A COMPARATIVE STUDY OF THE COMFORT RELATED PROPERTIES OF COMMERCIAL APPAREL FABRICS CONTAINING NATURAL AND MAN-MADE FIBRES

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Declaration

In accordance with Rule G 4.6.3, I hereby declare that the above-mentioned dissertation is my own work and that it has not previously been submitted for assessment to another University or for another qualification.

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ABSTRACT

The relationship between the fabric parameters, as independent variables, and the comfort related properties, as dependent variables, of commercial suiting fabrics, containing both natural and man-made fibres, have been studied. The fabric parameters measured in the study were mass, thickness, density, and air permeability. The comfort related properties, tested on a Permetest instrument, included water vapour permeability, water vapour resistance, and thermal resistance, with the moisture permeability index being derived. A total of 26 commercial suiting fabrics, covering a wide range of mass, as well as different fibre types and blends and fabric structures, was tested. The fibres covered, included wool, polyester, viscose, and cotton, while the fabric structures covered were 1x1 plain weave, 2x1 twill and 2x2 twill weave.

The objectives of this study were to determine the empirical relationships between the measured fabric properties and the measured comfort related properties, and to determine the role, if any, of fibre type and fabric structure, since many claims are made in practice concerning the relative advantages, in terms of comfort, of a specific fibre type or blend, or fabric structure, over others, some of which being supported by research results. Since the fabrics covered, were commercial and were not engineered so that the different fabric parameters (independent variables) and fibre type and blend, as well as fabric structure could be varied independently of each other, the effects of the various fabric parameters on the fabric comfort related properties were determined and quantified by multiple regression analyses (multi-linear and multi-quadratic), and the best fit regression equations, and contribution of each parameter to the overall fit established.

It was found that fabric thickness and fabric mass had the largest effect on the comfort related properties as measured here, fabric mass determining, to a large extent, water vapour permeability, and fabric thickness, thermal resistance. The rest of the fabric parameters included in the study had only a relatively small effect on the measured comfort related properties. The influence of fabric parameters, with particular reference to mass and thickness, on the measured comfort related properties, were much greater than that of fibre type or blend, or fabric structure. It was, therefore, concluded from this study, that the fabric parameters, as opposed to the intrinsic characteristics of a particular fibre, whether natural or man-made, largely determined those fabric comfort related properties measured here.

Key words: Permetest, thermophysiological comfort, water vapour resistance, thermal resistance, moisture permeability index, commercial suiting fabrics.

NOMENCLATURES

A_s = Body surface area of manikin, m²

B = Fabric cover factor

C = Heat loss by convection, kcal/hr

D = Moisture regain of fibre, %

E_d = Heat loss through water vapour diffusion, kcal/hr

E_r = Sum of the latent and sensible respiration heat loss

E_{re} = Latent respiration heat loss

E_{sw} = Heat loss by evaporation of sweat, kcal/hr

h = Fabric thickness (m)

H = Internal heat production of body, kcal/hr

H_d = Dry heat loss from the skin, W/m²

H_e = Evaporative heat loss, W/m²

H_t = Rate of heat transfer, W/m²

I_{cl} = Cloth index, clo

i_m = Moisture vapour permeability index

I_t = Thermal insulation, m²K/W

K = Conduction through clothing, kcal/hr

L = Dry respiration heat loss, kcal/hr

m = Fabric weight (g/cm^{-2})

M = Metabolic rate, kcal/hr

M_a = Moisture accumulation in clothing, %

P = Water vapour permeability, %

P_1 = Porosity of a textile

$\mathrm{P_{wo}}$ = water vapour saturate partial pressure valid for the temperature of air in the measuring laboratory, Pa

P_s = Water vapour pressure at skin, Pa

q_o = density of heat flux passing through the uncovered measuring head, W/m^{-2}

Q_{total} = Flow rate of air through textile (air permeability)

