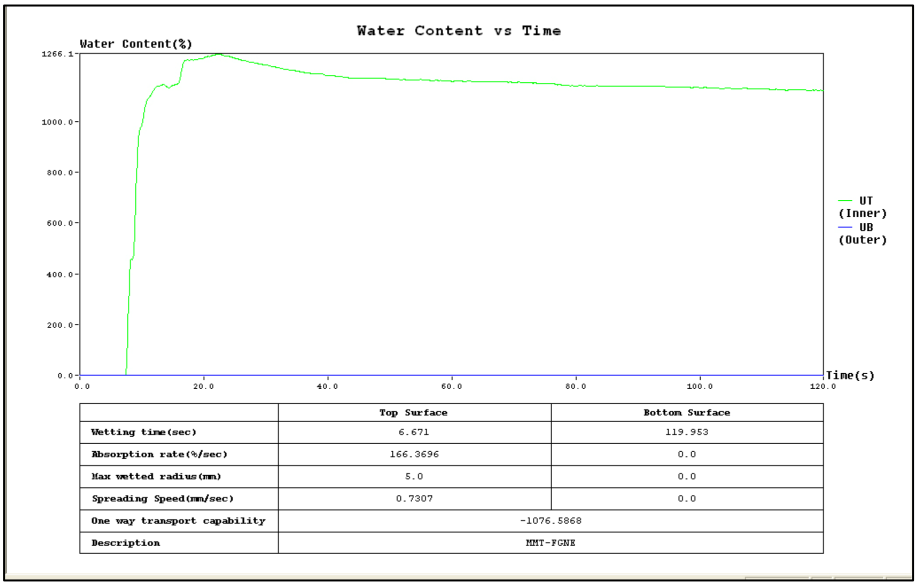


	Top Surface	Bottom Surface
Wetting time(sec)	7.406	54.438
Absorption rate(%/sec)	141.4109	44.2694
Max wetted radius(mm)	5.0	5.0
Spreading Speed(mm/sec)	0.6611	0.0916
One way transport capability	-392.5969	
Description	MMT-W71P29	

Figure 4.60.Water location vs time of W71P29

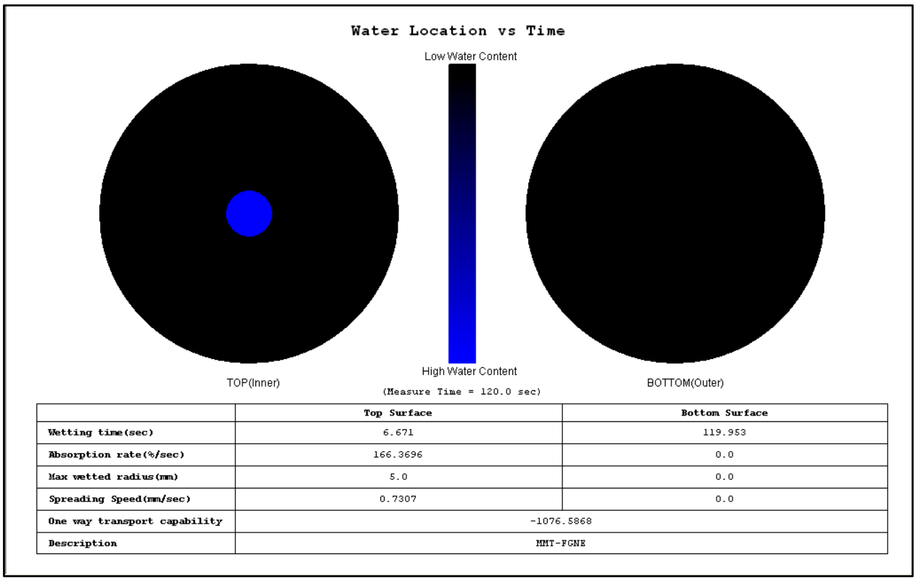
In the sample fabric FGNE the water content at the inner surface is higher than that of the outer surface but the water content at the inner surface did not increase with time and stayed at zero (Figure 4.61) This indicates that the inner surface stayed wet for the length of the testing time (Figure 4.62); the water solution was not transported to the outer surface. At the inner surface, the water content rose quickly at 6 seconds and continued until it reached the peak at 20 seconds (when the pumping time finished). The water content did not decrease but stayed steadily in the peak until the testing time finished. The water did not spread into a larger area and it had a very slow spreading speed.

Comparing the behaviour of water solution in this sample, it can be seen that the behaviour of the water solution in the sample fabrics W100 and MBW is opposite to that of the water solution of the sample fabric FGNE.



	Top Surface	Bottom Surface
Wetting time(sec)	6.671	119.953
Absorption rate(%/sec)	166.3696	0.0
Max wetted radius(mm)	5.0	0.0
Spreading Speed(mm/sec)	0.7307	0.0
One way transport capability	-1076.5868	
Description	MMT-FGNE	

Figure 4.61.Water content vs time of FGNE



	Top Surface	Bottom Surface
Wetting time(sec)	6.671	119.953
Absorption rate(%/sec)	166.3696	0.0
Max wetted radius(mm)	5.0	0.0
Spreading Speed(mm/sec)	0.7307	0.0
One way transport capability	-1076.5868	
Description	MMT-FGNE	

Figure 4.62.Water location vs time of FGNE

4.2.2.1.1 Wetting time

The mean grades of the top wetting time (WTt) and the bottom wetting time (WTb) of 14 sample fabrics (Table 4.19) are given in Figures 4.63 and 4.64. It can be seen that in non-blended sample fabrics, sample fabric P100 has a medium wetting time on the top and bottom surfaces. Sample fabric W100 has the same wetting time as P100 on the bottom surface but it has a lower grade than P100 in the top wetting time (no wetting). Sample fabric B100 has the fastest wetting time on both top and bottom surfaces due to the higher surface energy of bamboo compared to polyester and wool surface energy.

In blended fabrics, sample fabric W43P57 has the lowest top wetting time grade. As the percentage of polyester in the samples decreases, the bottom wetting time grade of the blended wool/polyester fabrics decreases as well. The top wetting time grade of the blended wool/bamboo fabrics also decreases as the percentage of bamboo fibre decreases. By contrast, as the percentage of the bamboo fibre increases, the bottom wetting time grade of the blended wool/bamboo fabrics decreases. All the wool/bamboo fabrics show a higher grade in wetting time compared with the wool/polyester fabrics. This means that wool/bamboo fabrics have a faster wetting time in both surfaces compared with the wool/polyester fabrics.

Comparing sample fabric W100 with all blended wool/polyester fabrics demonstrates that blending wool fibre with polyester fibre improved the wool top wetting time grade.

Comparing the sample fabrics W100 and B100 with all blended wool/bamboo fabrics indicates that blending wool fibre with bamboo fibre improved the 100% wool and 100% bamboo fabrics' top and bottom wetting time grade.

In commercial sample fabrics, sample fabric MGWP has the highest grade in top and bottom wetting times. Sample fabric MBW has the lowest grade in the top wetting time and sample fabric FGNE has the lowest grade in the bottom wetting time.

Of all the fabrics, sample fabric W35B65 has the fastest wetting time in the top surface (the highest grade) and the sample fabrics W60B40 and W52B48 have the fastest wetting time in the bottom surface.

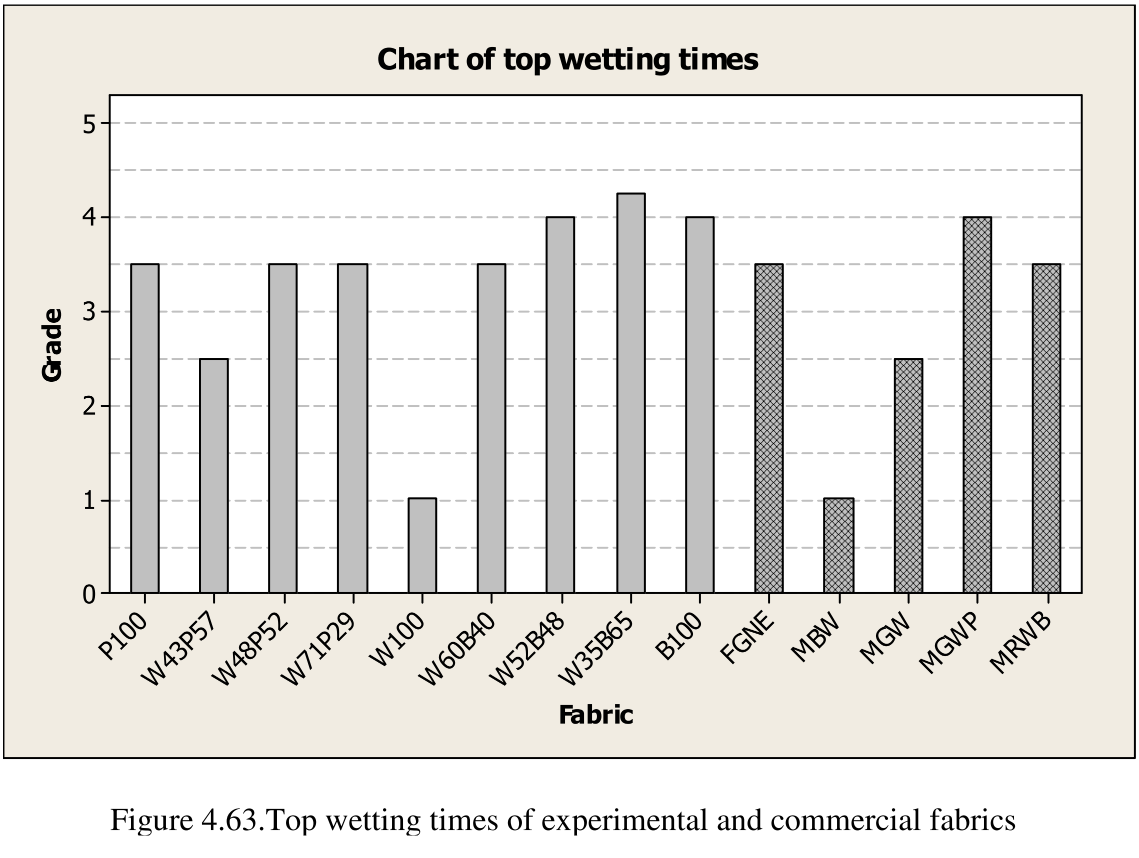


Figure 4.63.Top wetting times of experimental and commercial fabrics

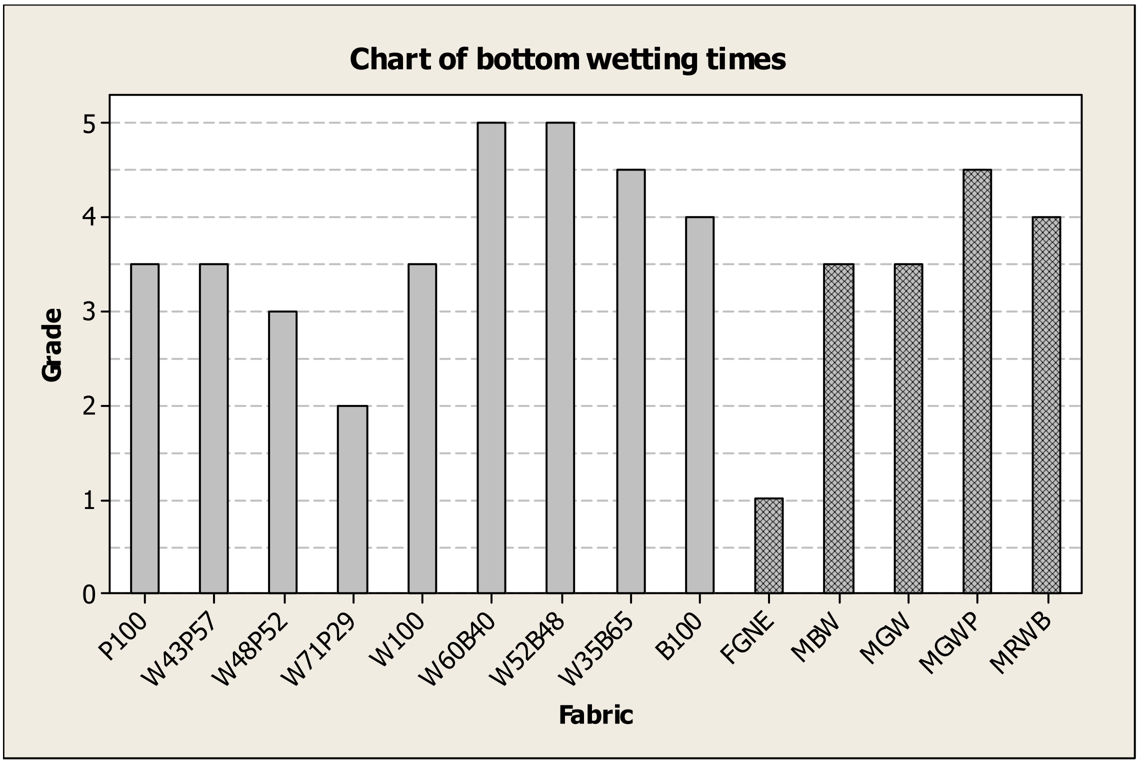


Figure 4.64.Bottom wetting times of experimental and commercial fabrics

4.2.2.1.2 Absorption rate

The mean grades of the top absorption rate (ARt) and the bottom absorption rate (ARb) of the 14 sample fabrics (Table 4.19) are given in Figures 4.65 and 4.66. Non-blended sample fabrics, P100 and B100, have a medium absorption rate in top and bottom surfaces while the W100 has a very slow top absorption rate but a very fast bottom absorption rate.

In wool/polyester sample fabrics, as the percentage of polyester fibre decreases, the top absorption rate of samples increases, and ranges from slow to very fast, while the bottom absorption rate decreases from a fast to medium rate. In wool/bamboo sample fabrics, as the percentage of bamboo fibre decreases, the top absorption rate also decreases from medium to slow, while the bottom absorption rate has the same medium absorption rate.

Comparing W100 with all blended wool/polyester sample fabrics and all blended wool/bamboo sample fabrics, indicates that blending wool fibre with polyester fibre and bamboo fibre improved the 100% wool sample top absorption rate grade.

The commercial fabric FGNE has a very fast top absorption rate, but a very slow bottom absorption rate. MBW and MGW fabrics have fast top and bottom absorption rates.

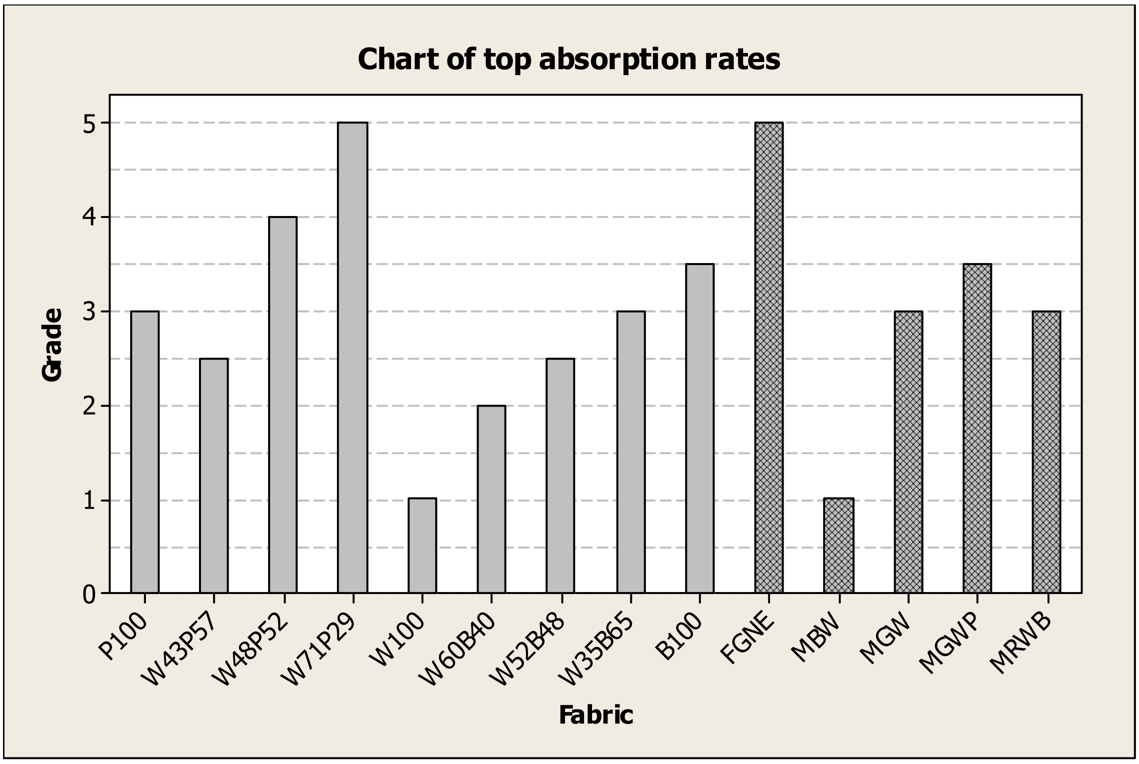


Figure 4.65.Top absorption rates of experimental and commercial fabrics

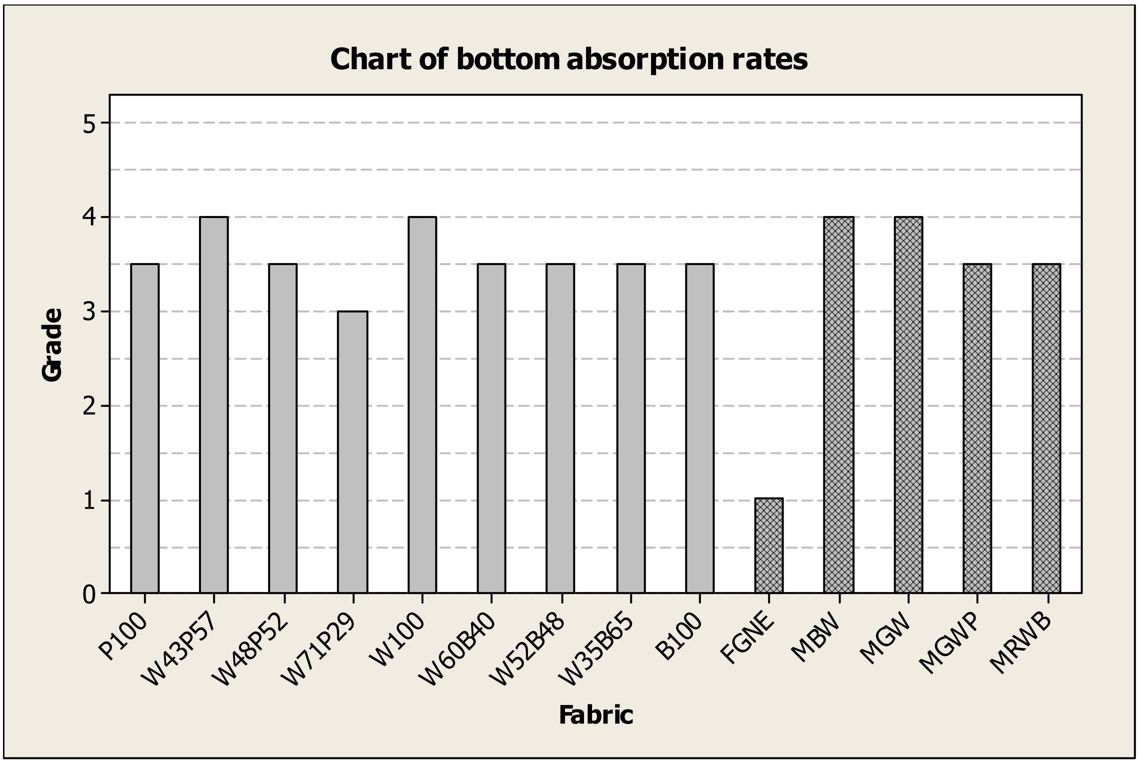


Figure 4.66.Bottom absorption rates of experimental and commercial fabrics

4.2.2.1.3 Maximum wetted radius

The mean grades of the top maximum wetted radius (MWRt) and the bottom maximum wetted radius (MWRb) of the 14 sample fabrics (Table 4.19) are given in Figures 4.67 and 4.68. In non-blended sample fabrics, P100 and B100 have the same grade in the top and bottom maximum wetted radius. They have a medium maximum wetted radius, while W100 has a lower grade than P100 and B100. It has grade 1, which means no wetting.

Blended sample fabrics, W45P57 and W48P52, have the same medium maximum wetted radius while W71P29 has the grade of 1 (no wetting). All blended wool/bamboo sample fabrics have a medium top maximum wetted radius but a large bottom maximum wetted radius (W52B48 and W60B40), while W35B65 has a medium bottom maximum wetted radius.

Comparing W100 with all blended wool/polyester fabrics and all blended wool/bamboo fabrics, indicates that blending wool fibre with polyester fibre and with bamboo fibre improved the top and bottom maximum wetted radius grade of 100% wool sample fabrics.

In commercial fabrics, all sample fabrics have the same grade in their top and bottom maximum wetted radius. FGNE and MBW have the lowest grade (no wetting), fabric MRWB has a medium maximum wetted radius, and MGWP and MGW have the highest grade of top and bottom maximum wetted radius. They have a large maximum wetted radius.

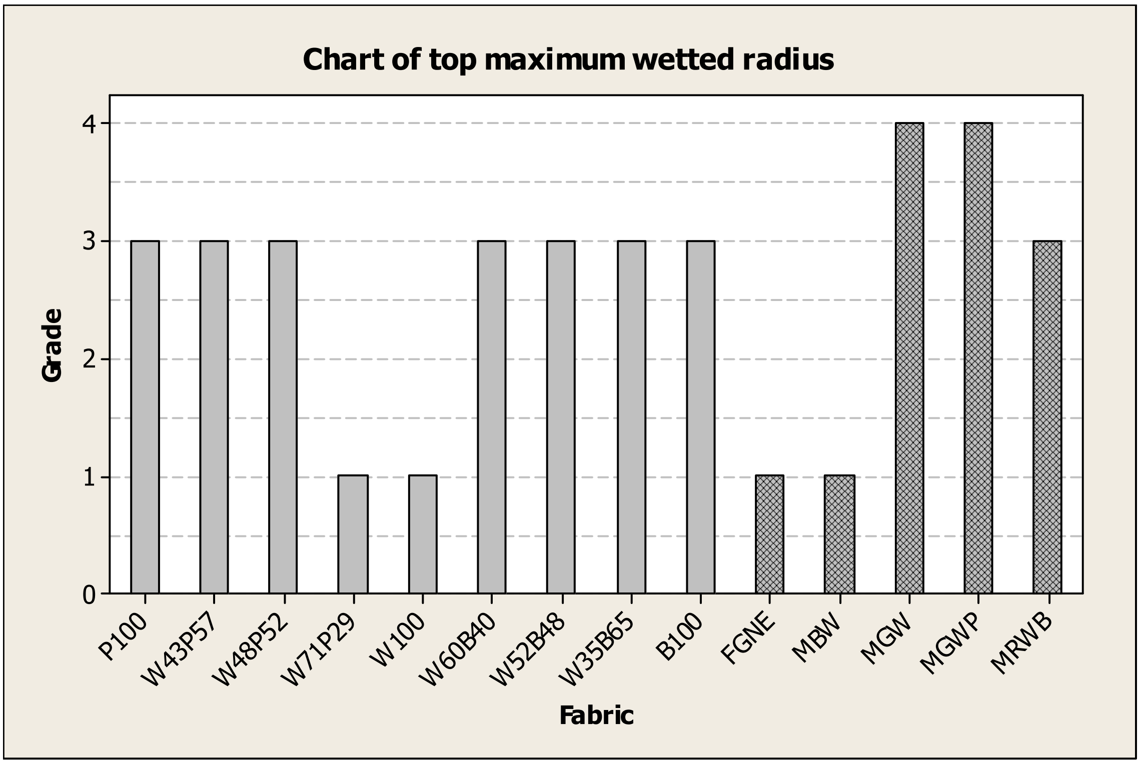


Figure 4.67.Top maximum wetted radius of experimental and commercial fabrics

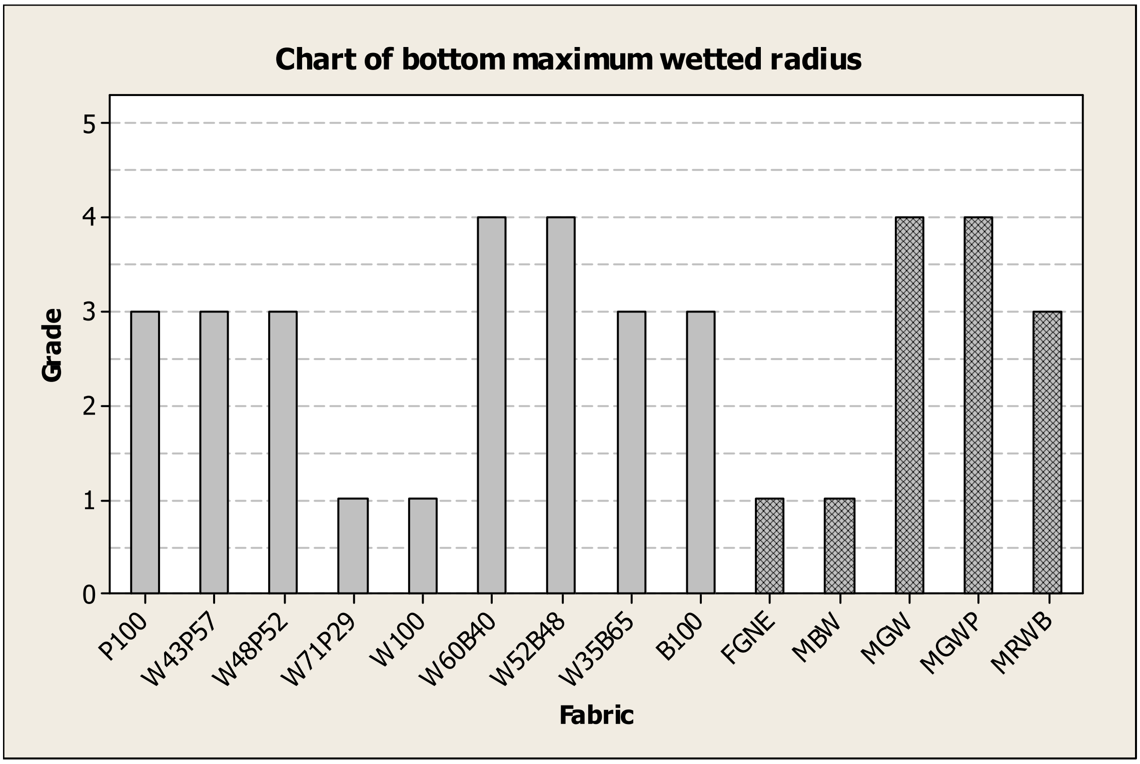


Figure 4.68.Bottom maximum wetted radius of experimental and commercial fabrics

4.2.2.1.4 Spreading speed

The mean grades of the top spreading speed (SSt) and the bottom spreading speed (SSb) of the 14 fabrics (Table 4.19) are given in Figures 4.69 and 4.70. In non-blended sample fabrics, 100% bamboo fabric (B100) has a medium spreading speed, 100% polyester fabric (P100) has a slow spreading speed and 100% wool fabric (W100) has a very slow spreading speed. The 100% bamboo fabric has the fastest spreading speed among non-blended fabrics.