Q_1 = Flow rate between warp and weft yarns, m^3/s

Q_2 = Flow rate through the fibres at intersection of warp and weft yarns

Q_3 = Flow rate through the fibres of warp yarns

Q_4 = Flow rate through the fibres of weft yarns, m^3/s

R = Heat loss by radiation, kcal/hr

R_{ct} = Thermal resistance, m^{2}K/W

R_t = Water vapour resistance, m^{2}Pa/W

S = Rate of body heat storage (under thermal equilibrium S=0), W/m^2

T = Fabric thickness, mm

T_a = Mean environmental temperature, °C

T_s = Area weighted mean skin temperature, °C

Y = Mean flow pore diameter, µm

V = Air velocity, m/s

W_k = External work

GREEK SYMBOLS

λ = Thermal conductivity, W/mK

ρ = Fibre density, g/cm^{-3}

φ = Relative humidity, %

CHAPTER 1: SCOPE OF THE STUDY

This chapter provides the objectives of the study, the research questions that will be answered, the limitations of the research, and it also gives an introduction to the importance of comfort, which is the central focus of this study.

1.1 Introduction

The consumer demand for comfort in clothing items continues to increase and has lead to a great deal of research projects, in academic, scientific, and industrial institutions. Comfort is a multidimensional concept, embodying various parameters within the composition and construction of textiles, as well as the design of clothing. The main purpose of clothing is to provide comfort and to protect the wearer from external environmental elements and climatic conditions, including severe cold and hot conditions (Matusiak, 2010 and Wardiningsih, 2001), as well as providing aesthetic appeal and the means for cultural expression. It is crucial for the human body to maintain a core temperature around 37°C (Matusiak, 2010); therefore, clothing is essential in the temperature control of the human body, whether providing insulation in cold climatic conditions, or enabling evaporation of sweat in hot climatic conditions (Voelker *et al.,* 2009).

Wang (2002) highlights that human beings are different from animal species due to the fact that humans cannot live without some form of protection, such as clothing, to protect against harsh climatic conditions. Clothing has evolved since ancient times, from simply providing protection and warmth, to providing highly functional performances (Wang, 2002). In the 21st century, people are also required to work under extreme conditions, for example in deep oceans, space, or near volcanoes, and appropriate clothing is required, to not only protect the wearer, but to maintain a level of thermal comfort (Wang, 2002). In essence, where textiles are directly interacting with the human body, thermal comfort is essential for survival (Wang, 2002). Various factors are involved in maintaining the thermal comfort of a human being, and are highly influenced by clothing, climatic conditions, and human physical activity. This study focuses on the impact that clothing has on maintaining the thermophysiological comfort of human beings, and on those textile variables which influence the breathability and thermal insulation of fabrics.

1.2 Problem statement

Clothing can be described as the 'second skin' of human beings (Voelker *et al.,* 2009). Clothing can influence, in fact determine, the level of comfort that the wearer will experience under different environmental and climatic conditions. Nevertheless, Slater (1991) and Fan (2009b) are of the opinion that comfort cannot be defined in quantitative terms, or even measured directly, due to the subjective nature and range of variables that are involved. There are, however, certain variables (comfort related variables or properties) that most people agree influence the comfort of clothing and can be used to examine clothing comfort in more detail. These include thermal transmission, air permeability and moisture vapour permeability and absorption, water resistance, psychological factors, fibre content, fabric construction, to name but a few (Slater, 1991). Therefore, this study will focus on specific, and the most widely accepted, comfort related parameters, as opposed to one individual aspect or component of comfort, since comfort is such a multidimensional concept. As already mentioned, a great deal of research has been carried out on the comfort related properties of textiles, from which it has emerged that thermal insulation, water vapour transmission, and air permeability, are the most important. The research has also shown that fabric structural parameters, such as thickness, weight and porosity, play the dominant role in determining the foregoing properties, with the type of fibre and fibre properties *per sé,* playing a smaller role. The bulk of the research was carried out on non-commercial fabrics (mostly fabrics specifically produced for the purpose of this particular study), and nevertheless, many claims are still being made concerning the supposed benefits or relative advantages of one type of commercially produced fibre of fabric, notably natural or man-made, over another.