In blended sample fabrics, all wool/polyester fabrics have a very slow top spreading speed while the bottom spreading speed ranges from slow to very slow speed. All wool/bamboo fabrics have a medium top spreading speed and a medium to very fast bottom spreading speed.

Comparing W100 with all blended wool/polyester sample fabrics indicates that blending wool fibre with polyester fibre improved the 100% wool bottom spreading speed grade.

Comparing W100 and B100 with all blended wool/bamboo sample fabrics indicates that blending wool fibre with bamboo fibre improved 100% wool and 100% bamboo top and bottom spreading speed grades.

In commercial sample fabrics, fabric MGWP has the fastest spreading speed in both surfaces, while fabrics FGNE, MBW and MGW have a very slow spreading speed.

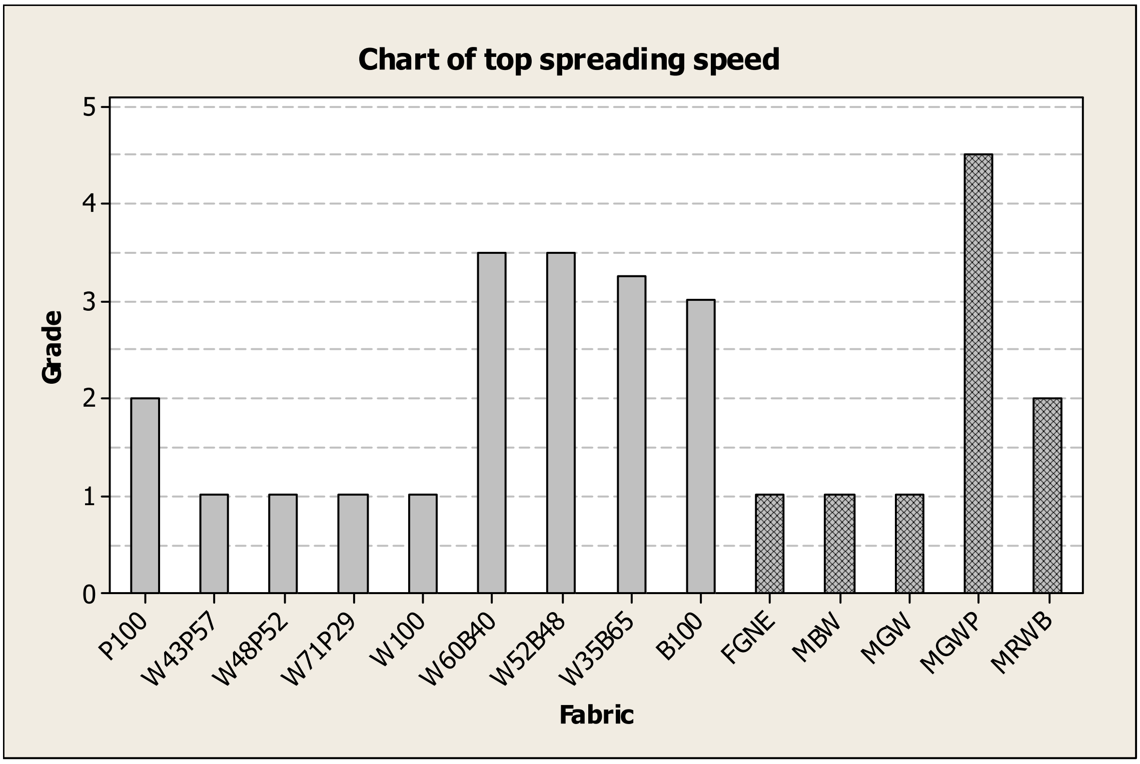


Figure 4.69.Top spreading speed of developed and commercial fabrics

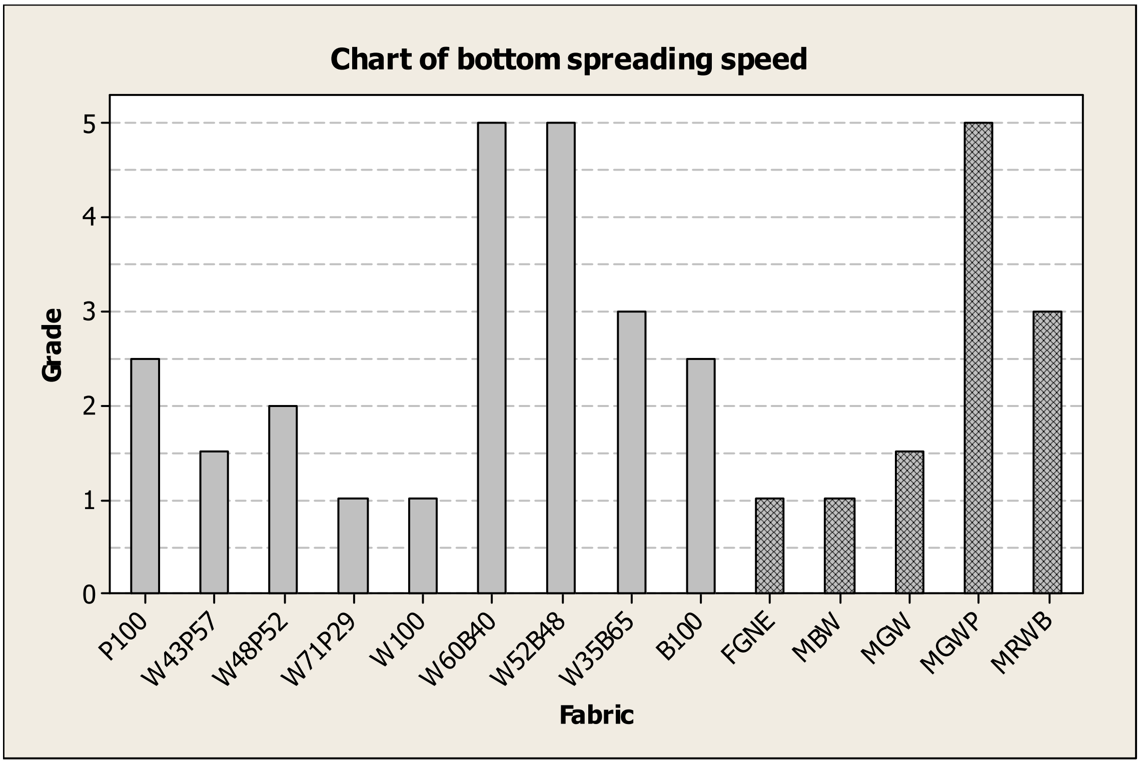


Figure 4.70.Bottom spreading speed of experimental and commercial fabrics

4.2.2.1.5 Accumulative one-way transport index and overall moisture management properties

The mean grades of the accumulative one-way transport index (AOTI) and overall moisture management capacity (OMMC) of 14 sample fabrics (Table 4.19) are given in Figures 4.71 and 4.72.

In non-blended sample fabrics, P100 has very good one-way transport capacity and overall moisture management capability. B100 has fair one-way transport capacity and overall moisture management capability and W100 has excellent one-way transport capacity and very good overall moisture management capability.

In wool/polyester blended sample fabrics, W43P57 has excellent one-way transport capacity and good overall moisture management capability, while W48P52 and W71P29 have poor one-way transport capacity and overall moisture management capability.

In wool/bamboo blended sample fabrics, W35B65 fabric has good one-way transport capacity and overall moisture management capability, while W52B48 and W60B40 fabrics have excellent one-way transport capacity and overall moisture management capability. W52B48 and W60B40 fabrics have the highest AOTI and OMMC grades.

Comparing W100 and B100 with all blended wool/bamboo sample fabrics indicates that blending wool fibre with bamboo fibre improved the top and bottom accumulative one-way transport index and overall moisture management capacity grade of 100% bamboo sample fabrics.

In commercial sample fabrics, MWB has excellent AOTI and very good OMMC and FGNE has poor AOTI and OMMC. Among all sample fabrics, W60B40 and W52B48 have the highest grade of OMMC, better than commercial fabrics.

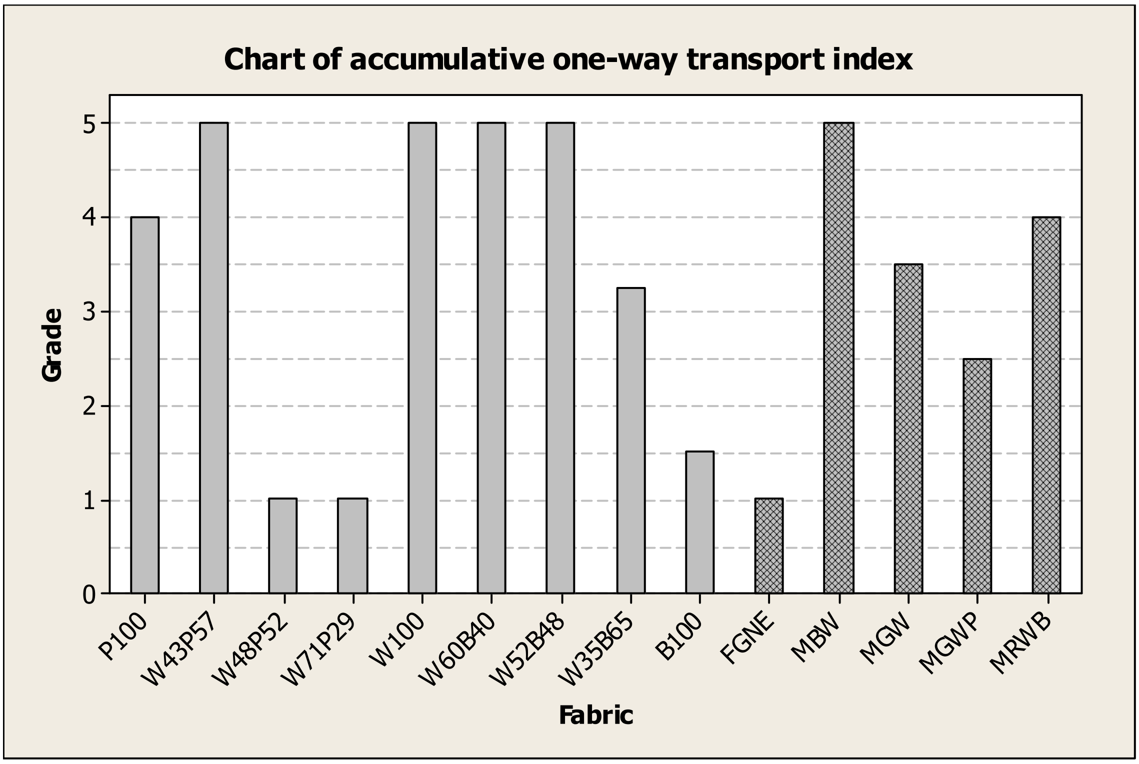


Figure 4.71.Accumulative one-way transfer index of experimental and commercial fabrics

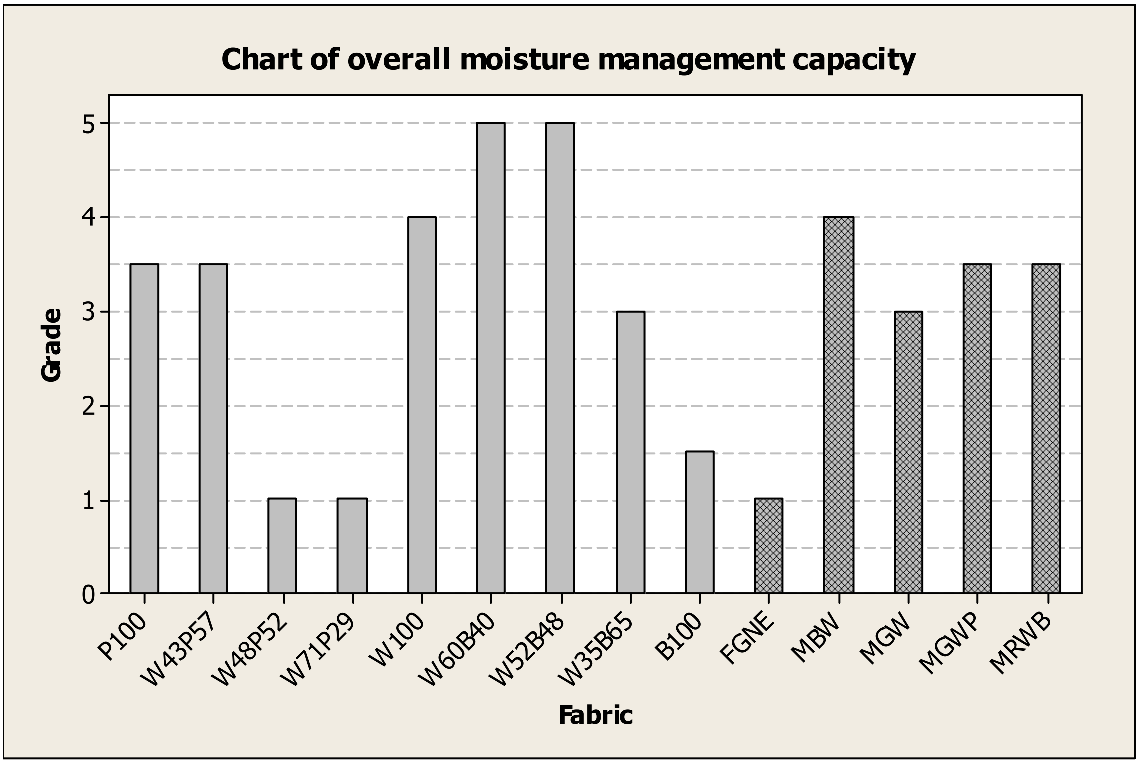


Figure 4.72.Overall moisture management capacity of experimental and commercial fabrics

The liquid moisture transfer performances of sample fabrics made of single fibre yarn were different from those of sample fabrics made of blended yarns. This was influenced by their fibre content since single fibre fabric properties are different from blended fibre fabric properties.

The liquid moisture transfer performances of the experimental sample fabrics were also influenced by the position of the yarns in the fabric. Because the blending was not done by intimate blend, but by putting two or several yarn ends together at knitting as in the plating technique, so that the fabric inner and outer surface made of different yarn. For example, when bamboo and wool yarn were knitted, the fabric inner surface would be made of wool yarn and the fabric outer surface would be made of bamboo yarn. This means that one layer of fabric was created but its inner and outer surfaces contained different fibres (Figure 4.73). This fibre position is compatible with the moisture transfer model in Figure 1.3 (d) in Chapter 1.

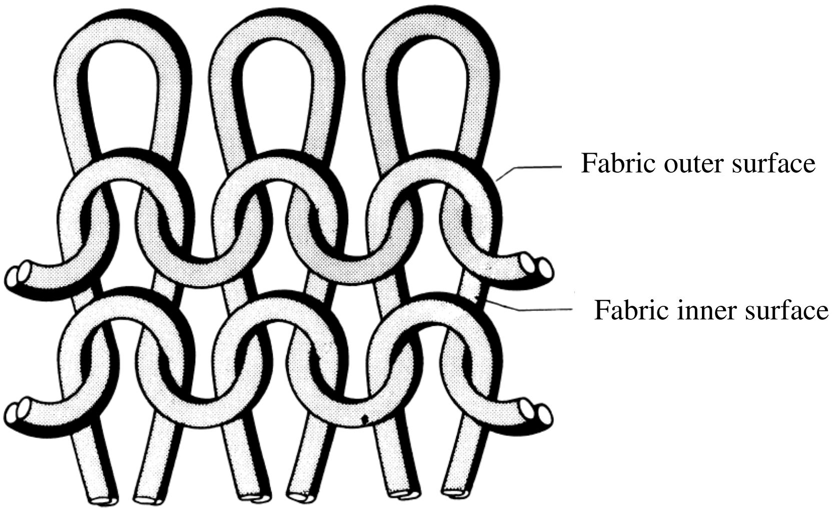


Figure 4.73.Fibre position in fabric (Spencer 2001)

In wool/polyester sample fabrics, wool yarn was placed and knitted as the top/inner surface of the fabric that will have direct contact with skin and polyester yarn was placed as the bottom/outer surface of the fabric. In this situation, wool, which has lower surface energy than polyester, acted as a hydrophobic fibre and polyester acted as a hydrophilic fibre.

In the wool/bamboo sample fabrics, wool yarn was placed as the top/inner surface of the fabric, having direct contact with the skin and bamboo yarn was placed as the bottom/outer surface of the fabric. In this situation, wool, which has lower surface energy than bamboo, acted as a hydrophobic fibre and bamboo acted as a hydrophilic fibre.

When the solution was dropped on the top surface of the fabric, the hydrophobic fibre wicked/transported the solution from the top and the hydrophilic fibre at the bottom of the fabric absorbed the solution, which was then evaporated into the atmosphere.

4.2.2.1.6 Fabric classification

In order to give a direct overall fabrics evaluation and the results for the liquid moisture management properties, each of the fabrics was classified into fabric type, based on the grades and values of indices (Yao et al. 2006). The fingerprints of moisture management properties of each fabric are given in Appendices.

Sample fabrics P100, W43P57, W35B65, W52B48, W60B40, MGW and MRBW were classified as moisture management fabrics. The properties of moisture management fabric are: medium to fast wetting, medium to fast absorption, large spreading area at the bottom surface, fast spreading at the bottom surface and good to excellent one-way liquid transport.

Sample fabrics W100 and MBW were classified as water-penetration fabrics. The properties of water-penetration fabric are: small spreading area and excellent one-way transport.

Sample fabric MGWP was classified as fast absorbing and quick drying. The properties of fast-absorbing and quick-drying fabrics are: medium to fast wetting, medium to fast absorption, large spreading area, fast spreading and poor one-way transport.

Sample fabrics W48P52 and B100 were classified as fast-absorbing and slow-drying fabrics. The properties of fast-absorbing and slow-drying fabrics are: medium to fast wetting, medium to fast absorption, small spreading area, slow spreading and poor one-way transport.

Sample fabric W71P29 was classified as a water-repellent fabric. The properties of water-repellent fabrics are: no wetting, no absorption, no spreading and poor one-way transport without external forces.

Sample fabric FGNE was classified as a waterproof fabric. The properties of waterproof fabrics are very slow absorption, slow spreading, no one-way transport and no penetration.

4.2.2.2. Thermal conductivity

Due to limited resources in thermal conductivity testing, not all experimental and commercial sample fabrics were tested. Only the fabrics that were categorised as moisture management fabrics and non-blended (100% single fibre) sample fabrics were tested for comparison.

Thermal conductivity results of the selected experimental and commercial sample fabrics are given in Figure 4.74. The figure shows that P100 has the highest thermal conductivity of all fabrics. Wool sample fabrics (W100 and MGW) have the lowest thermal conductivity compared to all 100% single fibre fabrics.

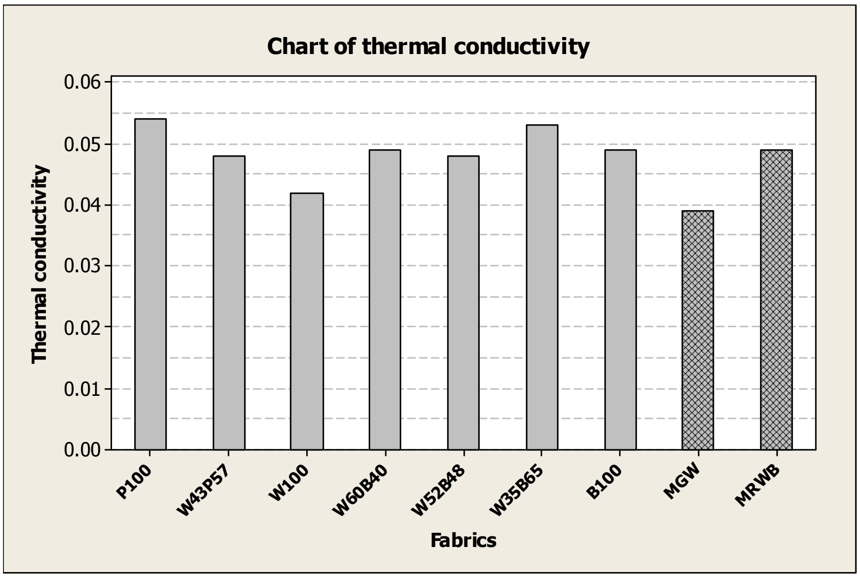


Figure 4.74.Thermal conductivity of selected experimental and commercial

The thermal conductivity of the sample fabrics was influenced by weight and thickness. As shown in Figure 4.75, as the weight of the fabric increased, the thermal conductivity also increased. The same relationship occurred in the thickness and thermal conductivity of the sample fabrics. The thermal conductivity of the fabric increased as the thickness increased (Figure 4.76).

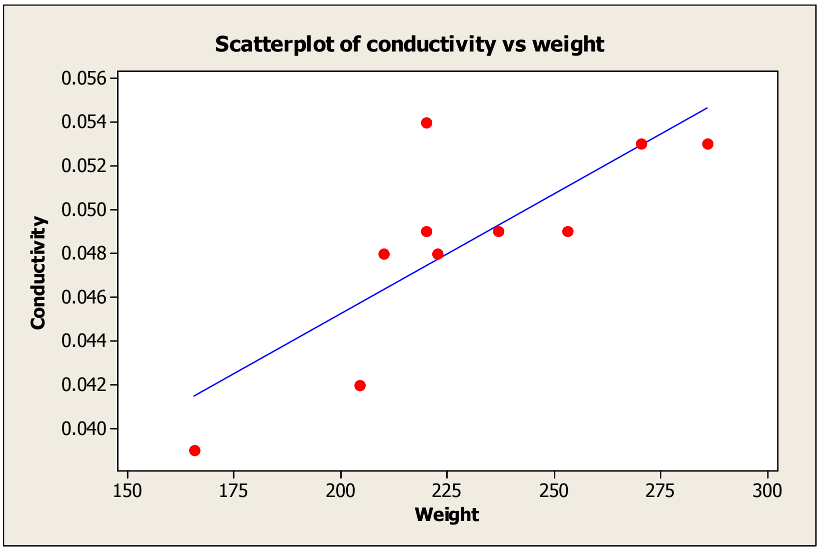


Figure 4.75.Scatterplot of fabric thermal conductivity versus weight

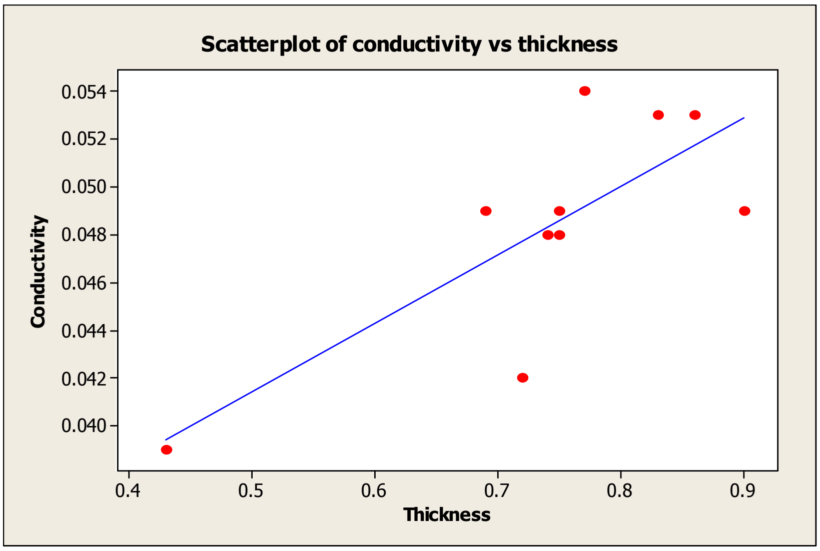


Figure 4.76.Scatterplot of fabric thermal conductivity versus thickness

4.2.2.3. Warm/cool feeling (*Qmax*)

In warm/cool feeling testing, not all experimental and commercial sample fabrics were tested. Only the fabrics categorised as moisture management fabrics and non-blended (100% single fibre) fabrics were tested for comparison.

Figure 4.77 indicates that 100% wool-knitted sample fabric has the warmest feeling while 100% bamboo-knitted sample fabric has the coolest feeling among 100% single fibre knitted fabrics. The larger the *Qmax* value the cooler the feeling, the smaller the *Qmax* value, the warmer the feeling.

In blended sample fabrics, the wool-polyester sample fabric (W43P57) has a warmer feeling compared with the 100% polyester sample fabric (P100) and has a cooler feeling compared with 100% wool-knitted sample fabrics. The same trend can be seen in wool-bamboo-knitted sample fabrics. All wool-bamboo sample fabrics have a cooler feeling (higher *Qmax*) than the 100% wool sample fabric (W100) and a warmer feeling (lower *Qmax*) than the 100% bamboo sample fabric (B100).

Comparing experimental and commercial sample fabrics, all blended experimental sample fabrics have lower *Qmax* than the commercial sample fabrics, which means that all blended experimental sample fabrics are warmer to the touch. This is advantageous for winter active sportswear.

The wool sample fabric feels warmer due to its fibres' crimp, which enables a large volume of air to be trapped in the spaces between the fibres. Since the sample consists largely of air it will give better thermal insulation and it feels warmer.

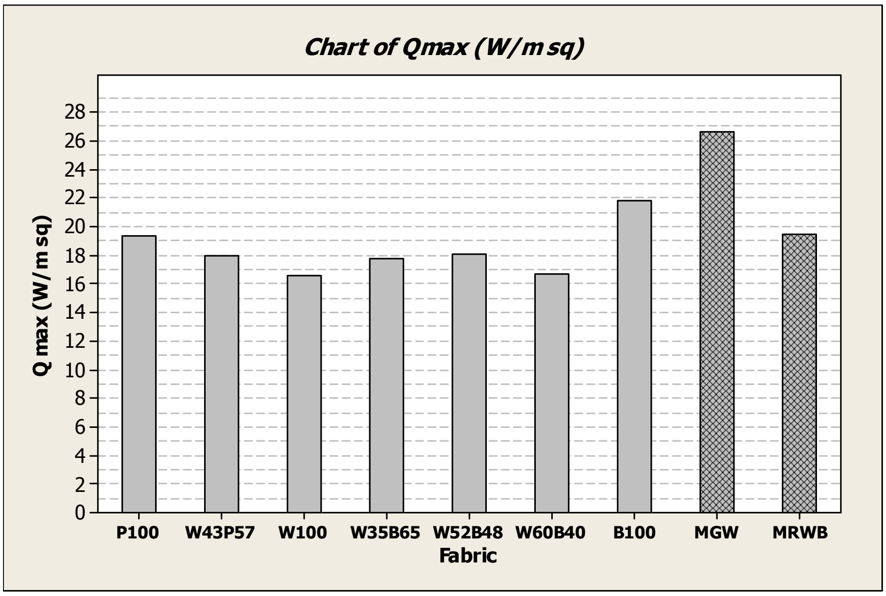


Figure 4.77.*Qmax* of selected experimental and commercial sample fabrics

4.2.3 Sensorial comfort properties

4.2.3.1 Bending length

The bending lengths (stiffness) of the 14 sample fabrics, which consist of nine experimental sample fabrics and five commercial sample fabrics, are given in Figure 4.78.

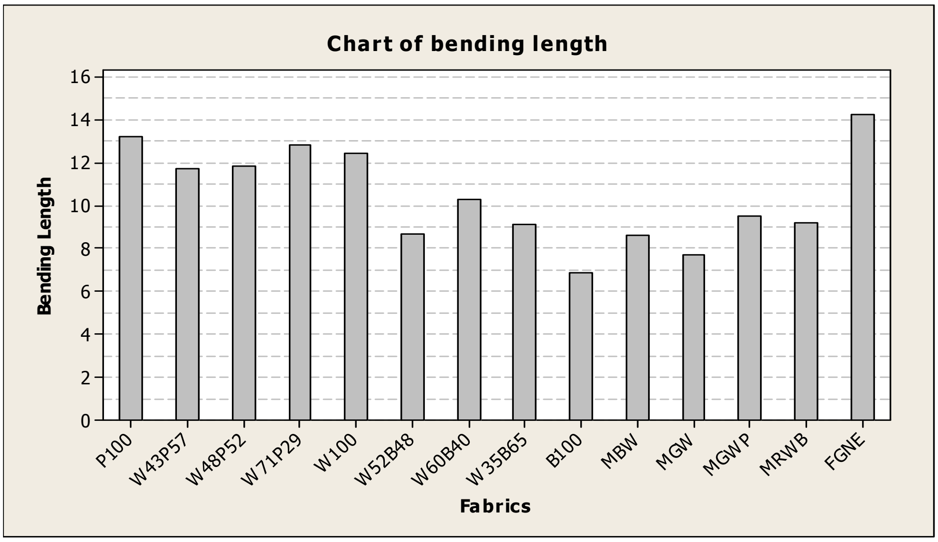


Figure 4.78.Bending length of experimental and commercial sample fabrics

It can be seen that B100 fabric has the lowest bending length while FGNE fabric has the highest bending length. According to Hohenstein Institute methods (Bartels & Umbach 2001) bending length of 5 or below is categorised as too ‘flabby’, while 27 or above is categorised as too stiff, and the range of 5 to 27 is categorised as comfortable. The optimum value for knitwear is considered to be 16 (Bartels & Umbach 2001). It can be seen that the bending length of all fabrics ranges from 6 to 14; they are all categorised as comfortable even though the value is not optimal.

It can be seen that the bending length value of blended experimental fabrics does not exceed the bending value of unblended experimental fabric. The bending length is dependent on the weight of the fabric and is therefore an important component of the drape of a fabric when it is hanging under its own weight (Saville 2004). The Pearson correlation between weight and bending length of sample fabric is 0.169 (Table 4.20). It showed no correlation between the weight and the bending length of the fabric. This is because the weight of the sample fabrics is similar.

4.2.3.2 Number of contact points

It has been found by numerous wearer trials with human subjects that the number of contact points between the fabric and the skin should be as low as possible. According to Hohenstein Institute methods (Bartels & Umbach 2001), to prevent a clammy, clinging sensation, the number of contact points with skin and the textile should not exceed 1500.

The number of contact points of experimental and commercial fabrics ranges from 100 to 450. As the number of contact points of the fabrics is less than 1500 (Figure 4.79), the experimental and commercial fabrics are expected to feel comfortable when the fabrics contact the skin and will not have a clinging or clammy sensation.

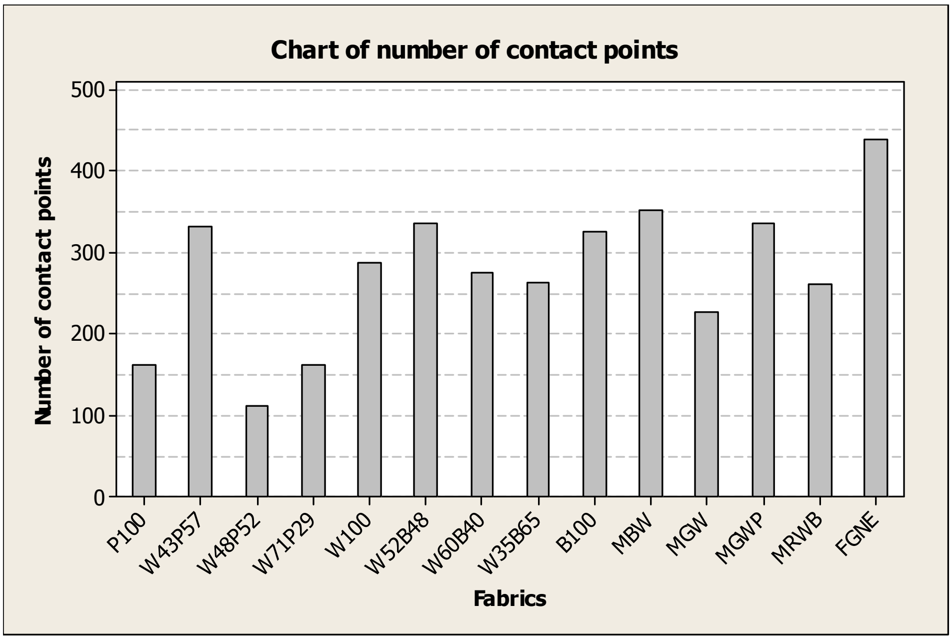


Figure 4.79.Number of contact points of experimental and commercial fabrics

4.2.4. Relationship between comfort properties and structural properties of experimental sample fabrics

The relationship between comfort properties and structural properties of the experimental sample fabrics was determined using the Pearson correlation (Table 4.20).

It can be seen that:

- Liquid moisture transfer of the experimental sample fabrics was not influenced by their weight, thickness, porosity, optical porosity or cover factor. In the experimental sample fabrics, the structural properties did not influence the liquid moisture transfer because the sample fabrics were produced almost with similar weight and cover factor. Since the factor that is different in the fabric was the blend ratio of fibres, it can be concluded that this has influenced the liquid moisture transfer of the fabrics.

- The bending length of the experimental sample fabrics was not influenced by fabric weight and thickness, since the sample fabrics were produced at almost the same weight and thickness, but it was influenced by porosity, optical porosity and the cover factor.
- The contact points of the experimental samples were not influenced by their structural properties.
- Fabric weight and thickness influenced the thermal conductivity of the experimental and commercial fabrics.
- Warm/cool feeling was influenced by fabric thickness.

Table 4.20.Pearson correlations between comfort properties and structural properties

Comfort Properties		Weight	Thickness	Porosity	Optical porosity	Cover factor
Liquid Moisture Transfer						
	WTt	0.303	0.346	-0.595	0.246	-0.407
	WTb	-0.074	0.033	-0.156	0.566	-0.209
	ARt	0.250	0.217	-0.279	-0.093	-0.099
	ARb	-0.212	-0.209	0.194	0.291	0.177
	MWRt	0.131	0.064	-0.466	0.525	-0.282
	MWRb	0.061	0.055	-0.445	0.591	-0.334
	SSt	0.071	0.317	-0.604*	0.527	-0.535
	SSb	0.002	0.288	-0.321	0.493	-0.346
	AOTI	-0.165	-0.055	0.542	0.063	0.295
	OMMC	-0.213	0	0.403	0.223	0.175
Bending Length		0.169	0.321	0.918*	-0.896*	0.734*
Contact Point		-0.209	0.039	-0.48	0.207	-0.616
Thermal Conductivity		0.794*	0.772*	-0.316	-0.351	0.216
Warm/Cool feeling		-0.569	-0.695*	-0.541	0.450	-0.123

* Linearly related

4.2.5. Test result recapitulation

According to the background research, the base layer is important for the direct cooling of the skin and for absorbing sweat (Nielsen 1991). The base layer provides the primary moisture management by wicking moisture away from the skin. The base layer garment should fit tightly in order to act efficiently (Higgins & Anand 2003). The inner layer that is designed to be worn next to the skin should have the following characteristics: good thermal conductivity, good moisture management and good tactile properties (Cao et al. 2006).

Based on the required characteristics of the base layer of winter active sportswear, the criteria to determine the good performance of the fabrics are:

- The MMT fabric classification should be moisture management fabrics.
- The OMMC grade should be 3–5 (good to excellent).
- The bending length should be 5–27 (Bartels & Umbach 2001).
- The number of contact points should not exceed 1500 (Bartels & Umbach 2001).
- The thermal conductivity should be high (good thermal conductivity).
- The *Qmax* should be small (warm feeling).

From Table 4.21, it can be seen that the sample fabrics P100, W43P57, W35B65, W52B48, W60B40 and MRWB have comfort properties that agree with the criteria for good performance of the fabrics for the base layer of winter active sportswear. All were classified as moisture management fabrics; they have good to excellent overall moisture management capacity; their bending length is between 5 and 27; their number of contact points is below 1500; they have high thermal conductivity and feel warm (small *Qmax*). It can be concluded that the sample fabrics P100, W43P57, W35B65, W52B48 and W60B40 (experimental sample fabrics) and MRWB (commercial sample fabric) have good comfort properties that are suitable for the base layer of winter active sportswear.

Table 4.21.Fabric comfort test result recapitulation

Fabric	**Sensorial comfort**				**Thermophysiological comfort**		**Good comfort condition**
	OMMC	**Fabric classification**	**Bending length**	**Number of contact points**	**Thermal conductivity**	**Qmax**	
P100	3.5	moisture management	13.21	162.00	0.054	19.333	v
W43P57	3.5	moisture management	11.67	331.33	0.048	17.907	v
W48P52	1.0	fast absorbing and slow drying	11.81	111.00			
W71P29	1.0	water-repellent	12.81	161.00			
B100	1.5	fast absorbing and slow drying	6.83	326.00	0.049	21.759	
W35B65	3.0	moisture management	9.13	262.33	0.053	17.778	v
W52B48	5.0	moisture management	8.69	335.00	0.048	18.037	v
W60B40	5.0	moisture management	10.27	275.00	0.049	16.704	v
W100	4.0	water penetration	12.44	287.00	0.042	16.556	
FGNE	1.0	water proof	14.23	437.67			
MBW	4.0	water penetration	8.56	352.00			
MGW	3.0	moisture management	7.71	226.67	0.039	26.630	
MGWP	3.5	fast absorbing and quick drying	9.48	336.00			
MRWB	3.5	moisture management	9.19	261.00	0.049	19.500	v

🟨 = selected based on base layer winter active sportswear fabric criteria

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

From the background research (Chapter 1), polyester fibre was selected for this research because polyester is the most common fibre used in sportswear, while wool was selected because wool fibre has good transport ability and has grown in use in sportswear. Bamboo was also selected because it is a relatively new fibre that offers properties suitable for base layer sportswear. Recently bamboo has been labelled a green and eco-friendly fibre. Research questions, the research hypothesis and limitations of the study were discussed in Chapter 2. Preliminary experiments were carried out to discover the liquid moisture transfer performance of knitted fabrics made of single fibre yarns (yarn made of one type of fibre) that would be used in the production of the experimental sample fabrics. Preliminary experiment sample fabrics were produced from single fibre yarn as single jerseys with different cover factors. It was concluded that the cover factor was influenced by loop length, and that the cover factor and the physical and structural properties of the fabric samples influenced their liquid moisture performance, depending on the fibre used.

The purpose of this research to produce knitted fabrics from blended fibres that are suitable for winter performance sportswear, was achieved. Five experimental samples were selected as fabrics with good comfort properties, suitable for the base layer of winter sportswear.

The first specific objective of this study was to measure the thermophysiological and sensorial comfort properties of knitted fabrics made from natural and synthetic blended yarns intended for winter active sportswear. This objective was achieved. Experimental and commercial samples for base layer winter active sportswear were measured for the following properties: liquid moisture transfer, bending length (stiffness), number of contact points, thermal conductivity and warm/cool feeling.

The second specific objective of this study was to gain insight into the relationship between thermophysiological and sensorial comfort and fibre composition, and construction of knitted fabric designed for winter active sportswear. This objective was achieved. The relationships are:

- Liquid moisture transfer of the experimental and commercial fabrics was not influenced by their physical properties.
- The fibre blend ratio influenced the liquid moisture transfer of fabrics.
- The contact points of the experimental samples were not influenced by their structural properties.
- Fabric weight and thickness influenced the thermal conductivity of the experimental and commercial fabrics.
- Warm/cool feeling was influenced by fabric thickness.

All of the commercial samples claimed to have good performance for base layer winter sportswear but some did not live up to these claims. From the five commercial samples only one sample had good performance.

5.2 Recommendations

- The experimental fabrics suitable for base layer winter active sportswear can be layered with middle layer and outer layer fabrics and tested using the skin model to determine their total thermal insulation. There is a minimal level of thermal insulation that must be provided even at very high activity levels. This is to prevent direct skin cooling and discomfort from low skin temperatures. With such minimal insulation, increased sweating and sweat evaporation must complement the other heat losses for preserving good heat balance and avoiding overheating.

- The experimental fabrics suitable for base layer winter active sportswear can be made into garments and put together with middle layer and outer layer garments as a clothing ensemble, and tested using a thermal manikin. Heat flow through a clothing system is three-dimensional and passes through combinations of layers of fabrics and air that vary in thickness. Form, fit, design and coverage of the body are other factors that modify the thermal insulation value.

- Microbial growth can be tested since the base layer has both a hygiene and a comfort function.

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APPENDICES

A.1. COMMERCIAL BASE LAYER WINTER SPORTSWEAR

Method:

Market research was done by collecting information of fibre that used in base layer winter sportswear from online shop from internet for the period of April 2007. The result was limited into several famous brands.

The result was tabulated in Table A.1.1

Table A.1.1. Commercial base layer winter sportswear

BRAND	PRODUCT	FIBERS
Bula		
	Long Underwear Pant for Women	Micro polyester
	Long Sleeve Zip Mock T-Neck for Women	Micro polyester
	Vega Top and Electra Bottom	95% microfiber nylon ,5% Lycra
	Zeta Top and Andromeda Bottom	95% microfiber nylon ,5% Lycra
Burton		
	Burton Compression Base Layer Shirt and Pant	DryLite Fabric (50% Dryarn, 42% Tactel®, 8% Lycra®)
	Burton Midweight Crewneck Long Sleeve Crew Top and Pant	polyester
	Burton Outlast Midweight Base Layer Shirt and Pant for Women	OUTLAST® Adaptive Comfort™
	Burton Outlast Midweight Base Layer Shirt and Pant	OUTLAST® Adaptive Comfort™
Berghouse		
	Boys Tech-T	100% microfibre polyester
	Girls Tech-T	100% microfibre polyester
	Injection Zip Neck Tee	100% microfibre polyester
	Long Sleeve Tech-T	100% microfibre polyester
	Long Sleeve Zip Tech-T	100% microfibre polyester
	Short Sleeved Tech-T	100% microfibre polyester
	SS X-Static® Tee	X-static® fibres
	Stretch Light Top	100% microfibre polyester

	Tech Base Boxer	100% microfibre polyester
	Tech Base Brief	100% microfibre polyester
	Tech Pants	100% microfibre polyester
	Women's Injection Zip Neck Tee	100% microfibre polyester
	Women's Long Sleeve Tech-T	100% microfibre polyester
	Women's Long Sleeve Zip Tech-T	100% microfibre polyester
	Women's Short Sleeved Tech-T	100% microfibre polyester
	Women's SS X-Static® Tee	X-static® fibres
	Women's Stretch Light Top	100% microfibre polyester
	Women's Tech Base Brief	100% microfibre polyester
	Women's Tech Base Vest	100% microfibre polyester
	Women's Tech Pant	100% microfibre polyester
	Women's X-Static® Top	X-static® fibres
	X-Static® SS Zip Neck	X-static® fibres
	X-Static® Top	X-static® fibres
Columbia		
	KIDS AUTHENTIC OUTDOOR CREW THERMAL	100% Soft spun Polyester
	KIDS AUTHENTIC OUTDOOR BOTTOM THERMAL	100% Soft spun Polyester
	ODYSSEY BOTTOM THERMAL	65% Soft spun Polyester ,35% Micro Filament Polyester
	ODYSSEY CREW THERMAL	65% Soft spun Polyester ,35% Micro Filament Polyester
	ODYSSEY ZIP THERMAL	65% Soft spun Polyester ,35% Micro Filament Polyester
	ODYSSEY SCOOP THERMAL	65% Soft spun Polyester ,35% Micro Filament

		Polyester
Dielsport		
	Women's polartec t-neck	100% polyester
	Men's fieldsensor t-neck	100% polyester
The North Face		
	M El Cap Delta	100% polyester
	M Cirque Top Delta 1/4 Zip	100% polyester
	M TKA 200 Delta	100% polyester
	M Aurora Zip Neck	100% polyester
	M Cirque Top	100% polyester
	M L/S Moxie 1/4 Zip	90% polyester, 10% elastane
	M TKA 100 Glacier 1/4 Zip	100% polyester
	M TKA 100 Pyrenees Crew	100% polyester
	M TKA Micro 1/4 Zip	100% polyester
	M El Cap Shirt	100% polyester
	M L/S Moxie Crew	93% polyester, 7% elastane
	M L/S Vaporwick Andes Ringer	100% polyester
	M L/S Performance Logo Tee	85% polyester, 15% cotton
	M Alpha Stretch Pant	87% polyester, 13% elastane
	M Moxie Tight	90% polyester, 10% elastane
	M TKA 100 Pant	100% polyester
	W Moxie Hoodie	90% polyester, 10% elastane
	W Zagros Fleece 1/2 Zip	67% polyester, 33% acrylic
	W Mossbud 1/4 Zip	100% polyester

	W Aurora Zip Neck	100% polyester
	W Momentum Shirt	95% polyester, 5% elastane
	W Proxi Fleece 1/4 Zip	100% polyester
	W Cirque Top	100% polyester
	W Cirque Mock Turtleneck	100% polyester
	W TKA 100 1/4 Zip	100% polyester
	W Moxie 1/4 Zip	90% polyester, 10% elastane
	W TKA 100 Glacier 1/4 Zip	100% polyester
	W El Cap Shirt	100% polyester
	W L/S Moxie Tee	90% polyester, 10% elastane
	W Vaporwick Kootenay Crossover	93% polyester, 7% elastane
	W L/S Beta Tek Tee	94% polyester, 6% elastane
	W Lora Mock Turtleneck	100% polyester
	W Vaporwick Jasper Crew	93% polyester, 7% elastane
	W Vaporwick Sawtooth Splitneck	93% polyester, 7% elastane
	W Vaporwick L/S Crew	93% polyester, 7% elastane
	W Performance L/S Logo Tee	85% polyester, 15% cotton
	W Performance L/S Ski Tee	85% polyester, 15% cotton
	W Moxie Pant	90% polyester, 10% elastane
	W Prolix Delta Pant	87% polyester, 13% elastane
	W Tka 100 Pant	100% polyester
Helly Hansen		
	Shirt, Crewneck, Super Series	100% Polypropylene
	Shirt, Crewneck, Thermal Wool Series	55% Polypropylene / 36% Wool / 9% Polyamide

	Shirt, Polo, Thermal Wool Series	55% Polypropylene / 36% Wool / 9% Polyamide
	Shirt, Tee, Super Series	100% Polypropylene
	Trousers, Super Series	100% Polypropylene
	Trousers, Thermal Wool Series	55% Polypropylene / 36% Wool / 9% Polyamide
Hot Chilly		
	Hot Chillys MTF3000 ladies jewel neck	92% spun polyester with 8% Lyrca
	Hot Chillys MTF3000 ladies low rise pants	92% spun polyester with 8% Lyrca
	Hot ChillysMTF3000 ladies zip t-neck	94% spun polyester with 6% Lyrca
Marmot		
	Midweight Crew LS	Polyester
	Midweight Zip LS	Polyester
	Midweight Crew SS	Polyester
	Midweight Bottom	Polyester
	Silkweight Zip LS	Polyester
	Silkweight Crew LS	Polyester
	Silkweight Crew SS	Polyester
	Silkweight Bottom	Polyester
	Women's Midweight Zip LS	Polyester
	Women's Midweight Crew LS	Polyester
	Women's Midweight Crew SS	Polyester
	Women's Midweight Bottom	Polyester
	Women's Midweight Capri	Polyester
	Women's Silkweight Zip LS	Polyester

	Women's Silkweight Crew LS	Polyester
	Women's Silkweight Bottom	Polyester
	Women's Silkweight Crew SS	Polyester
O' neil		
	THERMO-X VEST	PolarTec
	THERMO-X S/S CREW	PolarTec
	THERMO-X LS CREW	PolarTec
	THERMO-X L/S CREW	PolarTec
	THERMO X FULL	PolarTec
	THERMO-X SS CREW 13OZ	PolarTec
Patagonia		
	m Capilene 3 crew	polyester
	m Capilene 3 zip neck	polyester
	m Capilene 3 bottom	polyester
	m Capilene 4 zip neck	polyester
	m Capilene 4 bottoms	polyester
	m wool 2 crew	merino
	m wool 2 sleeveless	merino
	m wool 2 t shirt	merino
	m wool 2 zip neck	merino
	m wool 2 bottoms	merino

	w Capilene 3 crew	polyester
	w Capilene 3 zip neck	polyester
	w Capilene 3 bottom	polyester
	w Capilene 4 zip neck	polyester
	w Capilene 4 bottoms	polyester
	w wool 2 crew	merino
	w wool 2 sleeveless	merino
	w wool 2 t shirt	merino
	w wool 2 zip neck	merino
	w wool 2 bottoms	merino
PolarMax		
	Phase 2 Midweight - UNIFIT LONG SLEEVE	100% Acclimate Dry Polyester
	Phase 2 Midweight - UNIFIT PANT	100% Acclimate Dry Polyester
	Phase 2 Midweight - UNIFIT LONG SHORTS	100% Acclimate Dry Polyester
	Phase 3 Super Midweight - LONG SLEEVE	90% Acclimate Dry Polyester and 10% Spandex
	Phase 3 Super Midweight - PANT for MEN	90% Acclimate Dry Polyester and 10% Spandex
	Phase 3 Super Midweight - SHORT SLEEVE	90% Acclimate Dry Polyester and 10% Spandex
	Phase 3 Super Midweight- LONG SLEEVE for WOMEN	90% Acclimate Dry Polyester and 10% Spandex
		90% Acclimate Dry Polyester and 10% Spandex