The aim of this study was to compare the comfort related properties, namely thermal insulation, water vapour permeability and water vapour resistance, of commercial suiting fabrics, containing different natural and man-made fibres, using the Permetest instrument, developed and commercialised in the Czech Republic, and to establish whether the observed differences in the measured properties can be explained entirely or satisfactorily in terms of measureable differences in the fabric parameters, such as mass, thickness and density, or whether differences in fibre composition (i.e. fibre type and blend) and fabric weave structure, need also be taken into consideration.

The study also provides the opportunity to determine whether the same trends observed in previous studies with specially manufactured and other fabrics, apply to commercial fabrics. In addition, the interpretation of the results obtained from the Permetest, can provide an insight into the factors that contribute to the comfort related properties of commercial suiting fabrics and be used by the manufacturers of such fabrics.

In order to achieve the aims and objectives of this study, it is proposed to quantify the relationships between the various fabric comfort related properties and fabric parameters, using multiple regression analyses, and then to determine whether any unexplained or residual variations in the former can be related to the fabric composition; i.e. fibre type or blend, and fabric structure.

The research questions addressed in the study were as follows:

1. The quantitative relationships between the relative water vapour permeability and water vapour resistance, respectively, on the one hand, and on the other hand, fabric properties (mass, thickness, density and air permeability)?
2. The quantitative relationship between the thermal resistance and the fabric properties (mass, thickness, density and air permeability)?
3. The quantitative relationship between the moisture permeability index and the fabric properties (mass, thickness, density and air permeability)?
4. The role, if any, of the fibre type and blend in the above comfort related properties?
5. The role, if any, of fabric construction in the above comfort related properties?

1.3 Objectives of the research

The objective of the study was to compare the comfort related properties, namely thermal insulation, water vapour resistance and permeability, and moisture permeability index of commercial suiting fabrics, containing natural and man-made fibres, using a Permetest, and to empirically relate the values so obtained to the fabric mass, thickness, density, and air permeability, using multiple regression analysis. Furthermore, to determine whether any unexplained variations in the comfort related properties could be explained in terms of fibre type or fabric structure. The fabrics used in the study were commercially sourced suiting fabrics, of different fibre composition and fabric construction, ranging widely in fabric mass and therefore also in fabric thickness.

The main objectives of the study were as follows:

1. Determine and compare comfort related properties, namely thermal insulation, water vapour permeability and resistance, and moisture permeability index, of commercial suiting fabrics containing different natural and synthetic fibres, using a Permetest.
2. Using multiple regression and other appropriate statistical analyses, to quantify the effects of fabric, thickness, mass, density and air permeability on the thermal insulation, water vapour resistance and permeability, and moisture permeability index of the fabrics.
3. Determine the effect, if any, of fibre type and blend, as well as fabric structure, on the above mentioned comfort related properties, once allowance was made for the effects of fabric parameters, such as mass and thickness.

1.4 Limitations of the study

The limitations for the study include:

1. Commercially available suiting fabrics were sourced for the research study; therefore, the fabric properties such as thickness, mass, density and air permeability, as well as fabric structure and composition, could not be varied independently of one another. Nevertheless, this was allowed for in the

statistical analysis of the results. Fabrics were sourced with a considerable range in fabric mass (from 145 to 250 g/m²) and thickness (from 0.23 to 0.65mm), this being representative of the type of suiting fabrics produced in South Africa.

2. Fabric comfort related properties were tested using only the Permetest.
3. The suiting fabrics tested were limited to polyester, viscose, wool and cotton, with only certain of their blends. Only plain, 2x1 twill and 2x2 twill weave fabrics were covered.

1.5 Outline of dissertation

Chapter 1 provides a general background in terms of the importance of comfort and the role that clothing has to play to ensure not only the comfort of human beings, but survival in extreme environmental conditions. The chapter explains the purpose of the study, the various objectives of the study, and the research questions to be answered. Chapter 2 contains the literature review, and examines in detail the parameters that influence and determine the comfort of clothing. The chapter focuses on various different types of comfort, with special attention to thermophysiological comfort, and the impact of textiles. Equipment used to test comfort related properties are examined in Chapter 2, including a detailed analysis of the functioning of the Permetest, the instrument used in this study to measure the comfort related properties of textiles. Chapter 3 outlines the research methodology of the study, as well as the various materials and equipment used to obtain data to answer the research questions. In Chapter 4, the results of the tests are examined, and statistically analysed, to determine the relationships between the various comfort related properties of the commercial suiting fabrics, and the various fabric parameters. Chapter 5 contains the summary and conclusions, as well as recommendations for further work.

1.6 Definitions

The following definitions are important for the understanding of terms used in the research study.

Absorption: The penetration of a fibre by a foreign gas or liquid (Smith, 1982).

Adsorption: The coating of the surface of a fibre by a foreign gas, liquid or solid. The foreign matter does not penetrate the surface (Smith, 1982).

Air permeability test: A measure of the rate of passage of air through a unit area of fabric at a specified pressure difference (Textile Terms and Definitions, 1991)

Clo (cloth insulation): Unit of measurement that reflects the insulation of clothing (Orosa, 2009).

Comfort: A complex subjective sensation intimately associated with physical, physiological and psychological factors (Mehta and Harnett, 1981).

Conduction: Heat loss is accomplished through direct contact with another substance. The rate of exchange is determined by the temperature difference between the two substances and by their thermal conductivities (Saville, 1999).

Convection: The method of transferring energy through a medium which itself is moving (Mehta and Harnett, 1981).

Crimp: Natural wave of a wool fibre (Wingate and Mohler, 1984).

Desorption: The release of moisture from the textile (Starr, 2010).

Evaporation: A change of state from liquid to vapour (Mehta and Harnett, 1981).

Fibre: Textile raw material generally, characterised by flexibility, fineness and high ratio of length to thickness (Textile Terms and Definitions, 1991).

Hand (handle): The quality of a fabric or yarn assessed by the reaction obtained from the sense of touch. It is concerned with the judgement of roughness, smoothness, harshness, pliability, thickness, etc. (Textile Terms and Definitions, 1991).

Heat transfer: A method through which thermal energy is transported, namely, conduction, radiation and convection (Matusiak, 2010).

Hydrophilic: Water-loving, having an attraction to water (Saville, 1982).

Hydrophobic: Water hating, having little or no attraction to water (Saville, 1982).

Hygroscopic fibres: Absorbs moisture in the form of vapour (Zhou *et al.,* 2007). Hygroscopic fibres absorb moisture without feeling wet (Kadolph *et al.*, 1993).

Insulation: The resistance to passage of energy (Mehta and Harnett, 1981).

Insensible perspiration: The perspiration present in the form of vapour (Mehta and Harnett, 1981).

Man-made fibre: A manufactured fibre as distinct from a fibre that occurs naturally (Textile Terms and Definitions, 1991)

Micronaire value: A measurement of cotton fibre quality which is a reflection of both fineness and maturity. Low values indicate fine and/or immature fibres; high values indicate coarse and/or mature fibres. (Textile Terms and Definitions, 1991).

Moisture permeability index: A dimensionless ratio ranging from zero, for a non-vapour permeable material, to one, for a completely vapour permeable material (Mehta and Harnett, 1981).

Natural fibre: A fibre occurring in nature which is animal, vegetable of mineral in origin (Textile Terms and Definitions, 1991).