	Phase 3 Super Midweight - PANT for WOMEN	
Rossignol		
	Rossignol SRBL Long Sleeve Zip T-Neck	92% polyester and 8% Lycra
	Rossignol SRBL Boot Top Cut Pants	92% polyester and 8% Lycra
Scott		
	3/4 Pants Curve	90% polyamide, 10% elastane
	3/4 Pants Curve w	90% polyamide, 10% elastane
	Pants Outlast	97% acrylic, 3% elastane
	Pants Outlast w	97% acrylic, 3% elastane
	Pants Sportwool	65% polyester, 35% wool
	Pants Sportwool w	65% polyester, 35% wool
	Shirt Coolmax s/sl	60% polyester, 31% polyamide, 9% elastane
	Shirt Outlast l/sl	97% acrylic, 3% elastane
	Shirt Outlast w	97% acrylic, 3% elastane
	Shirt Slant l/sl	90% polyamide, 10% elastane
	Shirt Slant l/sl w	90% polyamide, 10% elastane
	Shirt Sportwool	65% polyester, 35% wool
	Shirt Sportwool w	65% polyester, 35% wool
	Shorts Coolmax	60% polyester, 31% polyamide, 9% elastane
Snow angel		
	Thermal intimates	92% Tactel,8% Lycra
	Angel cashmere	10% Chasmere,65% Micromodal,25%Nylon
	Cybersilk	87% CoolMAX Alta,13% Lycra

	doeskin	87%microtherm polyester,13%lycra
	chamonix	88%microtherm polyester,12%lycra
Spyder		
	Spyder Form Base Layer Tops for Men	48% Polypropylene, 48% Nylon, 4% Spandex
	Spyder Form Base Layer Pants for Men	48% Polypropylene, 48% Nylon, 4% Spandex
	Spyder Form Base Layer Tops for Women	48% Polypropylene, 48% Nylon, 4% Spandex
	Spyder Form Base Layer Pants for Women	48% Polypropylene, 48% Nylon, 4% Spandex
US Ski		
	US Ski Team Adrenaline Selectech	100% polyester
Mont Adventure		
	El Gringo and La Gringa Pants	polartec
	Power Stretch Hoodie	polartec
	Women's Slinx	polartec
	Slinx Polo	polartec
Mountain Design		
	delux zip polo	polyester
	delux ls crew top	polyester
	Extreme pants	100% polypropylene
	Delux pants	Polyester
	Extreme top	100% polypropylene

	Premium unisex zip polo	100% polypropylene
	Premium unisex ls top contrast	100% polypropylene
	Premium unisex ls top	100% polypropylene
	Premium unisex pants	100% polypropylene
	Premium unisex ss top	100% polypropylene
	Zeal	100% merino
	Pulse	100% merino
	Ls zip polo	100% merino
	Ls crew top	100% merino
	Ss crew top	100% merino
	Long Johns	100% merino
	delux zip polo w	polyester
	delux ls crew top w	polyester
	Delux pants w	polyester
	Esprit	100% merino
	Impulse	100% merino
	Ls zip polo w	100% merino
	Long Johns w	100% merino
	Ls crew top	100% merino
	Ss v neck top	100% merino
	crew tank top	100% merino
	Joey top	100% polypropylene
	Joey pants	100% polypropylene
Mover		

Sportswear		
	Merino pullover (Men)	100 %Merino wool
	Fleece pullover (Women)	92 % polyester, 8 % lycra
	Fleece jacket (Women)	93 % polyester, 7 % lycra
	Fleece V-neck (Women	92 % polyester, 8 % lycra
	Merino jacket (Women)	100 %Merino wool
	Fleece T-neck (Men)	92 % polyester, 8 % lycra
	Fleece jacket (Men)	93 % polyester, 7 % lycra
	Merino t-shirt (Men)	100 %Merino wool
	Merino jacket (Men)	101 %Merino wool
	Fleece sleeveless (Women)	92 % polyester, 8 % lycra
	Merino pullover (Women)	100% Merino wool
	Merino t-shirt (Women)	100% Merino wool
	Fleece pullover (Men)	92 % polyester, 8 % lycra
Obermeyer		
	Men's UG 100 Micro Zip-T	UltraGear®
	Men's Marathon Zip-T	UltraGear®
	Men's Mesh UG Top	UltraGear®
	Men's UG Pro 50 Crew	Polartec® PowerDry - 100% Polyester
	Men's UG Pro 50 Zip-T	Polartec® PowerDry - 100% Polyester
	Men's UG Pro 75 Zip-T	Polartec® four-way PowerStretch
	Men's UG Pro 150 Zip-T	Polartec® four-way PowerStretch
	Men's UG Pro 50 Tight	Polartec® PowerDry - 100% Polyester
	Men's UG Pro 75 Tight	Polartec® four-way PowerStretch

	Men's UG Pro 150 Tight	Polartec® four-way PowerStretch
	UltraGear® Micro Zip-T	UltraGear®
	UltraGear® Pro 50 Shaped Mock-T	UltraGear®
	UltraGear® Pro 50 Shaped Zip-T	Polartec® PowerDry - 100% Polyester
	UltraGear® Pro 75 Shaped Zip-T	Polartec® four-way PowerStretch
	UltraGear® Pro 150 Shaped Zip-T	Polartec® four-way PowerStretch
	UltraGear® Pro 50 Tight	Polartec® PowerDry - 100% Polyester
	UltraGear® Pro 75 Tight	Polartec® four-way PowerStretch
	UltraGear® Pro 150 Tight	Polartec® four-way PowerStretch
Vaude		
	Women's Endurance Pullover	62% Polyester, 38% Lycra
	Women's El Cap Tights	92% Polyester, 8% Elasthane
	Women's Micro Vera LS halfzip	100% Polyester
	Women's Micro Mikeli	100% Polyester
	Women's Micro Catlins	100% Polyester
	Women's Seamless Tee	100% Polyester
	Women's Thermo Base LS Shirt	95% Tactel Aquator, 5% Elastane
	Women's Thermo Base Shirt	95% Tactel Aquator, 5% Elastane
	Women's Thermo Base Tight	95% Tactel Aquator, 5% Elastane
	Thermo Base LS Shirt	95% Tactel Aquator, 5% Elastane

A.2. EXPERIMENTAL DATA

Wool Knitted Fabrics

Table.A.2.1. Weight of wool knitted fabrics (g/m^2)

Fabric	1	2	3	4	5	Mean	SD	CV
1	82	81	82	83	82	82.00	0.71	0.86
2	88	89	88	88	89	88.40	0.55	0.62
3	102	102	103	104	101	102.40	1.14	1.11
4	108	107	106	106	108	107.00	1.00	0.93
5	126	118	124	124	121	122.60	3.13	2.55
6	133	132	132	131	131	131.80	0.84	0.63
7	136	136	135	135	137	135.80	0.84	0.62
8	138	138	142	137	138	138.60	1.95	1.41
9	145	147	146	144	145	145.40	1.14	0.78
10	152	150	151	152	152	151.40	0.89	0.59
11	156	155	157	157	156	156.20	0.84	0.54

Table.A.2.2. Thickness of wool knitted fabrics (mm)

Fabric	1	2	3	4	5	Mean	SD	CV
1	0.39	0.40	0.40	0.41	0.40	0.40	0.01	1.77
2	0.41	0.39	0.41	0.41	0.41	0.41	0.01	2.20
3	0.43	0.41	0.42	0.42	0.42	0.42	0.01	1.68
4	0.41	0.43	0.42	0.43	0.42	0.42	0.01	1.88
5	0.43	0.45	0.44	0.44	0.44	0.44	0.01	1.73
6	0.44	0.45	0.44	0.45	0.44	0.44	0.01	1.23
7	0.46	0.44	0.45	0.44	0.44	0.45	0.01	2.01
8	0.45	0.43	0.45	0.44	0.45	0.44	0.01	1.89
9	0.45	0.45	0.46	0.46	0.45	0.45	0.01	1.21
10	0.46	0.45	0.46	0.48	0.45	0.46	0.01	2.27
11	0.45	0.46	0.46	0.48	0.46	0.46	0.01	2.47

Table.A.2.3. Wales/cm of wool knitted fabrics

Fabric	1	2	3	4	5	Mean	SD	CV
1	9	9	9	9	9	9	0.00	0.00
2	10	10	10	10	10	10	0.00	0.00
3	11	11	11	11	11	11	0.00	0.00
4	12	12	12	12	12	12	0.00	0.00
5	13	13	13	13	13	13	0.00	0.00
6	14	14	14	14	14	14	0.00	0.00
7	15	15	15	15	15	15	0.00	0.00
8	15	15	15	15	15	15	0.00	0.00
9	15	15	15	15	15	15	0.00	0.00
10	16	16	16	16	16	16	0.00	0.00
11	16	16	16	16	16	16	0.00	0.00

Table.A.2.4 Courses/cm of wool knitted fabrics

Fabric	1	2	3	4	5	Mean	SD	CV
1	10	10	10	10	10	10	0.00	0.00
2	11	11	11	11	11	11	0.00	0.00
3	13	13	13	13	13	13	0.00	0.00
4	13	13	13	13	13	13	0.00	0.00
5	14	14	14	14	14	14	0.00	0.00
6	15	15	15	15	15	15	0.00	0.00
7	16	16	16	16	16	16	0.00	0.00
8	17	17	17	17	17	17	0.00	0.00
9	18	18	18	18	18	18	0.00	0.00
10	18	18	18	18	18	18	0.00	0.00
11	19	19	19	19	19	19	0.00	0.00

Bamboo Knitted fabrics

Table.A.2.5. Weight of bamboo knitted fabrics (g/m^2)

Fabric	1	2	3	4	5	Mean	SD	CV
B1	234	227	228	228	226	228.60	3.13	1.37
B2	208	212	208	210	209	209.40	1.67	0.80
B3	196	196	197	198	197	196.80	0.84	0.43
B4	193	200	194	195	194	195.20	2.77	1.42
B5	179	169	175	176	177	175.20	3.77	2.15
B6	158	165	158	161	159	160.20	2.95	1.84
B7	155	160	162	158	160	159.00	2.65	1.66
B8	147	150	149	149	150	149.00	1.22	0.82
B9	138	139	139	138	139	138.60	0.55	0.40
B10	132	136	131	134	133	133.20	1.92	1.44
B11	131	130	131	130	129	130.20	0.84	0.64
B12	126	124	126	125	126	125.40	0.89	0.71
B13	121	122	118	120	121	120.40	1.52	1.26

Table.A.2.6. Thickness of bamboo knitted fabrics (mm)

Fabric	1	2	3	4	5	Mean	SD	CV
B1	0.71	0.67	0.68	0.69	0.70	0.69	0.02	2.29
B2	0.68	0.68	0.67	0.68	0.69	0.68	0.01	1.04
B3	0.67	0.67	0.68	0.67	0.66	0.67	0.01	1.06
B4	0.66	0.68	0.66	0.67	0.68	0.67	0.01	1.49
B5	0.64	0.65	0.65	0.65	0.66	0.65	0.01	1.09
B6	0.64	0.63	0.63	0.63	0.63	0.63	0.00	0.71
B7	0.61	0.65	0.62	0.64	0.63	0.63	0.02	2.51
B8	0.61	0.61	0.60	0.60	0.61	0.61	0.01	0.90
B9	0.57	0.56	0.58	0.57	0.57	0.57	0.01	1.24
B10	0.57	0.57	0.56	0.56	0.58	0.57	0.01	1.47
B11	0.56	0.56	0.57	0.56	0.56	0.56	0.00	0.80
B12	0.56	0.53	0.53	0.55	0.54	0.54	0.01	2.41
B13	0.52	0.55	0.54	0.53	0.54	0.54	0.01	2.13

Table.A.2.7. Wales/cm of bamboo knitted fabrics

Fabric	1	2	3	4	5	Mean	SD	CV
B1	11	11	11	12	12	11.4	0.55	4.80
B2	11	11	11	11	11	11	0.00	0.00
B3	10	10	11	11	10	10.4	0.55	5.27
B4	10	10	10	10	10	10	0.00	0.00
B5	10	10	10	10	10	10	0.00	0.00
B6	10	10	10	10	10	10	0.00	0.00
B7	9	9	9	9	9	9	0.00	0.00
B8	9	9	9	9	9	9	0.00	0.00
B9	9	9	9	9	9	9	0.00	0.00
B10	9	9	9	9	9	9	0.00	0.00
B11	9	9	9	9	9	9	0.00	0.00
B12	8	8	8	8	8	8	0.00	0.00
B13	8	8	8	8	8	8	0.00	0.00

Table.A.2.8. Courses/cm of bamboo knitted fabrics

Fabric	1	2	3	4	5	Mean	SD	CV
B1	14	14	14	14	14	14	0.00	0.00
B2	13	13	13	13	13	13	0.00	0.00
B3	12	12	12	12	12	12	0.00	0.00
B4	11	11	11	11	11	11	0.00	0.00
B5	10	10	10	10	10	10	0.00	0.00
B6	9	9	9	9	9	9	0.00	0.00
B7	9	9	9	9	9	9	0.00	0.00
B8	7	7	8	8	7	7.4	0.55	7.40
B9	7	7	7	7	7	7	0.00	0.00
B10	6	6	7	7	6	6.4	0.55	8.56
B11	6	6	6	6	6	6	0.00	0.00
B12	5	5	6	6	5	5.4	0.55	10.14
B13	5	5	5	5	5	5	0.00	0.00

Commercial and experimental knitted fabrics

Table.A.2.9. Weight of commercial knitted fabrics (g/m^2)

Fabrics	1	2	3	4	5	Mean	SD	CV
MBW	154	151	151	152	151	151.80	1.30	0.86
MGW	165	167	165	166	165	165.60	0.89	0.54
MRWB	249	252	256	255	253	253.00	2.74	1.08
MGWP	163	162	161	161	162	161.80	0.84	0.52
FGNE	217	211	214	215	214	214.20	2.17	1.01

Table.A.2.10. Weight of experimental knitted fabrics (g/m^2)

Fabrics	1	2	3	4	5	Mean	SD	CV
P100	220	221	221	220	218	220.00	1.22	0.56
W43P57	220	222	222	224	225	222.60	1.95	0.88
W48P52	236	234	238	237	239	236.80	1.92	0.81
W71P29	224	224	226	227	228	225.80	1.79	0.79
W100	208	204	205	200	205	204.40	2.88	1.41
W35B65	276	269	269	271	266	270.20	3.70	1.37
W52B48	210	208	212	211	209	210.00	1.58	0.75
W60B40	233	241	238	235	237	236.80	3.03	1.28
B100	214	222	222	224	218	220.00	4.00	1.82

Table.A.2.11. Thickness of commercial knitted fabrics (mm)

Fabrics	1	2	3	4	5	Mean	SD	CV
MBW	0.54	0.55	0.53	0.55	0.54	0.54	0.01	1.55
MGW	0.43	0.43	0.43	0.43	0.43	0.43	0.00	0.00
MRWB	0.89	0.9	0.91	0.9	0.9	0.90	0.01	0.79
MGWP	0.83	0.81	0.82	0.82	0.81	0.82	0.01	1.02
FGNE	0.79	0.8	0.81	0.8	0.8	0.80	0.01	0.88

Table.A.2.12. Thickness of experimental knitted fabrics (mm)

Fabrics	1	2	3	4	5	Mean	SD	CV
P100	0.76	0.76	0.76	0.79	0.77	0.77	0.01	1.69
W43P57	0.75	0.76	0.74	0.75	0.76	0.75	0.01	1.12
W48P52	0.76	0.74	0.77	0.74	0.76	0.75	0.01	1.79
W71P29	0.72	0.72	0.71	0.71	0.72	0.72	0.01	0.76
W100	0.72	0.72	0.72	0.71	0.71	0.72	0.01	0.76
W35B65	0.86	0.81	0.82	0.84	0.84	0.83	0.02	2.35
W52B48	0.72	0.73	0.74	0.76	0.76	0.74	0.02	2.42
W60B40	0.75	0.75	0.75	0.76	0.76	0.75	0.01	0.73
B100	0.7	0.7	0.69	0.69	0.68	0.69	0.01	1.21

Table.A.2.13. Courses/cm of experimental knitted fabrics

Fabrics	1	2	3	4	5	Mean	SD	CV
P100	15	15	15	15	15	15	0.00	0.00
W43P57	15	15	15	15	15	15	0.00	0.00
W48P52	15	14	15	14	15	14.6	0.55	3.75
W71P29	14	14	14	14	14	14	0.00	0.00
W100	13	13	13	13	13	13	0.00	0.00
W35B65	12	12	12	12	12	12	0.00	0.00
W52B48	13	13	13	13	13	13	0.00	0.00
W60B40	13	13	13	13	13	13	0.00	0.00
B100	15	15	15	15	15	15	0.00	0.00

Table.A.2.14.Wales/cm of experimental knitted fabrics

Fabrics	1	2	3	4	5	Mean	SD	CV
P100	11	11	11	11	11	11	0.00	0.00
W43P57	11	11	11	11	11	11	0.00	0.00
W48P52	11	11	11	11	11	11	0.00	0.00
W71P29	11	11	11	11	11	11	0.00	0.00
W100	11	11	11	11	11	11	0.00	0.00
W35B65	9	9	9	9	9	9	0.00	0.00
W52B48	11	11	11	11	11	11	0.00	0.00
W60B40	10	10	10	10	10	10	0.00	0.00
B100	11	11	11	11	11	11	0.00	0.00

Table A.2.15. Yarn Diameter of experimental fabrics

No	Fabric	Yarn count (Tex)	Yarn diameter(mm)
1	P100	44.4	0.020
2	W43P57	38.9	0.019
3	W48P52	42.2	0.020
4	W71P29	38.9	0.020
5	W100	40	0.020
6	W35B65	56.6	0.027
7	W52B48	38.3	0.021
8	W60B40	46.1	0.023
9	B100	36.6	0.024

Table A.2.16. Fibre density

No	fibre	density
1	Polyester	1.38
2	Wool	1.32
3	Bamboo	0.8

Table A.2.17. Fibre density on experimental fabrics

No	Fabric	density
1	P100	1.38
2	W43P57	1.35
3	W48P52	1.35
4	W71P29	1.21
5	W100	1.32
6	W35B65	0.98
7	W52B48	1.07
8	W60B40	1.11
9	B100	0.80

Table A.2.18. Experimental fabrics porosity

No	Fabrics	Porosity
1	P100	79.24
2	W43P57	78.14
3	W48P52	76.76
4	W71P29	73.84
5	W100	78.37
6	W35B65	67.01
7	W52B48	73.56
8	W60B40	71.76
9	B100	60.26

Table A.2.19. Optical porosity of commercial fabrics

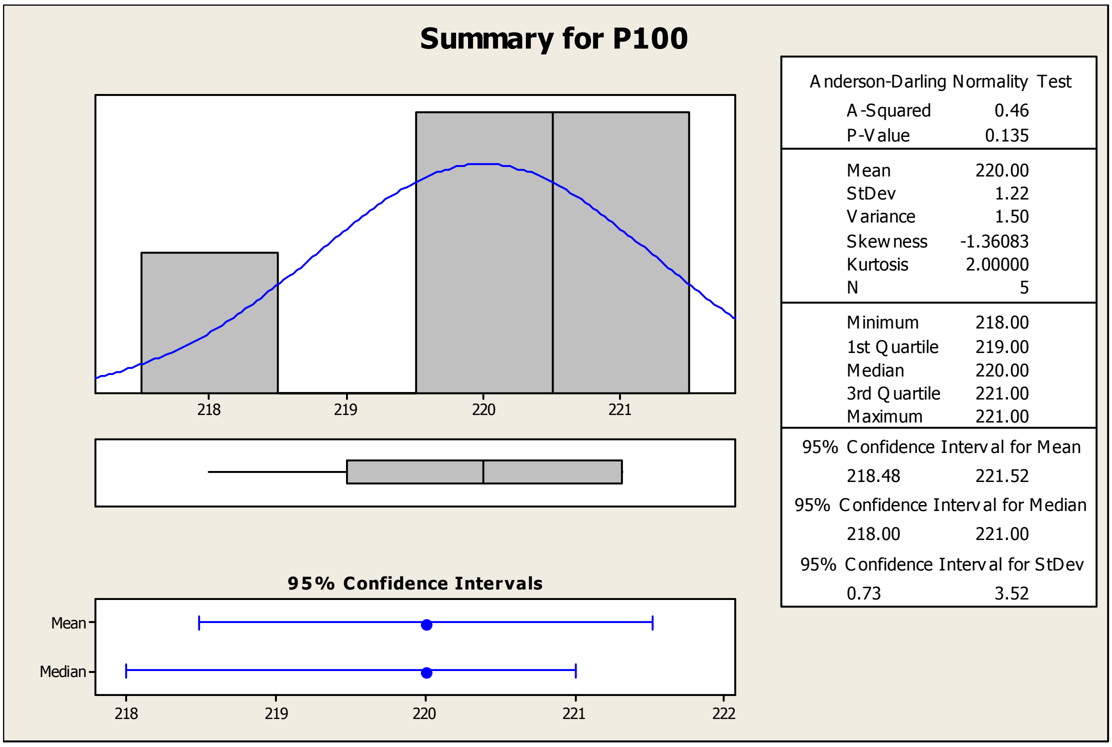
No	Fabrics		Black Count	White Count	Black %	White %
1	FGNE	Mean	399603.33	15116.67	96.35	**3.65**
		Std. Dev.	3217.57	3217.57	0.77	0.77
		1	401461.00	13259.00	96.80	3.20
		2	401461.00	13259.00	96.80	3.20
		3	395888.00	18832.00	95.46	4.54
2	MBW	Mean	365840.00	48880.00	88.22	**11.78**
		Std. Dev.	8775.79	8775.79	2.11	2.11
		1	355893.00	58827.00	85.82	14.18
		2	372489.00	42231.00	89.82	10.18
		3	369138.00	45582.00	89.01	10.99
3	MGW	Mean	363438.00	51282.00	87.63	**12.37**
		Std. Dev.	6488.53	6488.53	1.56	1.56
		1	365430.00	49290.00	88.11	11.89
		2	356187.00	58533.00	85.89	14.11
		3	368697.00	46023.00	88.90	11.10
4	MGWP	Mean	360597.00	54123.00	86.95	**13.05**
		Std. Dev.	10259.77	10259.77	2.47	2.47
		1	348766.00	65954.00	84.10	15.90
		2	365980.00	48740.00	88.25	11.75
		3	367045.00	47675.00	88.50	11.50
5	MRWB	Mean	376275.33	38444.67	90.73	**9.27**
		Std. Dev.	3232.25	3232.25	0.78	0.78
		1	378036.00	36684.00	91.15	8.85
		2	378245.00	36475.00	91.20	8.80
		3	372545.00	42175.00	89.83	10.17

Table A.2.20. Optical porosity of experimental fabrics

No	Fabrics		Black Count	White Count	Black %	White %
1	P100	Mean	393924	20796.00	94.99	**5.01**
		Std. Dev.	3886.29	3886.29	0.94	0.94
		1	393770	20950.00	94.95	5.05
		2	390117	24603.00	94.07	5.93
		3	397885	16835.00	95.94	4.06
2	W43P57	Mean	381977.33	32742.67	92.11	**7.89**
		Std. Dev.	1198.44	1198.44	0.29	0.29
		1	382897	31823.00	92.33	7.67
		2	382413	32307.00	92.21	7.79
		3	380622	34098.00	91.78	8.22
3	W48P52	Mean	388310.67	26409.33	93.63	**6.37**
		Std. Dev.	4642.76	4642.76	1.12	1.12
		1	384403	30317.00	92.69	7.31
		2	393443	21277.00	94.87	5.13
		3	387086	27634.00	93.34	6.66
4	W71P29	Mean	389506	25214.00	93.92	**6.08**
		Std. Dev.	1909.68	1909.68	0.46	0.46
		1	387687	27033.00	93.48	6.52
		2	389336	25384.00	93.88	6.12
		3	391495	23225.00	94.40	5.60
5	W100	Mean	388205.33	26514.67	93.61	**6.39**
		Std. Dev.	3383.92	3383.92	0.82	0.82
		1	385807	28913.00	93.03	6.97
		2	386733	27987.00	93.25	6.75
		3	392076	22644.00	94.54	5.46
6	W35B65	Mean	379582.33	35137.67	91.53	**8.47**
		Std. Dev.	3552.54	3552.54	0.86	0.86
		1	383371	31349.00	92.44	7.56
		2	379050	35670.00	91.40	8.60
		3	376326	38394.00	90.74	9.26
7	W52B48	Mean	357021.33	57698.67	86.09	**13.91**
		Std. Dev.	7357.42	7357.42	1.77	1.77
		1	352359	62361.00	84.96	15.04
		2	353202	61518.00	85.17	14.83
		3	365503	49217.00	88.13	11.87
8	W60B40	Mean	373601.33	41118.67	90.09	**9.91**
		Std. Dev.	8318.09	8318.09	2.01	2.01
		1	376773	37947.00	90.85	9.15
		2	379867	34853.00	91.60	8.40
		3	364164	50556.00	87.81	12.19
9	B100	Mean	365609	49111.00	88.16	**11.84**
		Std. Dev.	1941.64	1941.64	0.47	0.47
		1	363525	51195.00	87.66	12.34
		2	365935	48785.00	88.24	11.76
		3	367367	47353.00	88.58	11.42

A.3. NORMALITY CHECKING FOR ANOVA

Weight

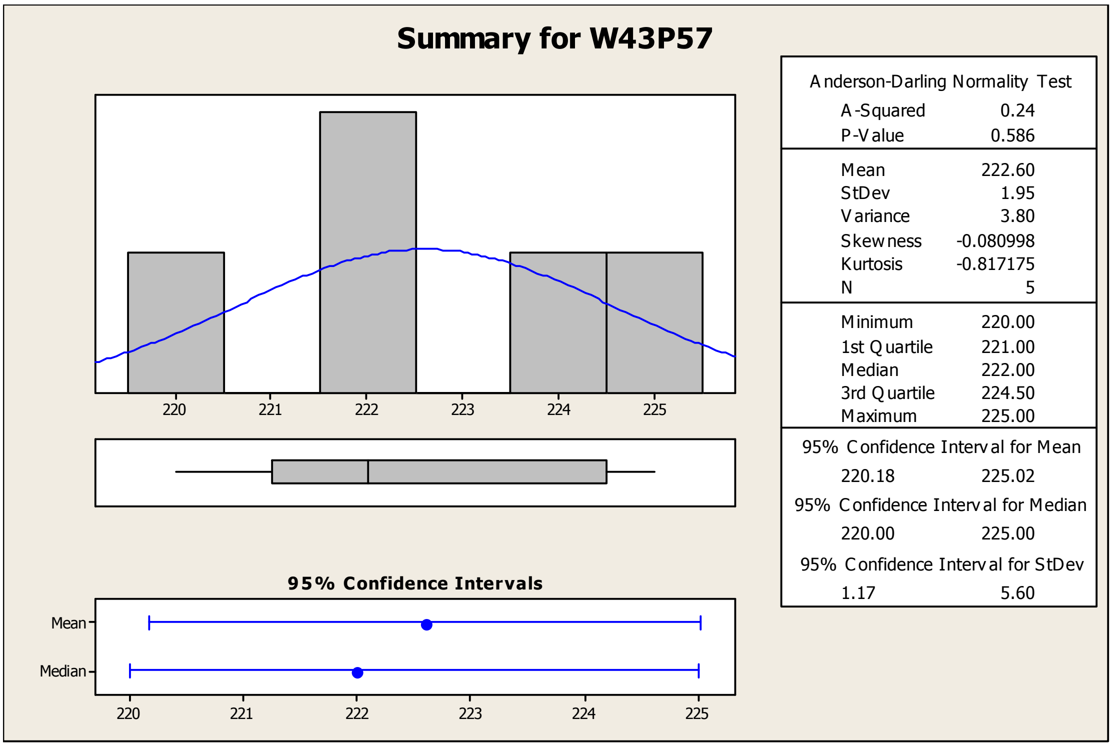


Anderson-Darling Normality Test
A-Squared 0.46
P-Value 0.135

Mean 220.00
StDev 1.22
Variance 1.50
Skewness -1.36083
Kurtosis 2.00000
N 5

Minimum 218.00
1st Quartile 219.00
Median 220.00
3rd Quartile 221.00
Maximum 221.00

95% Confidence Interval for Mean
218.48 221.52
95% Confidence Interval for Median
218.00 221.00
95% Confidence Interval for StDev
0.73 3.52

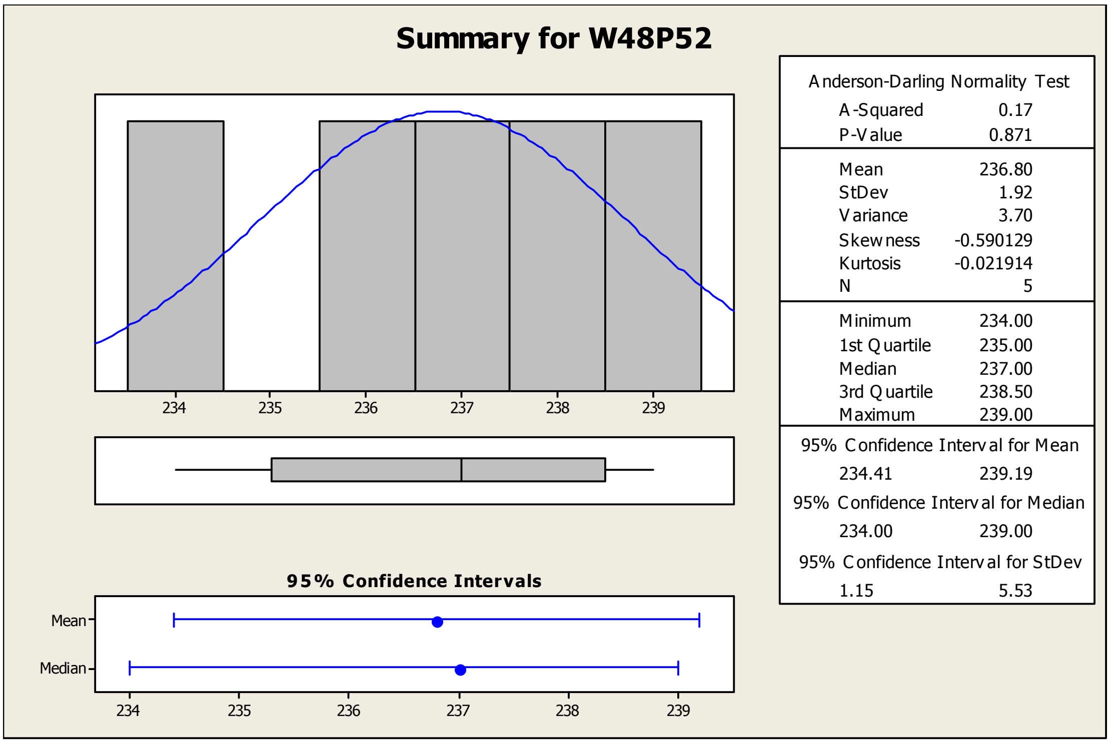


Anderson-Darling Normality Test
A-Squared 0.24
P-Value 0.586

Mean 222.60
StDev 1.95
Variance 3.80
Skewness -0.080998
Kurtosis -0.817175
N 5

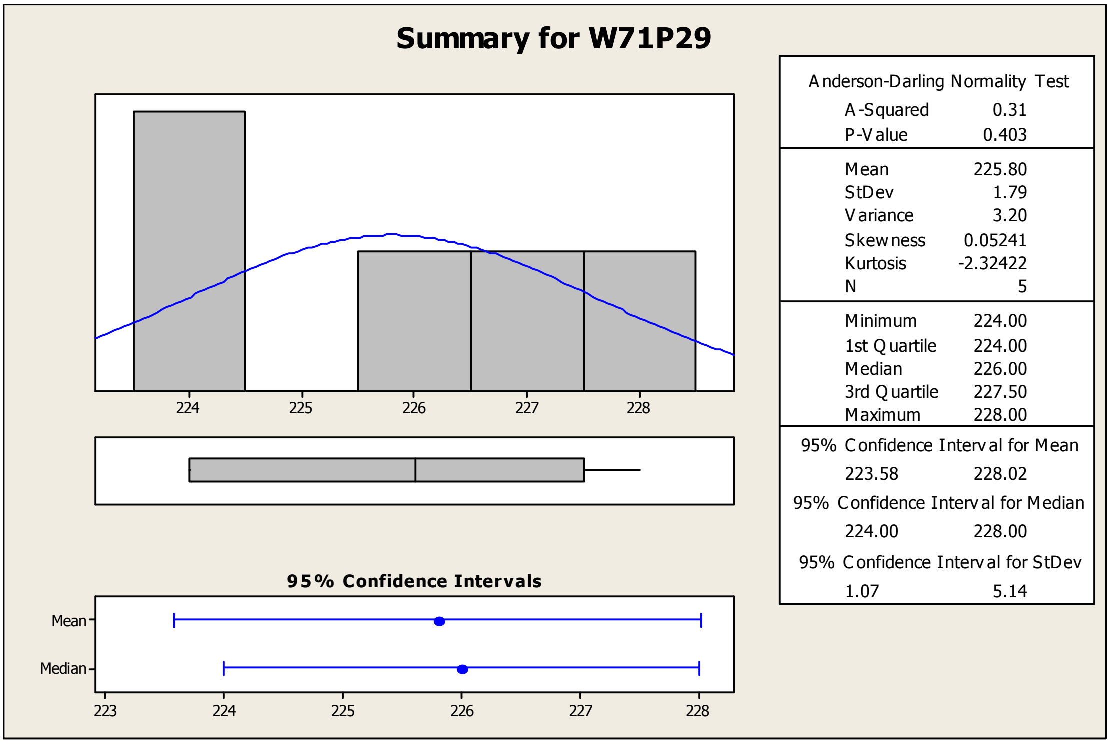
Minimum 220.00
1st Quartile 221.00
Median 222.00
3rd Quartile 224.50
Maximum 225.00

95% Confidence Interval for Mean
220.18 225.02
95% Confidence Interval for Median
220.00 225.00
95% Confidence Interval for StDev
1.17 5.60



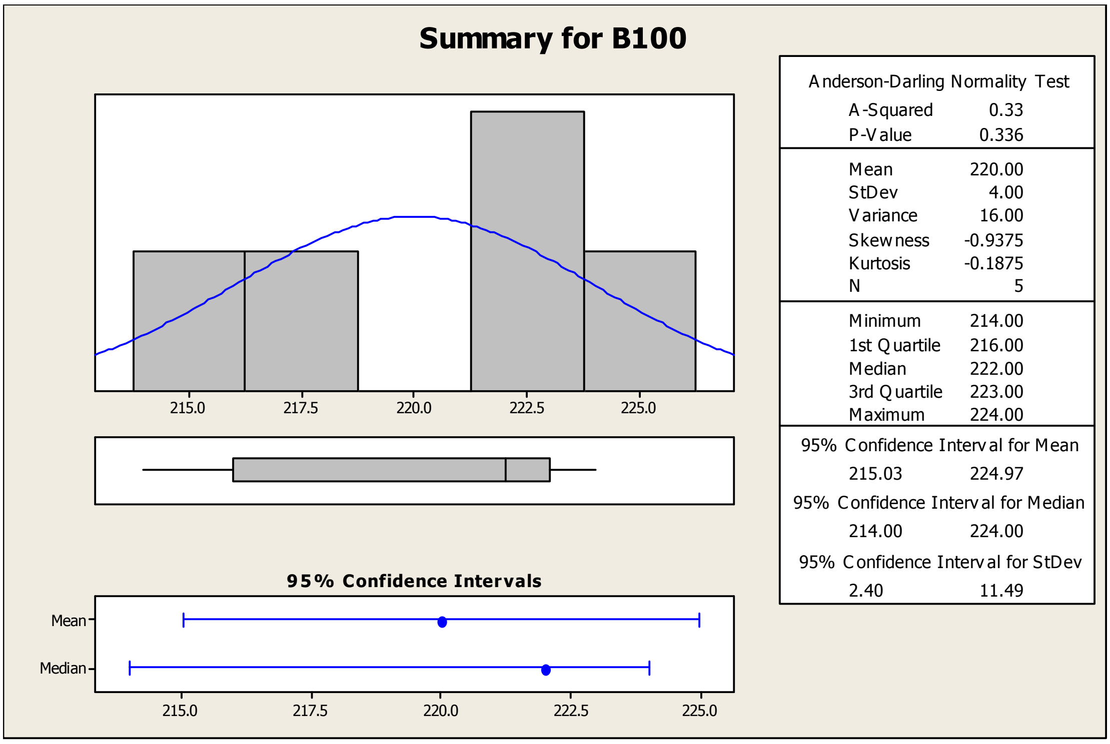
Summary for W48P52

Anderson-Darling Normality Test	
A-Squared	0.17
P-Value	0.871
Mean	236.80
StDev	1.92
Variance	3.70
Skewness	-0.590129
Kurtosis	-0.021914
N	5
Minimum	234.00
1st Quartile	235.00
Median	237.00
3rd Quartile	238.50
Maximum	239.00
95% Confidence Interval for Mean	
234.41	239.19
95% Confidence Interval for Median	
234.00	239.00
95% Confidence Interval for StDev	
1.15	5.53



Summary for W71P29

Anderson-Darling Normality Test	
A-Squared	0.31
P-Value	0.403
Mean	225.80
StDev	1.79
Variance	3.20
Skewness	0.05241
Kurtosis	-2.32422
N	5
Minimum	224.00
1st Quartile	224.00
Median	226.00
3rd Quartile	227.50
Maximum	228.00
95% Confidence Interval for Mean	
223.58	228.02
95% Confidence Interval for Median	
224.00	228.00
95% Confidence Interval for StDev	
1.07	5.14



Summary for B100

Anderson-Darling Normality Test

A-Squared	0.33
P-Value	0.336
Mean	220.00
StDev	4.00
Variance	16.00
Skewness	-0.9375
Kurtosis	-0.1875
N	5
Minimum	214.00
1st Quartile	216.00
Median	222.00
3rd Quartile	223.00
Maximum	224.00

95% Confidence Interval for Mean

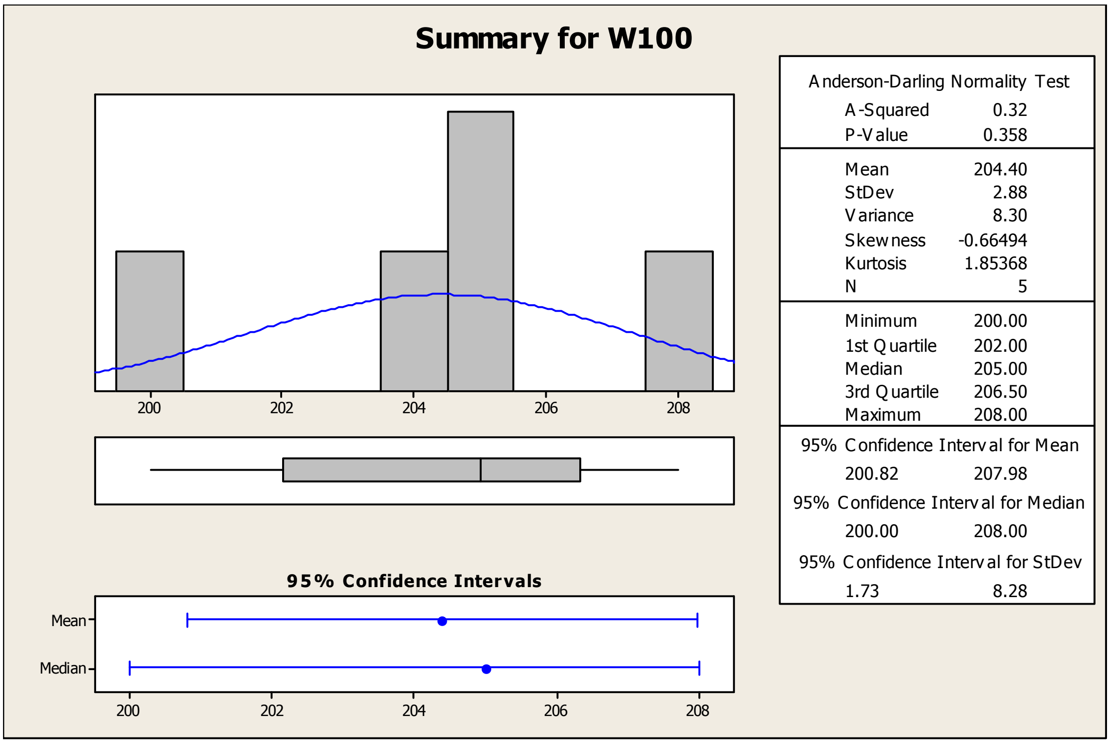
215.03 224.97

95% Confidence Interval for Median

214.00 224.00

95% Confidence Interval for StDev

2.40 11.49



Summary for W100

Anderson-Darling Normality Test

A-Squared	0.32
P-Value	0.358
Mean	204.40
StDev	2.88
Variance	8.30
Skewness	-0.66494
Kurtosis	1.85368
N	5
Minimum	200.00
1st Quartile	202.00
Median	205.00
3rd Quartile	206.50
Maximum	208.00

95% Confidence Interval for Mean

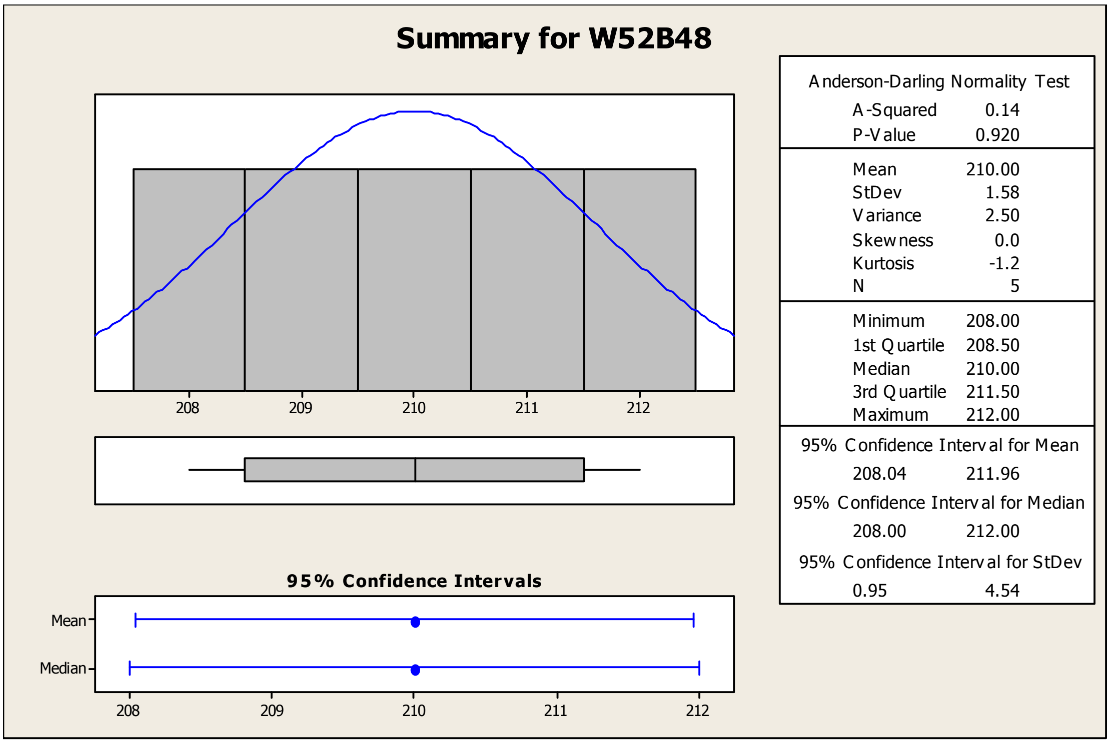
200.82 207.98

95% Confidence Interval for Median

200.00 208.00

95% Confidence Interval for StDev

1.73 8.28

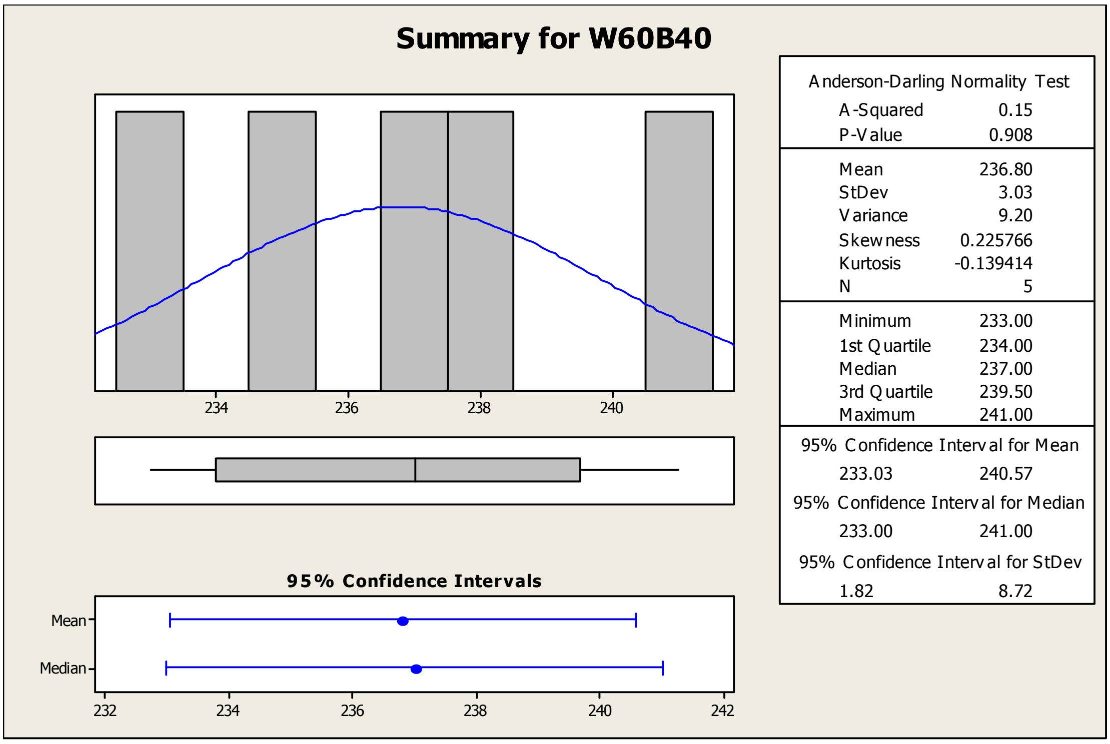

Summary for W52B48

Anderson-Darling Normality Test
A-Squared 0.14
P-Value 0.920

Mean 210.00
StDev 1.58
Variance 2.50
Skewness 0.0
Kurtosis -1.2
N 5

Minimum 208.00
1st Quartile 208.50
Median 210.00
3rd Quartile 211.50
Maximum 212.00

95% Confidence Interval for Mean
208.04 211.96
95% Confidence Interval for Median
208.00 212.00
95% Confidence Interval for StDev
0.95 4.54

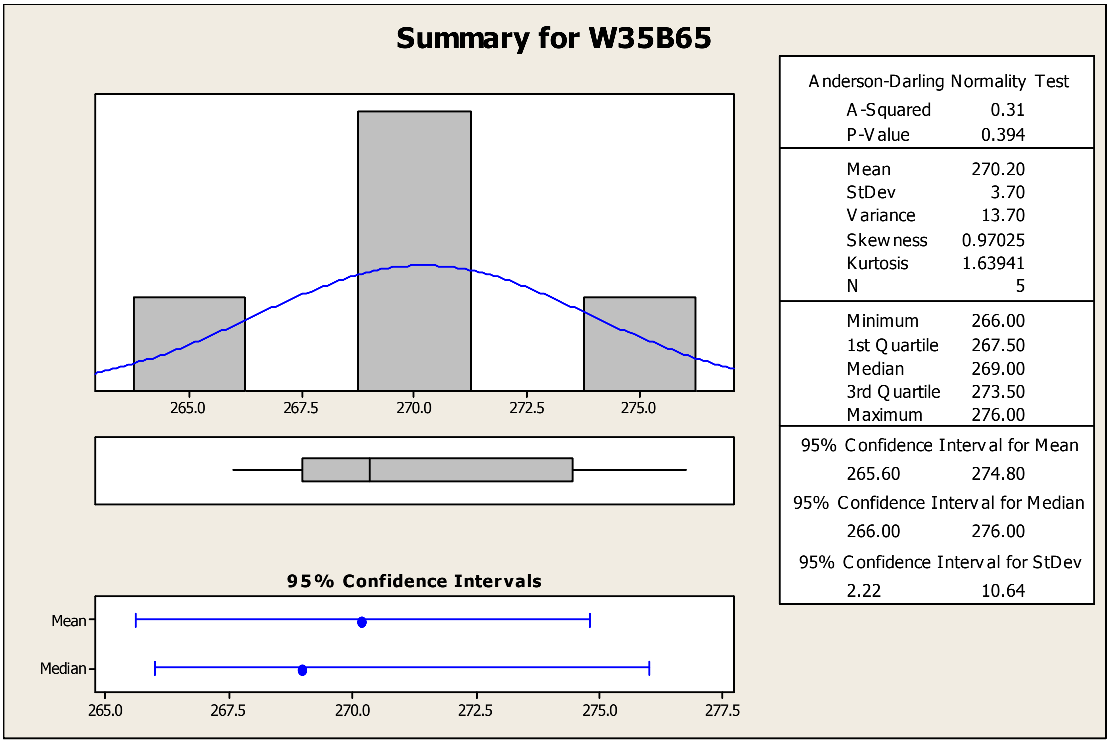

Summary for W60B40

Anderson-Darling Normality Test
A-Squared 0.15
P-Value 0.908

Mean 236.80
StDev 3.03
Variance 9.20
Skewness 0.225766
Kurtosis -0.139414
N 5

Minimum 233.00
1st Quartile 234.00
Median 237.00
3rd Quartile 239.50
Maximum 241.00

95% Confidence Interval for Mean
233.03 240.57
95% Confidence Interval for Median
233.00 241.00
95% Confidence Interval for StDev
1.82 8.72



Anderson-Darling Normality Test

A-Squared	0.31
P-Value	0.394
Mean	270.20
StDev	3.70
Variance	13.70
Skewness	0.97025
Kurtosis	1.63941
N	5
Minimum	266.00
1st Quartile	267.50
Median	269.00
3rd Quartile	273.50
Maximum	276.00

95% Confidence Interval for Mean

265.60 274.80

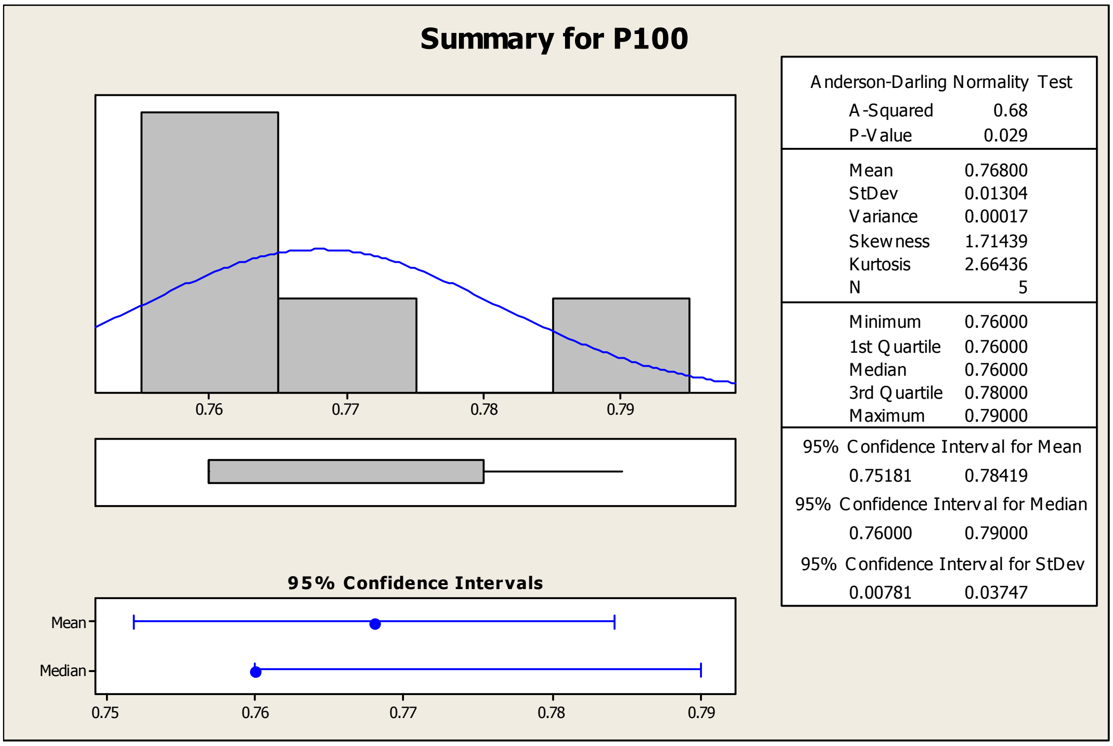
95% Confidence Interval for Median

266.00 276.00

95% Confidence Interval for StDev

2.22 10.64

Thickness

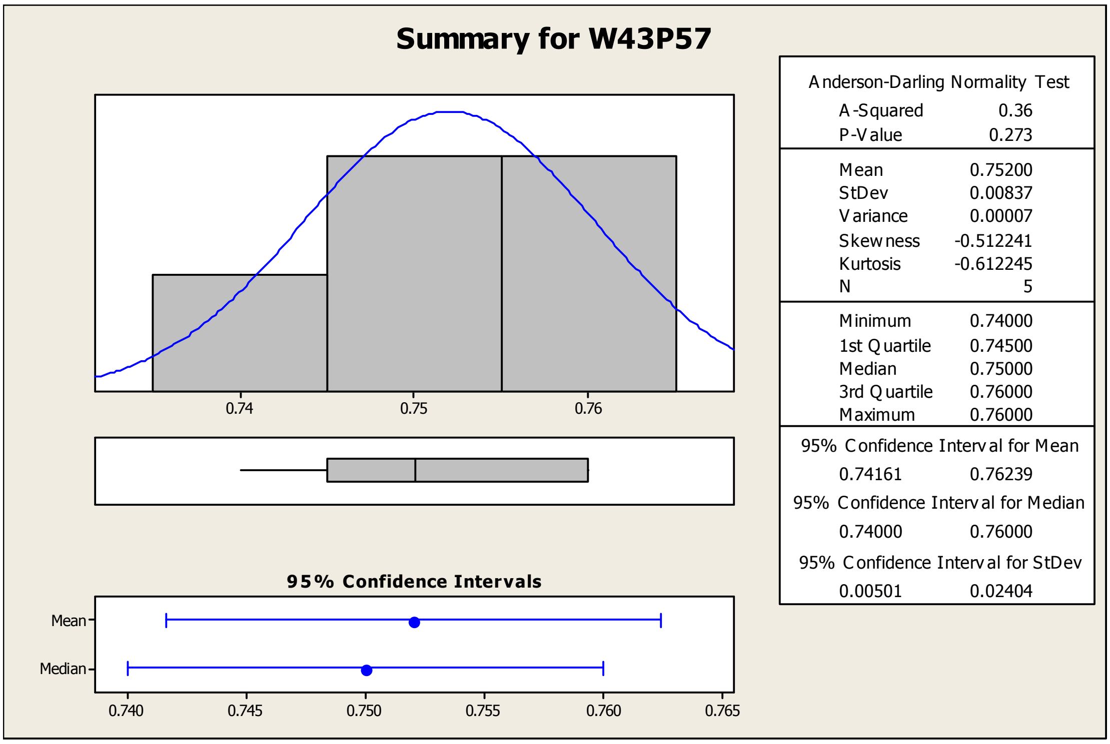


Anderson-Darling Normality Test
A-Squared 0.68
P-Value 0.029

Mean 0.76800
StDev 0.01304
Variance 0.00017
Skewness 1.71439
Kurtosis 2.66436
N 5

Minimum 0.76000
1st Quartile 0.76000
Median 0.76000
3rd Quartile 0.78000
Maximum 0.79000

95% Confidence Interval for Mean
0.75181 0.78419
95% Confidence Interval for Median
0.76000 0.79000
95% Confidence Interval for StDev
0.00781 0.03747

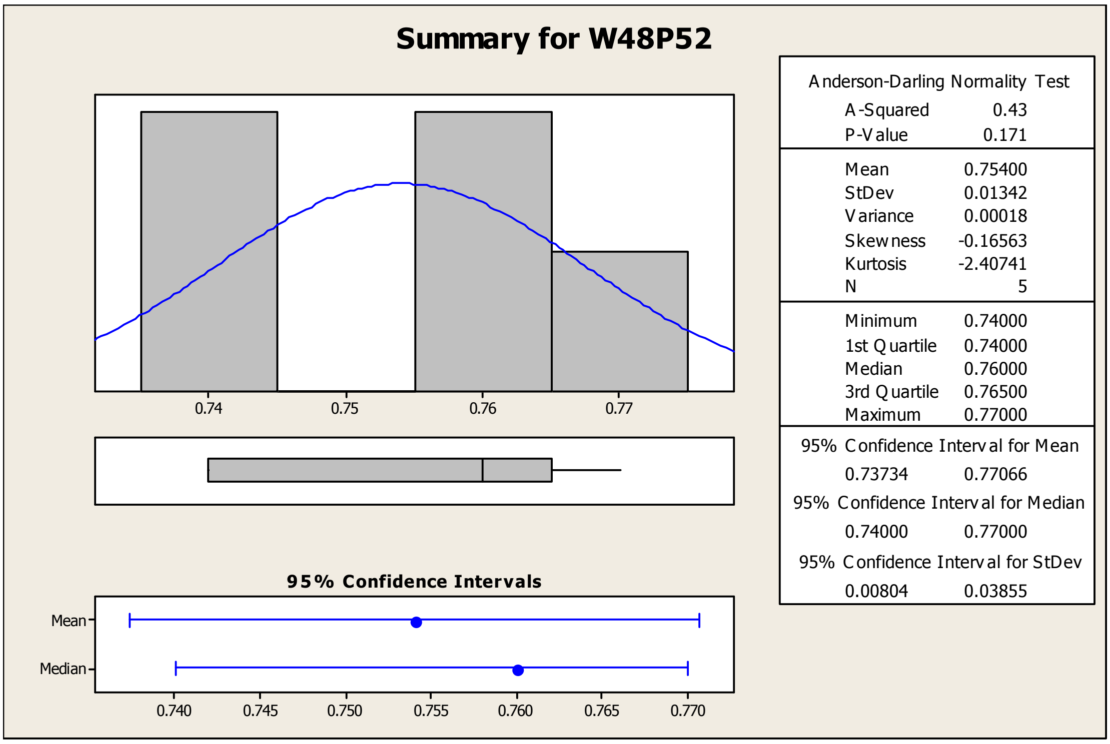


Anderson-Darling Normality Test
A-Squared 0.36
P-Value 0.273

Mean 0.75200
StDev 0.00837
Variance 0.00007
Skewness -0.512241
Kurtosis -0.612245
N 5

Minimum 0.74000
1st Quartile 0.74500
Median 0.75000
3rd Quartile 0.76000
Maximum 0.76000

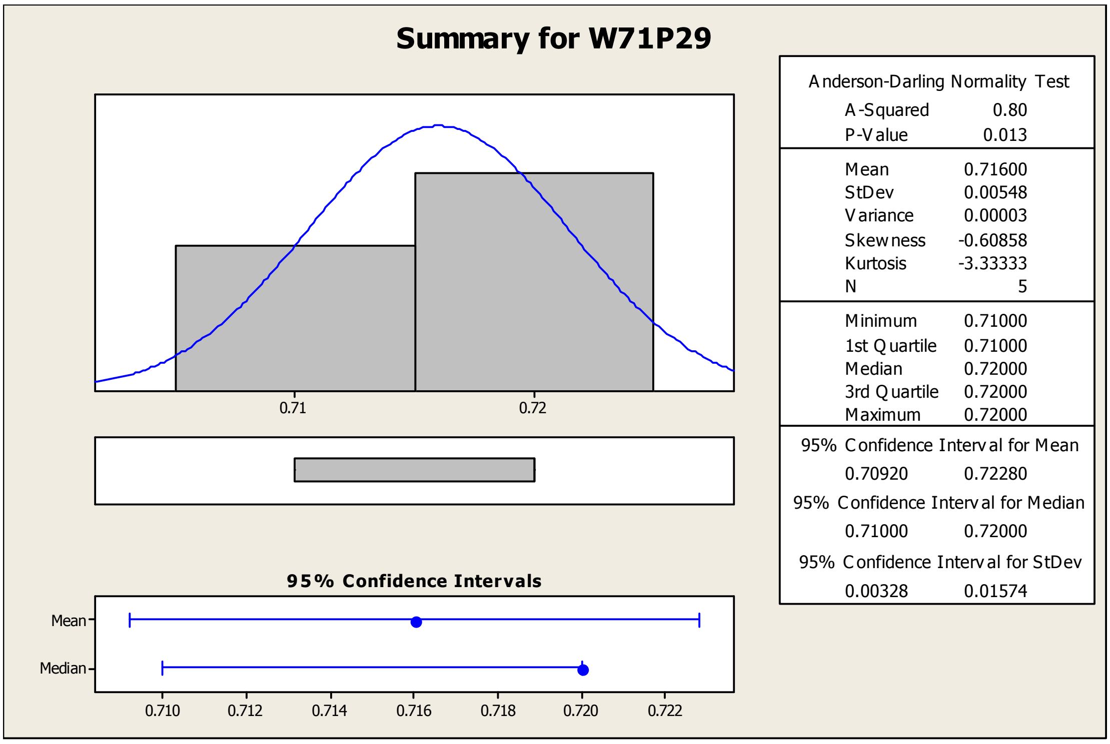
95% Confidence Interval for Mean
0.74161 0.76239
95% Confidence Interval for Median
0.74000 0.76000
95% Confidence Interval for StDev
0.00501 0.02404


Summary for W48P52

Anderson-Darling Normality Test
A-Squared 0.43
P-Value 0.171

Mean	0.75400
StDev	0.01342
Variance	0.00018
Skewness	-0.16563
Kurtosis	-2.40741
N	5
Minimum	0.74000
1st Quartile	0.74000
Median	0.76000
3rd Quartile	0.76500
Maximum	0.77000

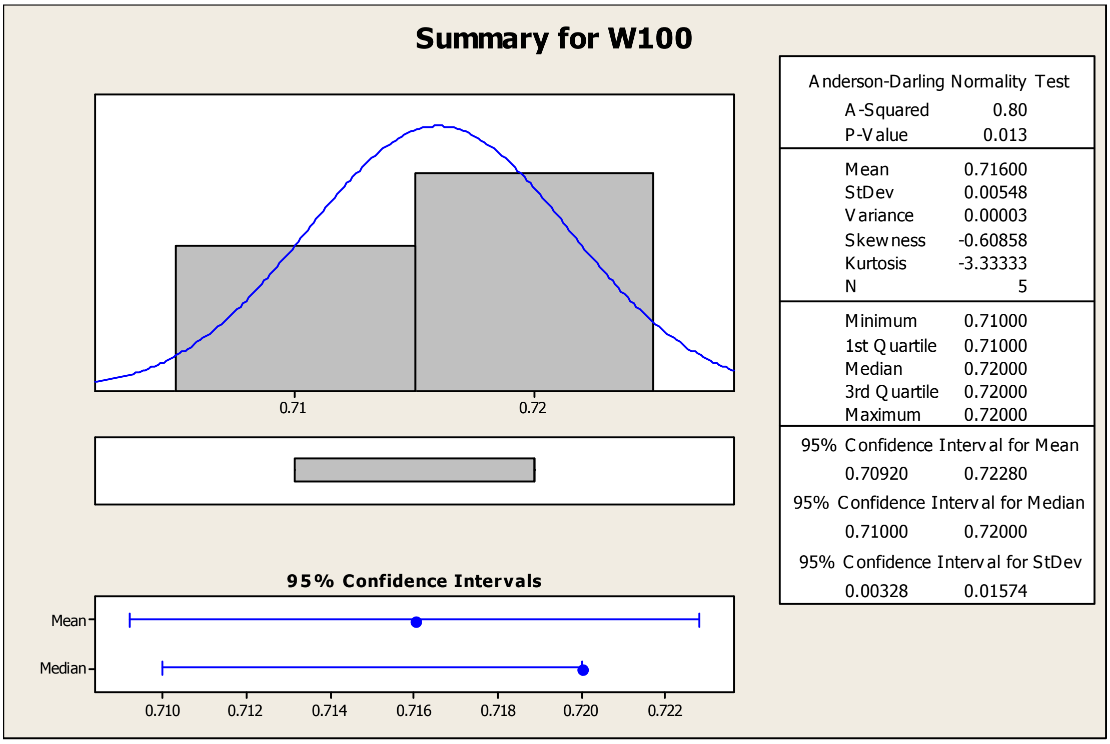
95% Confidence Interval for Mean
0.73734 0.77066
95% Confidence Interval for Median
0.74000 0.77000
95% Confidence Interval for StDev
0.00804 0.03855


Summary for W71P29

Anderson-Darling Normality Test
A-Squared 0.80
P-Value 0.013

Mean	0.71600
StDev	0.00548
Variance	0.00003
Skewness	-0.60858
Kurtosis	-3.33333
N	5
Minimum	0.71000
1st Quartile	0.71000
Median	0.72000
3rd Quartile	0.72000
Maximum	0.72000

95% Confidence Interval for Mean
0.70920 0.72280
95% Confidence Interval for Median
0.71000 0.72000
95% Confidence Interval for StDev
0.00328 0.01574



Summary for W100

Anderson-Darling Normality Test

A-Squared	0.80
P-Value	0.013
Mean	0.71600
StDev	0.00548
Variance	0.00003
Skewness	-0.60858
Kurtosis	-3.33333
N	5
Minimum	0.71000
1st Quartile	0.71000
Median	0.72000
3rd Quartile	0.72000
Maximum	0.72000

95% Confidence Interval for Mean

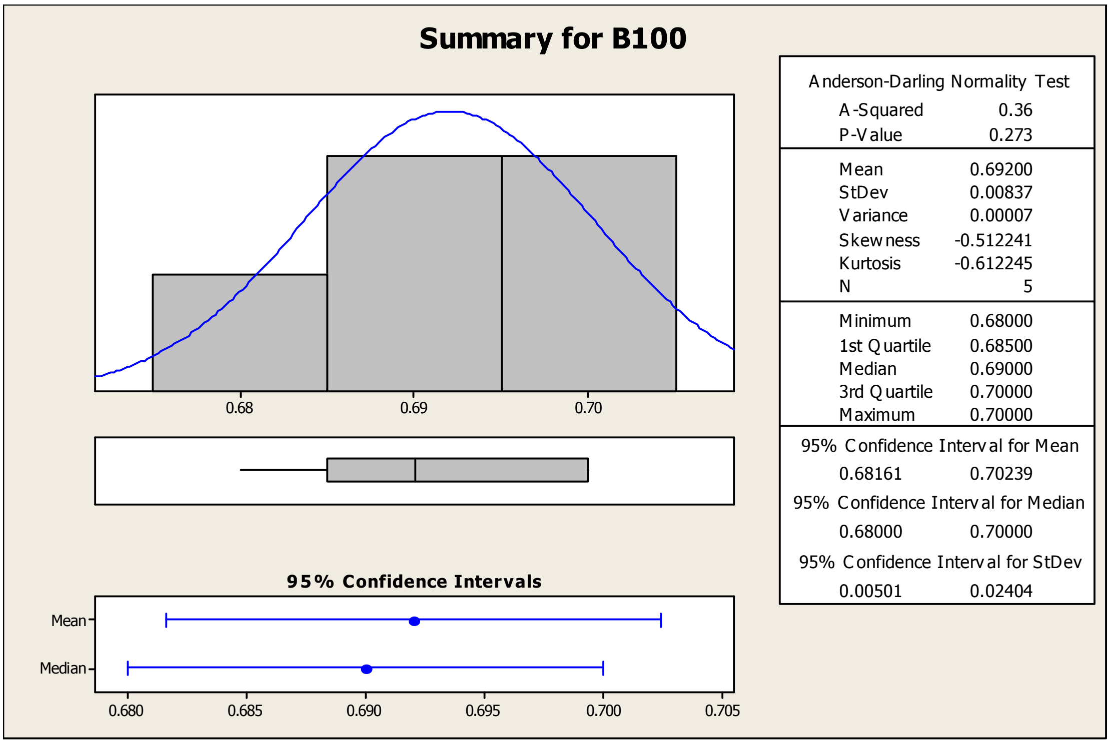
0.70920 0.72280

95% Confidence Interval for Median

0.71000 0.72000

95% Confidence Interval for StDev

0.00328 0.01574



Summary for B100

Anderson-Darling Normality Test

A-Squared	0.36
P-Value	0.273
Mean	0.69200
StDev	0.00837
Variance	0.00007
Skewness	-0.512241
Kurtosis	-0.612245
N	5
Minimum	0.68000
1st Quartile	0.68500
Median	0.69000
3rd Quartile	0.70000
Maximum	0.70000

95% Confidence Interval for Mean

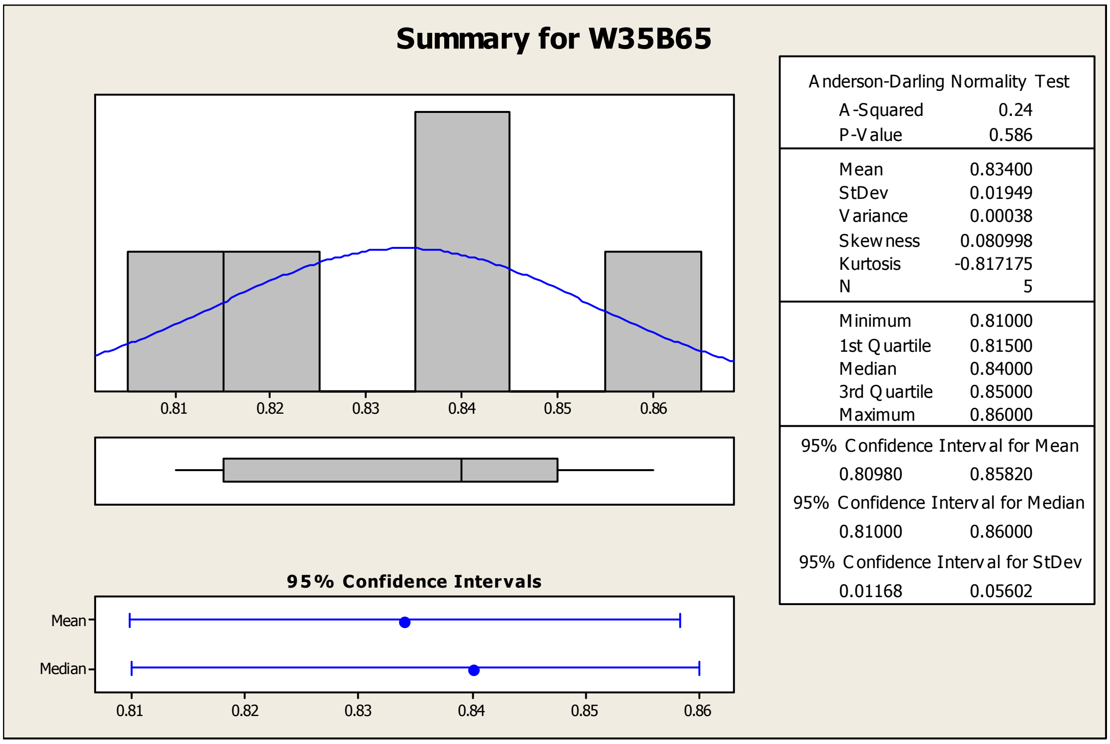
0.68161 0.70239

95% Confidence Interval for Median

0.68000 0.70000

95% Confidence Interval for StDev

0.00501 0.02404

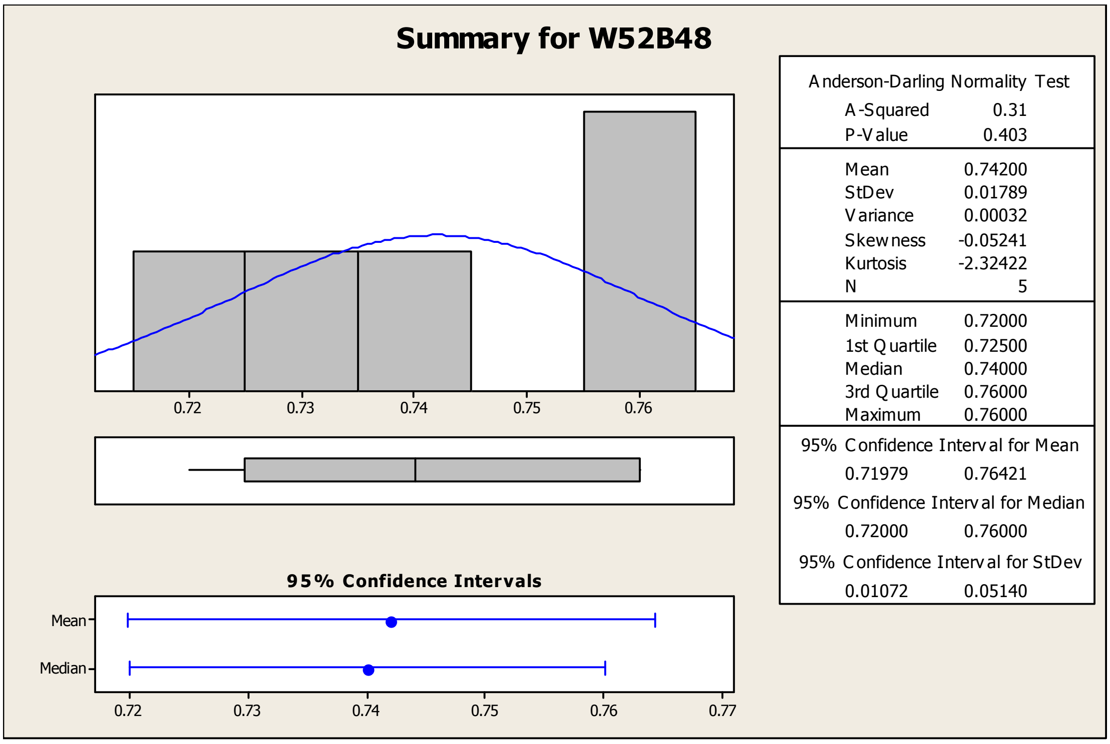


```
Anderson-Darling Normality Test
   A-Squared          0.24
   P-Value           0.586

   Mean            0.83400
   StDev           0.01949
   Variance        0.00038
   Skewness       0.080998
   Kurtosis      -0.817175
   N                     5

   Minimum         0.81000
   1st Quartile    0.81500
   Median          0.84000
   3rd Quartile    0.85000
   Maximum         0.86000

 95% Confidence Interval for Mean
   0.80980         0.85820
95% Confidence Interval for Median
   0.81000         0.86000
 95% Confidence Interval for StDev
   0.01168         0.05602
```

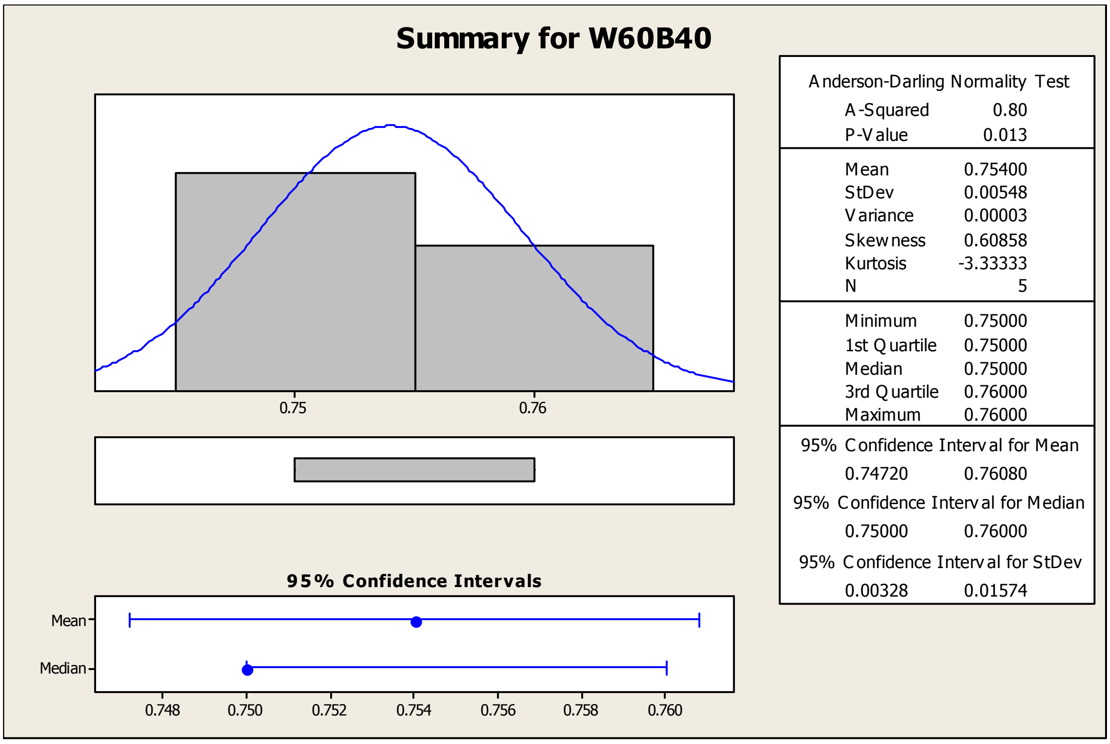


```
Anderson-Darling Normality Test
   A-Squared          0.31
   P-Value           0.403

   Mean            0.74200
   StDev           0.01789
   Variance        0.00032
   Skewness       -0.05241
   Kurtosis       -2.32422
   N                     5

   Minimum         0.72000
   1st Quartile    0.72500
   Median          0.74000
   3rd Quartile    0.76000
   Maximum         0.76000

 95% Confidence Interval for Mean
   0.71979         0.76421
95% Confidence Interval for Median
   0.72000         0.76000
 95% Confidence Interval for StDev
   0.01072         0.05140
```



```
Anderson-Darling Normality Test
     A-Squared            0.80
     P-Value             0.013

     Mean              0.75400
     StDev             0.00548
     Variance          0.00003
     Skewness          0.60858
     Kurtosis         -3.33333
     N                       5

     Minimum           0.75000
     1st Quartile      0.75000
     Median            0.75000
     3rd Quartile      0.76000
     Maximum           0.76000
 95% Confidence Interval for Mean
     0.74720           0.76080
95% Confidence Interval for Median
     0.75000           0.76000
 95% Confidence Interval for StDev
     0.00328           0.01574
```

A.4 .ANOVA

Data display experimental samples weight

C1	C2	C3	C4	C5	C6	C7	C8	C9
P100	W43P57	W48P52	W71P29	W100	W35B65	W52B48	W60B40	B100
220	220	236	224	208	276	210	233	214
221	222	234	224	204	269	208	241	222
221	222	238	226	205	269	212	238	222
220	224	237	227	200	271	211	235	224
218	225	239	228	205	266	209	237	218

One-way ANOVA: weight: C1, C2, C3, C4, C5, C6, C7, C8, C9

```
Source  DF        SS       MS       F      P
Factor   8  14877.20  1859.65  270.39  0.000
Error   36    247.60     6.88
Total   44  15124.80

S = 2.623   R-Sq = 98.36%   R-Sq(adj) = 98.00%


                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level   N    Mean  StDev  ---------+---------+---------+---------+
C1      5  220.00   1.22          (*)
C2      5  222.60   1.95           (*)
C3      5  236.80   1.92                  (*-)
C4      5  225.80   1.79             (*)
C5      5  204.40   2.88  (*)
C6      5  270.20   3.70                                   (*)
C7      5  210.00   1.58     (*)
C8      5  236.80   3.03                  (*-)
C9      5  220.00   4.00          (*)
                          ---------+---------+---------+---------+
                                 220       240       260       280

Pooled StDev = 2.62
```

Variables:
C1 = weight of fabric in P100
C2 = weight of fabric in W43P57
C3 = weight of fabric in W48P52
C4 = weight of fabric in W71P29
C5 = weight of fabric in W100
C6 = weight of fabric in W35B65
C7 = weight of fabric in W52B48
C8 = weight of fabric in W60B40
C9 = weight of fabric in B100

1.Ho: $\mu1=\mu2=\mu3=\mu4=\mu5=\mu6=\mu7=\mu8=\mu9$
Ha: at least one mean is different from the others

2. $\alpha= 0.05$

3. Assume Ho is true. F= MSB/MSW   F(k-1,N-k)
   For this case, k=9, N=45 and F=1859.65/6.88=270.30   F(8,36)

Variation	Sum of squares	Degrees of freedom	Mean squares	F
Between	14877.2	8	1859.2	270.39
Within	247.60	36	6.88	2.18 (F table)

4. Reject Ho if F > 2.18

5. Decision: since F = 270.39> 2.18, reject Ho
   Conclusion: There is sufficient evidence at the 5% level of significance to conclude that at least one of the mean weights of fabrics is different from other means.

Data display experimental samples thickness

C1	C2	C3	C4	C5	C6	C7	C8	C9
P100	W43P57	W48P52	W71P29	W100	W35B65	W52B48	W60B40	B100
0.76	0.75	0.76	0.72	0.72	0.86	0.72	0.75	0.7
0.76	0.76	0.74	0.72	0.72	0.81	0.73	0.75	0.7
0.76	0.74	0.77	0.71	0.72	0.82	0.74	0.75	0.69
0.79	0.75	0.74	0.71	0.71	0.84	0.76	0.76	0.69
0.77	0.76	0.76	0.72	0.71	0.84	0.76	0.76	0.68

One-way ANOVA: thickness: C1, C2, C3, C4, C5, C6, C7, C8, C9

```
Source  DF        SS        MS      F      P
Factor   8  0.065511  0.008189  57.58  0.000
Error   36  0.005120  0.000142
Total   44  0.070631

S = 0.01193   R-Sq = 92.75%   R-Sq(adj) = 91.14%


                                Individual 95% CIs For Mean Based on
                                Pooled StDev
Level      N     Mean    StDev  ----+---------+---------+---------+-----
C1         5  0.76800  0.01304                 (--*-)
C2         5  0.75200  0.00837              (-*--)
C3         5  0.75400  0.01342               (-*-)
C4         5  0.71600  0.00548       (-*-)
C5         5  0.71600  0.00548       (-*-)
C6         5  0.83400  0.01949                             (-*-)
C7         5  0.74200  0.01789            (-*--)
C8         5  0.75400  0.00548               (-*-)
C9         5  0.69200  0.00837  (-*--)
                                ----+---------+---------+---------+-----
                                  0.700     0.750     0.800     0.850

Pooled StDev = 0.01193
```

Variables:
C1 = weight of fabric in P100
C2 = weight of fabric in W43P57
C3 = weight of fabric in W48P52
C4 = weight of fabric in W71P29
C5 = weight of fabric in W100
C6 = weight of fabric in W35B65
C7 = weight of fabric in W52B48
C8 = weight of fabric in W60B40
C9 = weight of fabric in B100

1.Ho: $\mu1=\mu2=\mu3=\mu4=\mu5=\mu6=\mu7=\mu8=\mu9$
Ha: at least one mean is different from the others

2. $\alpha= 0.05$

3. Assume Ho is true. F= MSB/MSW F(k-1,N-k)
For this case, k=9, N=45 and F=0.008189/0.000142=57.58 F(8,36)

Variation	Sum of squares	Degrees of freedom	Mean squares	F
Between	0.065511	8	0.008189	57.58
Within	0.005120	36	0.000142	2.18 (F table)

4. Reject Ho if F > 2.18

5. Decision: since F = 57.58 > 2.18, reject Ho
Conclusion: There is sufficient evidence at the 5% level of significance to conclude that at least one of the mean thicknesses of fabrics is different from other means.

A.5. THE FINGERPRINTS OF MOISTURE MANAGEMENT PROPERTIES OF FABRICS

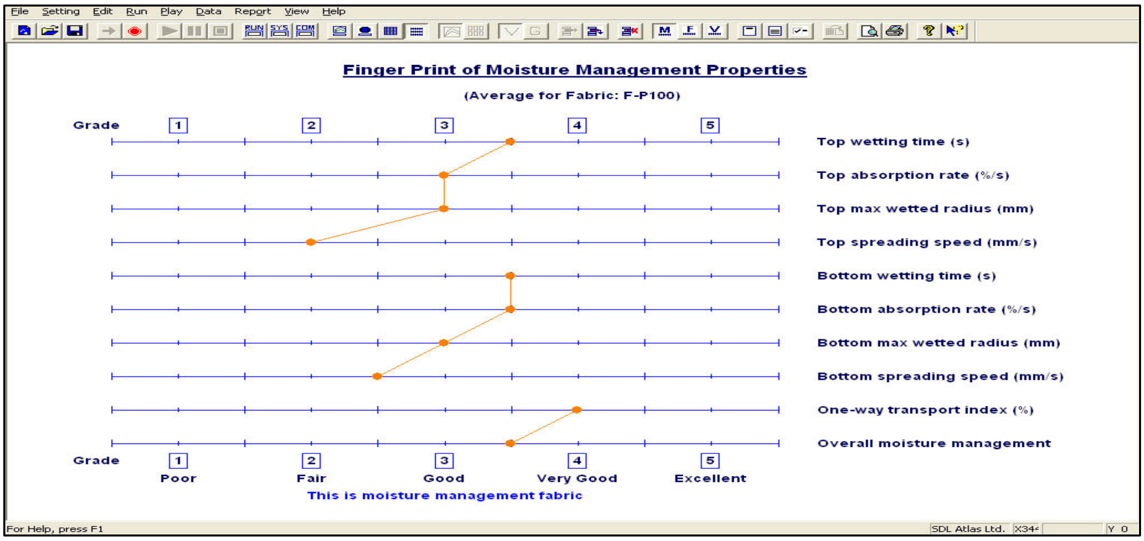


Figure A.5.1.Fingerprint moisture management properties of P100

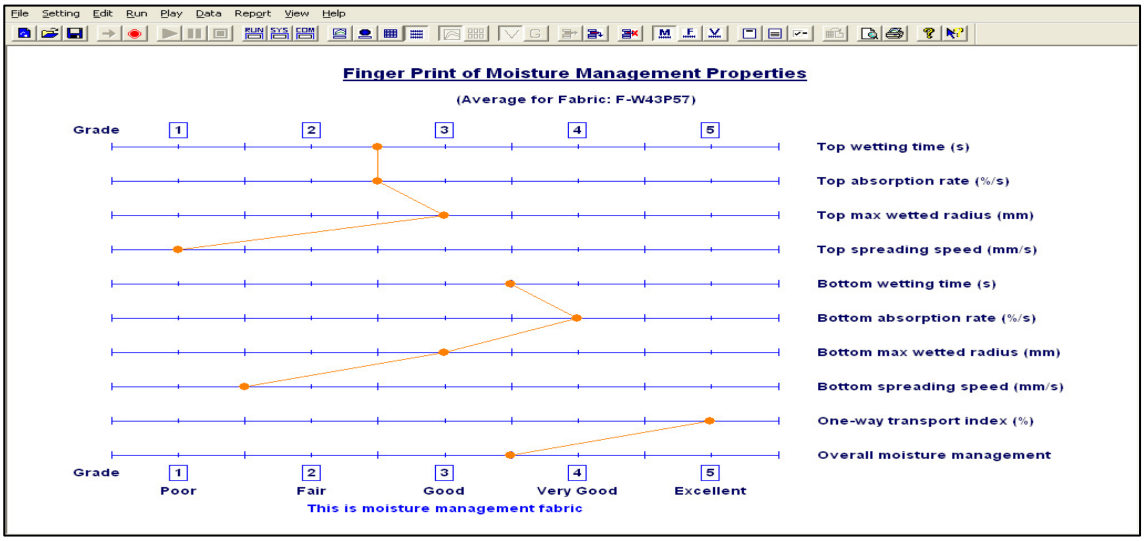


Figure A.5.2.Fingerprint moisture management properties of W43P57

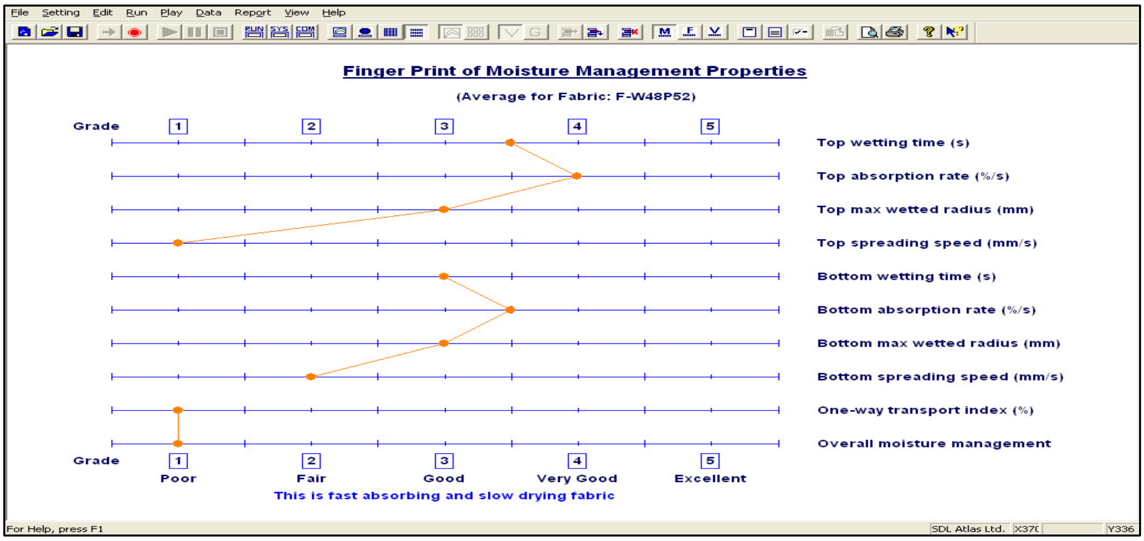


Figure A.5.3.Fingerprint moisture management properties of W48P52

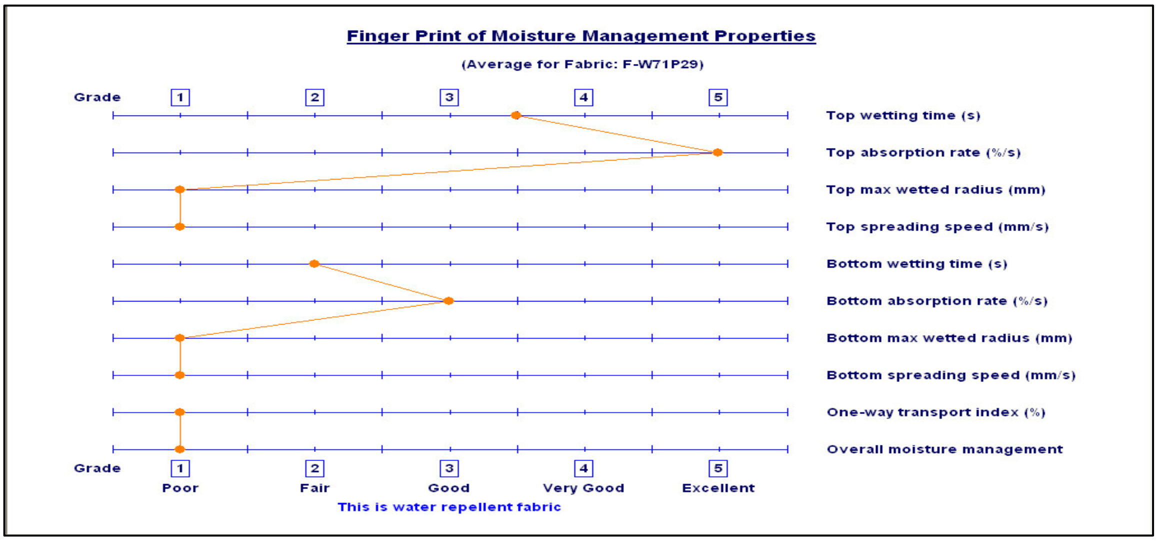


Figure A.5.4.Fingerprint moisture management properties of W71P29

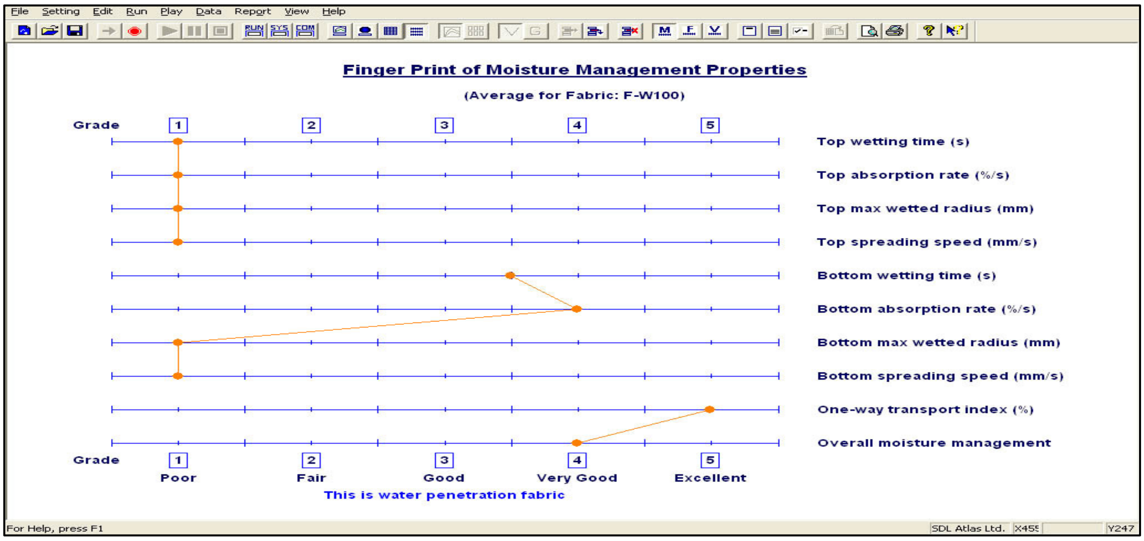
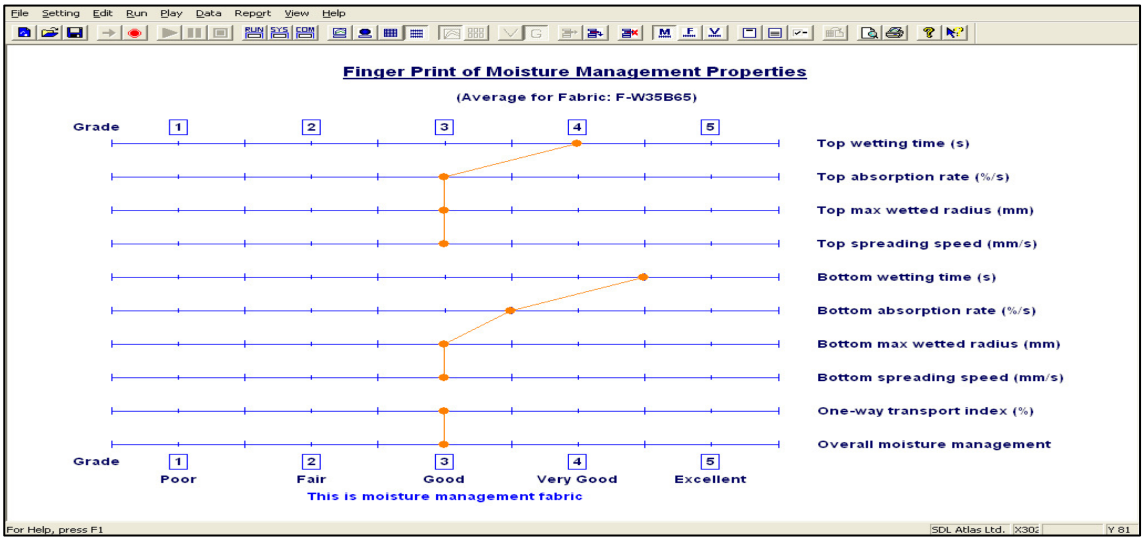


Figure A.5.5.Fingerprint moisture management properties of W100

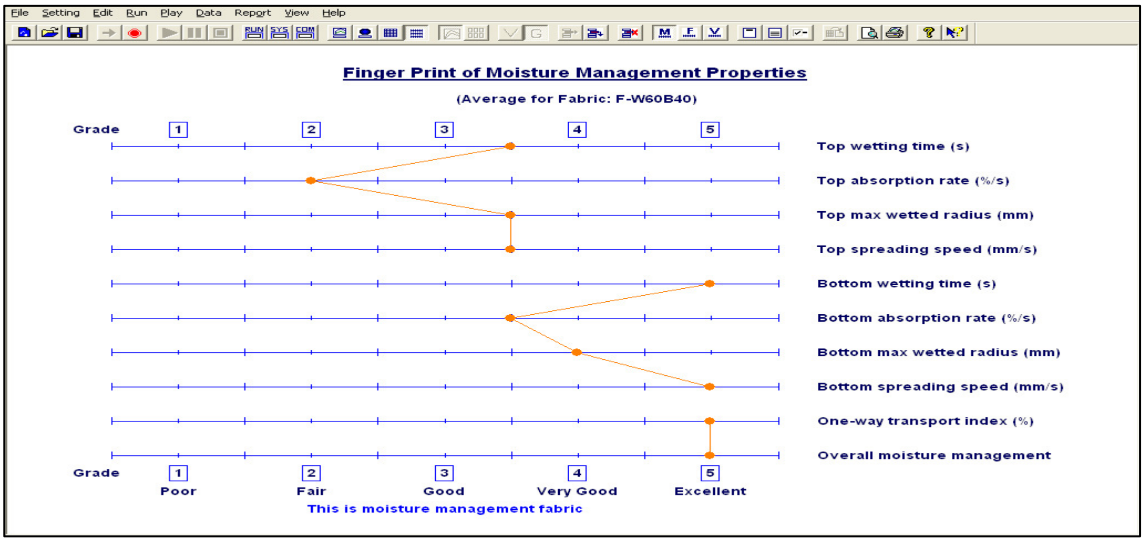


Finger Print of Moisture Management Properties

(Average for Fabric: F-W35B65)

This is moisture management fabric

Figure A.5.6.Fingerprint moisture management properties of W35B65

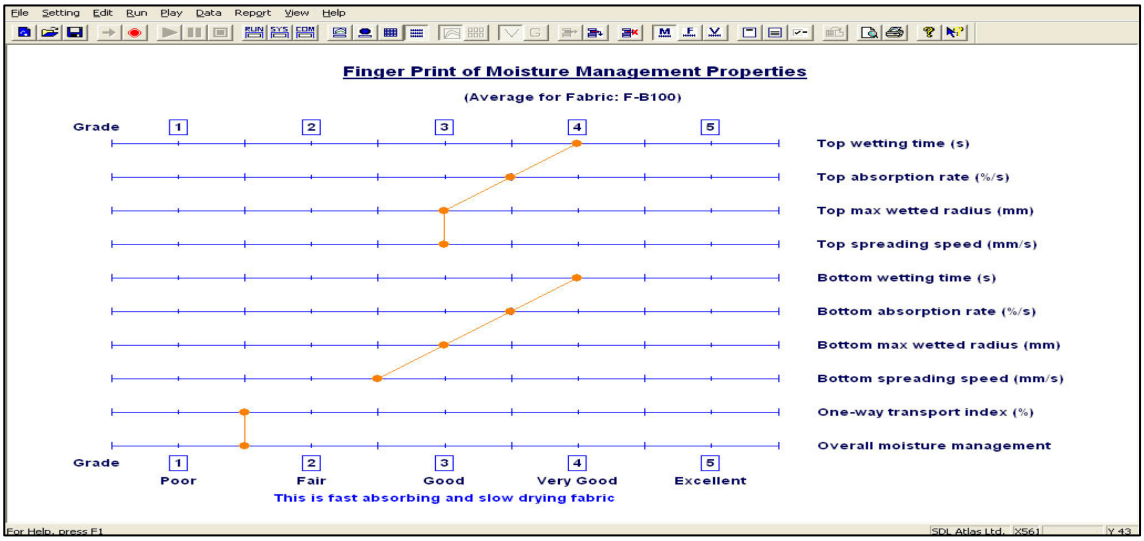


Finger Print of Moisture Management Properties

(Average for Fabric: F-W60B40)

This is moisture management fabric

Figure A.5.7.Fingerprint moisture management properties of W60B40

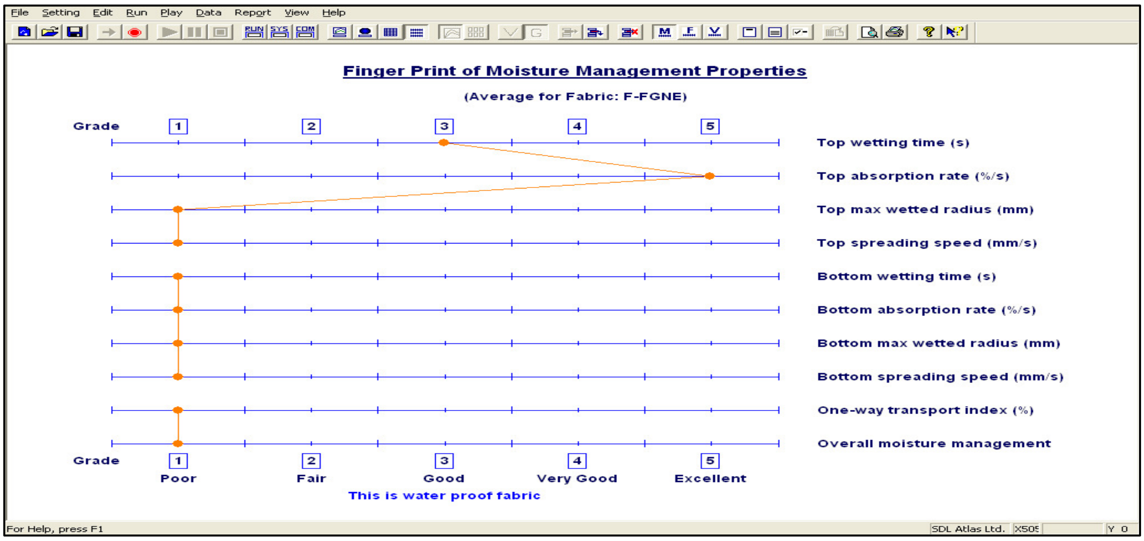


Finger Print of Moisture Management Properties

(Average for Fabric: F-B100)

This is fast absorbing and slow drying fabric

Figure A.5.8.Fingerprint moisture management properties of B100

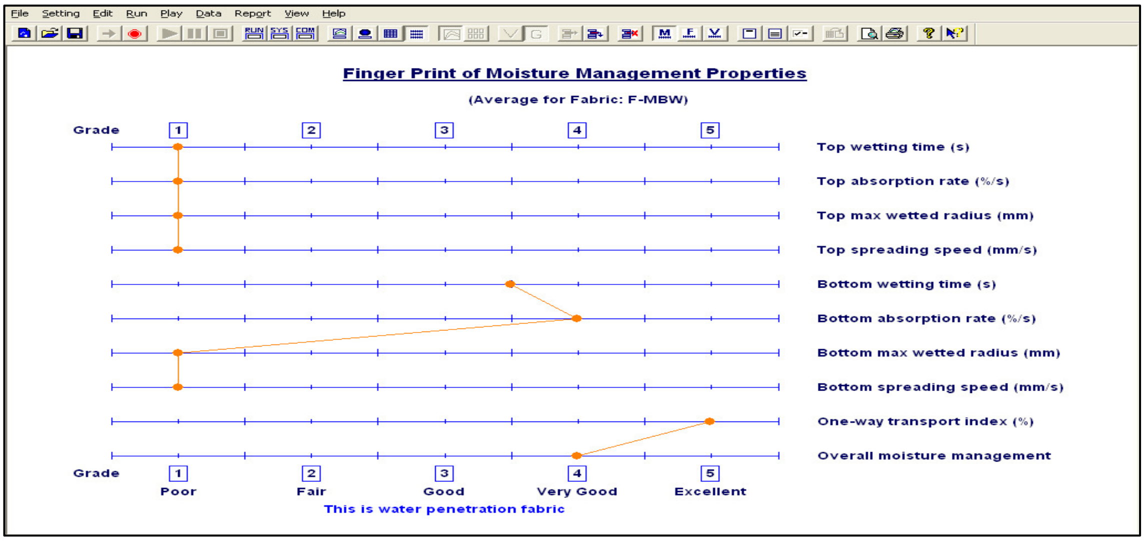


Finger Print of Moisture Management Properties

(Average for Fabric: F-FGNE)

This is water proof fabric

Figure A.5.9.Fingerprint moisture management properties of FGNE

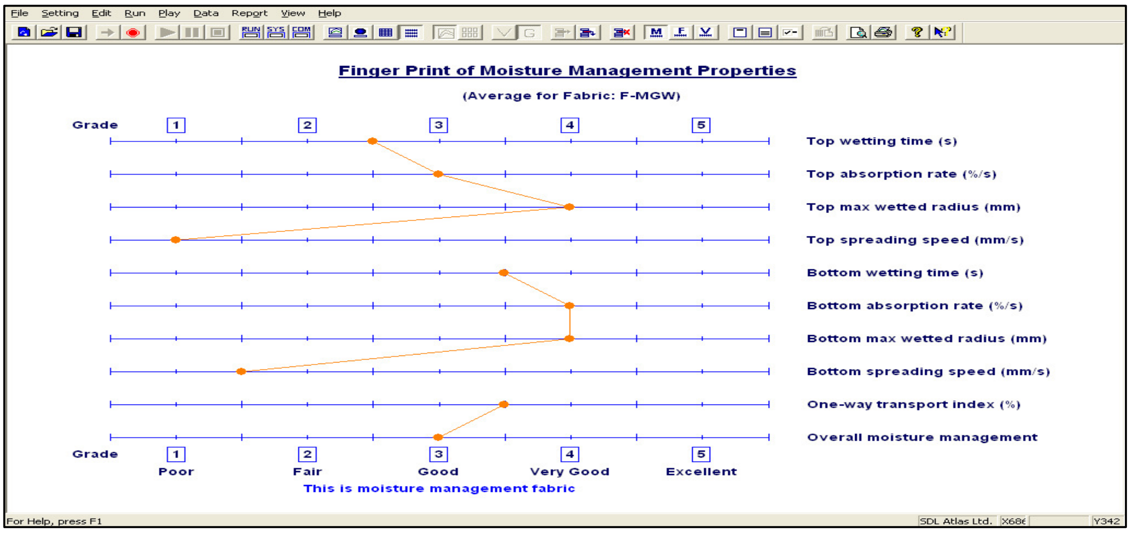


Finger Print of Moisture Management Properties

(Average for Fabric: F-MBW)

This is water penetration fabric

Figure A.5.10.Fingerprint moisture management properties of MBW

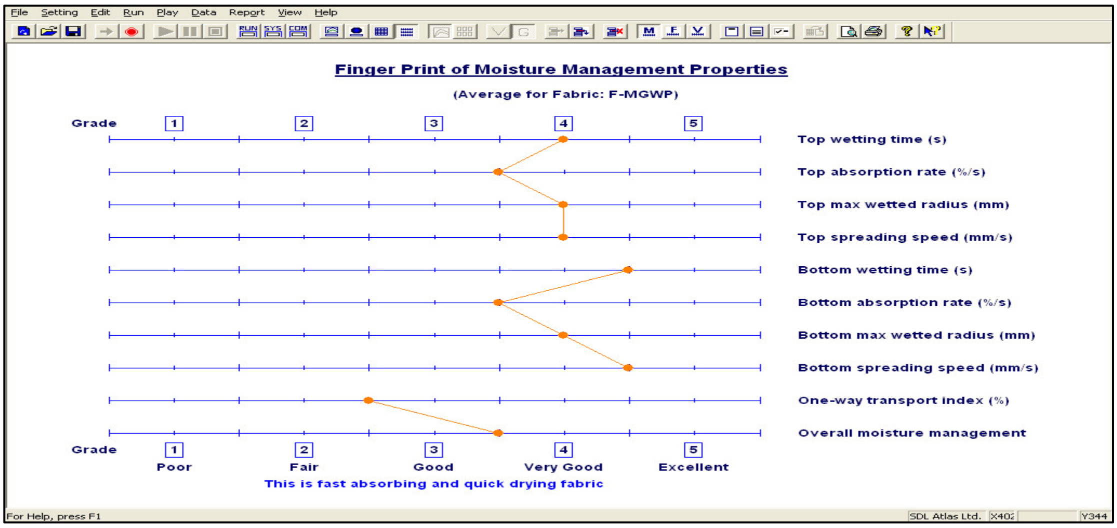


Finger Print of Moisture Management Properties

(Average for Fabric: F-MGW)

This is moisture management fabric

Figure A.5.11.Fingerprint moisture management properties of MGW

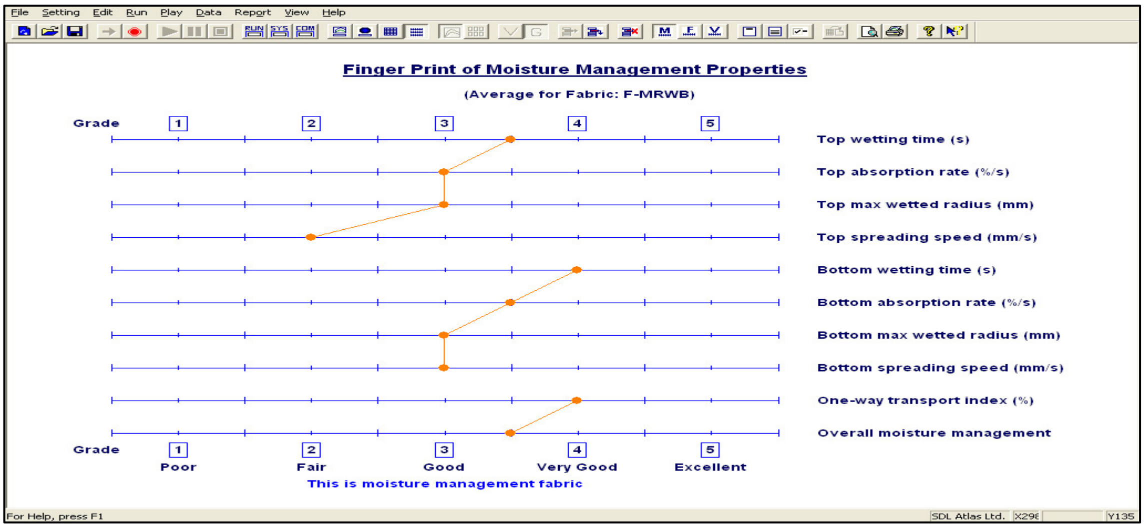


Finger Print of Moisture Management Properties

(Average for Fabric: F-MGWP)

This is fast absorbing and quick drying fabric

Figure A.5.12.Fingerprint moisture management properties of MGWP



Finger Print of Moisture Management Properties

(Average for Fabric: F-MRWB)

This is moisture management fabric

Figure A.5.13.Fingerprint moisture management properties of MRWB

A.6. REGRESSION ANALYSIS

WOOL KNITTED FABRICS

Regression Analysis: WTt versus Cover factor

```
The regression equation is
WTt = - 6 + 65.1 Cover factor


Predictor       Coef  SE Coef      T      P
Constant        -6.3    107.0  -0.06  0.954
Cover factor   65.14    69.62   0.94  0.374


S = 47.8282   R-Sq = 8.9%   R-Sq(adj) = 0.0%


Analysis of Variance

Source          DF     SS    MS     F      P
Regression       1   2003  2003  0.88  0.374
Residual Error   9  20588  2288
Total           10  22590
```

Regression Analysis: WTb versus Cover factor

```
The regression equation is
WTb = 57.7 - 27.3 Cover factor


Predictor        Coef  SE Coef      T      P
Constant        57.69    43.48   1.33  0.217
Cover factor   -27.27    28.29  -0.96  0.360


S = 19.4391   R-Sq = 9.4%   R-Sq(adj) = 0.0%


Analysis of Variance

Source          DF      SS     MS     F      P
Regression       1   351.1  351.1  0.93  0.360
Residual Error   9  3400.9  377.9
Total           10  3752.0


Unusual Observations

      Cover
Obs  factor    WTb   Fit  SE Fit  Residual  St Resid
 11    1.79  49.69  8.87    9.57     40.82     2.41R

R denotes an observation with a large standardized residual.
```

Regression Analysis: ARt versus Cover factor

```
The regression equation is
ARt = 65 - 19.2 Cover factor


Predictor       Coef  SE Coef      T      P
Constant        64.6    144.9   0.45  0.666
Cover factor  -19.23    94.29  -0.20  0.843


S = 64.7779   R-Sq = 0.5%   R-Sq(adj) = 0.0%


Analysis of Variance

Source          DF     SS    MS     F      P
Regression       1    175   175  0.04  0.843
Residual Error   9  37766  4196
Total           10  37940


Unusual Observations

      Cover
Obs  factor    ARt   Fit  SE Fit  Residual  St Resid
 11    1.79  159.4  30.1    31.9     129.3      2.29R

R denotes an observation with a large standardized residual.
```

Regression Analysis: ARb versus Cover factor

```
The regression equation is
ARb = - 200 + 173 Cover factor


Predictor        Coef  SE Coef      T      P
Constant      -199.81    37.30  -5.36  0.000
Cover factor   172.64    24.27   7.11  0.000


S = 16.6743   R-Sq = 84.9%   R-Sq(adj) = 83.2%


Analysis of Variance

Source          DF     SS     MS      F      P
Regression       1  14069  14069  50.60  0.000
Residual Error   9   2502    278
Total           10  16571
```

Regression Analysis: MWRt versus Cover factor

```
The regression equation is
MWRt = 6.50 - 3.37 Cover factor


Predictor       Coef  SE Coef      T      P
Constant       6.500    5.517   1.18  0.269
Cover factor  -3.373    3.590  -0.94  0.372


S = 2.46648   R-Sq = 8.9%   R-Sq(adj) = 0.0%
```

```
Analysis of Variance

Source          DF      SS     MS     F      P
Regression       1   5.372  5.372  0.88  0.372
Residual Error   9  54.752  6.084
Total           10  60.123


Unusual Observations

      Cover
Obs  factor   MWRt    Fit  SE Fit  Residual  St Resid
  3    1.37  6.670  1.879   0.924     4.791      2.10R

R denotes an observation with a large standardized residual.
```

Regression Analysis: MWRb versus Cover factor

```
The regression equation is
MWRb = 18.2 - 7.59 Cover factor


Predictor       Coef  SE Coef      T      P
Constant      18.231    9.147   1.99  0.077
Cover factor  -7.594    5.952  -1.28  0.234


S = 4.08926   R-Sq = 15.3%   R-Sq(adj) = 5.9%


Analysis of Variance

Source          DF      SS     MS     F      P
Regression       1   27.22  27.22  1.63  0.234
Residual Error   9  150.50  16.72
Total           10  177.72


Unusual Observations

      Cover
Obs  factor   MWRb   Fit  SE Fit  Residual  St Resid
  3    1.37  18.33  7.83    1.53     10.50      2.77R

R denotes an observation with a large standardized residual.
```

Regression Analysis: SSt versus Cover factor

```
The regression equation is
SSt = 1.21 - 0.655 Cover factor


Predictor        Coef  SE Coef      T      P
Constant       1.2055   0.9319   1.29  0.228
Cover factor  -0.6549   0.6064  -1.08  0.308


S = 0.416612   R-Sq = 11.5%   R-Sq(adj) = 1.6%
```

```
Analysis of Variance

Source          DF      SS      MS     F      P
Regression       1  0.2025  0.2025  1.17  0.308
Residual Error   9  1.5621  0.1736
Total           10  1.7646


Unusual Observations

      Cover
Obs  factor    SSt    Fit  SE Fit  Residual  St Resid
  3    1.37  1.300  0.308   0.156     0.992      2.57R

R denotes an observation with a large standardized residual.
```

Regression Analysis: SSb versus Cover factor

```
The regression equation is
SSb = 3.98 - 1.61 Cover factor


Predictor       Coef  SE Coef      T      P
Constant       3.978    3.560   1.12  0.293
Cover factor  -1.606    2.317  -0.69  0.506


S = 1.59179   R-Sq = 5.1%   R-Sq(adj) = 0.0%


Analysis of Variance

Source          DF      SS     MS     F      P
Regression       1   1.217  1.217  0.48  0.506
Residual Error   9  22.804  2.534
Total           10  24.021
```

Regression Analysis: AOTI versus Cover factor

```
The regression equation is
AOTI = 2093 - 576 Cover factor


Predictor       Coef  SE Coef      T      P
Constant      2093.4    998.4   2.10  0.065
Cover factor  -576.0    649.7  -0.89  0.398


S = 446.358   R-Sq = 8.0%   R-Sq(adj) = 0.0%


Analysis of Variance

Source          DF       SS      MS     F      P
Regression       1   156612  156612  0.79  0.398
Residual Error   9  1793117  199235
Total           10  1949728
```

```
Unusual Observations

      Cover
Obs  factor  AOTI   Fit  SE Fit  Residual  St Resid
 11    1.79   175  1062     220      -887     -2.28R

R denotes an observation with a large standardized residual.
```

Regression Analysis: OMMC versus Cover factor

```
The regression equation is
OMMC = 0.465 + 0.136 Cover factor


Predictor       Coef  SE Coef     T      P
Constant      0.4649   0.2951  1.58  0.150
Cover factor  0.1359   0.1920  0.71  0.497


S = 0.131929   R-Sq = 5.3%   R-Sq(adj) = 0.0%


Analysis of Variance

Source          DF       SS       MS     F      P
Regression       1  0.00872  0.00872  0.50  0.497
Residual Error   9  0.15665  0.01741
Total           10  0.16536


Unusual Observations

      Cover
Obs  factor    OMMC     Fit  SE Fit  Residual  St Resid
  4    1.40  0.9200  0.6551  0.0462    0.2649      2.14R

R denotes an observation with a large standardized residual.
```

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Regression Analysis: WTt versus cover factor

```
The regression equation is
WTt = - 0.345 + 2.60 cover factor


Predictor        Coef  SE Coef      T      P
Constant      -0.3454   0.2634  -1.31  0.216
cover factor   2.6047   0.2070  12.58  0.000


S = 0.165406   R-Sq = 93.5%   R-Sq(adj) = 92.9%


Analysis of Variance

Source          DF      SS      MS       F      P
Regression       1  4.3330  4.3330  158.37  0.000
Residual Error  11  0.3009  0.0274
Total           12  4.6339
```

Regression Analysis: WTb versus cover factor

```
The regression equation is
WTb = - 0.805 + 3.14 cover factor


Predictor        Coef  SE Coef      T      P
Constant      -0.8045   0.2814  -2.86  0.016
cover factor   3.1424   0.2212  14.21  0.000


S = 0.176748   R-Sq = 94.8%   R-Sq(adj) = 94.4%


Analysis of Variance

Source          DF      SS      MS       F      P
Regression       1  6.3068  6.3068  201.88  0.000
Residual Error  11  0.3436  0.0312
Total           12  6.6505
```

Regression Analysis: Art versus cover factor

```
The regression equation is
Art = 72.6 - 12.0 cover factor


Predictor         Coef  SE Coef       T      P
Constant        72.557    1.224   59.27  0.000
cover factor  -12.0221   0.9619  -12.50  0.000


S = 0.768754   R-Sq = 93.4%   R-Sq(adj) = 92.8%


Analysis of Variance

Source          DF      SS      MS       F      P
Regression       1  92.308  92.308  156.19  0.000
Residual Error  11   6.501   0.591
Total           12  98.809
```

Regression Analysis: Arb versus cover factor

```
The regression equation is
Arb = 64.9 - 10.8 cover factor


Predictor        Coef  SE Coef      T      P
Constant       64.856    2.664  24.35  0.000
cover factor  -10.761    2.093  -5.14  0.000


S = 1.67282   R-Sq = 70.6%   R-Sq(adj) = 67.9%


Analysis of Variance

Source          DF       SS      MS      F      P
Regression       1   73.957  73.957  26.43  0.000
Residual Error  11   30.782   2.798
Total           12  104.739
```

```
Unusual Observations

      cover
Obs  factor     Arb     Fit  SE Fit  Residual  St Resid
  1    1.62  51.113  47.423   0.897     3.690      2.61R
  2    1.56  45.119  48.069   0.792    -2.950     -2.00R

R denotes an observation with a large standardized residual.
```

Regression Analysis: MWRt versus cover factor

```
The regression equation is
MWRt = 36.6 - 13.9 cover factor


Predictor        Coef  SE Coef      T      P
Constant       36.599    1.799  20.34  0.000
cover factor  -13.860    1.414  -9.80  0.000


S = 1.13007   R-Sq = 89.7%   R-Sq(adj) = 88.8%


Analysis of Variance

Source          DF      SS      MS      F      P
Regression       1  122.70  122.70  96.08  0.000
Residual Error  11   14.05    1.28
Total           12  136.74
```

Regression Analysis: MWRb versus cover factor

```
The regression equation is
MWRb = 36.9 - 14.6 cover factor


Predictor        Coef  SE Coef      T      P
Constant       36.856    2.378  15.50  0.000
cover factor  -14.577    1.869  -7.80  0.000


S = 1.49351   R-Sq = 84.7%   R-Sq(adj) = 83.3%


Analysis of Variance

Source          DF      SS      MS      F      P
Regression       1  135.72  135.72  60.85  0.000
Residual Error  11   24.54    2.23
Total           12  160.26
```

Regression Analysis: SSt versus cover factor

```
The regression equation is
SSt = 10.0 - 4.98 cover factor


Predictor        Coef  SE Coef       T      P
Constant      10.0200   0.4743   21.12  0.000
cover factor  -4.9838   0.3727  -13.37  0.000


S = 0.297882   R-Sq = 94.2%   R-Sq(adj) = 93.7%
```

```
Analysis of Variance

Source          DF      SS      MS       F      P
Regression       1  15.864  15.864  178.78  0.000
Residual Error  11   0.976   0.089
Total           12  16.840
```

Regression Analysis: SSb versus cover factor

```
The regression equation is
SSb = 9.86 - 5.01 cover factor


Predictor        Coef  SE Coef       T      P
Constant       9.8626   0.5242   18.81  0.000
cover factor  -5.0067   0.4120  -12.15  0.000


S = 0.329235   R-Sq = 93.1%   R-Sq(adj) = 92.4%


Analysis of Variance

Source          DF      SS      MS       F      P
Regression       1  16.010  16.010  147.70  0.000
Residual Error  11   1.192   0.108
Total           12  17.202
```

Regression Analysis: AOTI versus cover factor

```
The regression equation is
AOTI = - 65.7 + 5.37 cover factor


Predictor       Coef  SE Coef      T      P
Constant      -65.74    12.06  -5.45  0.000
cover factor   5.371    9.476   0.57  0.582


S = 7.57303   R-Sq = 2.8%   R-Sq(adj) = 0.0%


Analysis of Variance

Source          DF      SS     MS     F      P
Regression       1   18.42  18.42  0.32  0.582
Residual Error  11  630.86  57.35
Total           12  649.28


Unusual Observations

      cover
Obs  factor    AOTI     Fit  SE Fit  Residual  St Resid
  6    1.30  -73.31  -58.76    2.15    -14.56     -2.00R

R denotes an observation with a large standardized residual.
```

Regression Analysis: OMMC versus cover factor

```
The regression equation is
OMMC = 0.658 - 0.282 cover factor


Predictor          Coef  SE Coef       T      P
Constant        0.65798  0.03410   19.29  0.000
cover factor  -0.28200  0.02680  -10.52  0.000


S = 0.0214184   R-Sq = 91.0%   R-Sq(adj) = 90.1%


Analysis of Variance

Source          DF        SS        MS       F      P
Regression       1  0.050789  0.050789  110.71  0.000
Residual Error  11  0.005046  0.000459
Total           12  0.055835
```