Physiological comfort: The achievement of thermal equilibrium at normal body temperature with the minimum amount of bodily regulation (Choudhury *et al.*, 2011).

Radiation: Heat is transferred by way of electromagnetic waves. The waves can pass through air without imparting much heat to it; however, when they strike an object their energy is largely transformed into heat (Saville, 1999).

Regenerated fibre: A fibre formed from a solution of a natural polymer or of a chemical derivative of a natural polymer and having the same chemical constitution as the natural polymer from which the solution or derivative was made (Textile Terms and Definitions, 1991)

Scales: Protective covering of the wool fibre (Wingate and Mohler, 1984).

Sensible perspiration: The perspiration present in the form of liquid (Mehta and Harnett, 1981).

Thermal comfort: The condition in which a person can maintain a balance between production and loss of heat at normal body temperature and without sweating (Mehta and Harnett, 1981).

Thermal resistance: The ratio of the temperature difference between the two faces of the material to the rate of heat transfer per unit area of the material, normal to the faces (Holcombe 1984). Thermal resistance is a measure of the resistance that a garment provides against heat loss from the body of the wearer to the external environment (Clulow, 1984).

Water vapour permeability: A fabric's ability to transport water vapour, for example from the skin surface through the fabric to the external environment (Gericke and Van der Pol, 2010). Heat is taken from the body in order supply the latent heat needed to evaporate the moisture from the skin (Saville, 1999).

Water vapour resistance: The resistance against the transport of water vapour through a fabric (Gericke and Van der Pol, 2010).

Wicking: The penetration and movement of liquids, under the influence of capillary forces, along or through a textile material, or the textile element of a coated fabric, or along interstices formed by the textile element and the coating polymer of the coated fabric (Denton and Daniels, 2002).

CHAPTER 2: LITERATURE REVIEW

2.1 Comfort

2.1.1 Introduction to comfort

It is stated by Fan (2009b) that comfort is one of the most important requirements of any human being. According to the Oxford Advanced Learner's Dictionary (2006), comfort is defined as 'the state of being physically relaxed and free from pain'. Comfort is influenced by a range of psychological, physiological and physical factors between a human being and the external environment (Broega *et al.,* n.d., Havenith, n.d., Malik and Sinha, 2012., and Slater, 1991). According to Kothari (2006), the human mind responds to changes in the environment which includes the effect of clothing between the body and the environment. Several factors, such as the properties of fibres, yarns, fabrics and garments, influence comfort, and must be taken into consideration when developing suitable apparel products. The main purpose of clothing is to provide physiological comfort in terms of climatic conditions, the level of activity and the individual characteristics of people (Dominiak and Frydrych, 2013).

Slater (1991) and Fan (2009b) are both of the opinion that comfort cannot be defined in quantitative terms due to the subjective nature and range of variables that are involved. According to Slater (1991) and Ravandi and Valizadeh (2011), what one person perceives as comfortable might not necessarily be perceived as comfortable for another person, due to different physiological responses to climate and environmental conditions, social norms and other external factors. Ravandi and Valizadeh (2011) are of the opinion that it is easier to define discomfort, the opposite of comfort, in terms of prickliness, hot or cold conditions, tightness and moisture. Nevertheless, there are certain variables which most people agree which influence the comfort of clothing, and can be used to examine comfort in more detail, for example thermal transmission, moisture vapour permeability, water resistance, psychological factors, fibre content, and fabric construction (Slater, 1991). Therefore, Slater (1991) is of the opinion that it is not possible to measure comfort as a single entity, due to the matter of subjectivity; however, individual factors for example thermal insulation and moisture transmission can be examined to assess the level of comfort.

The heat that is produced by a human body is measured in Watts per square metre, W/m^2 (Qian, 2005). The heat is a result of the metabolic action of the body, and results in a core temperature of 37ºC, with an acceptable fluctuation of ± 2ºC (Fan, 2009b). In addition to the core temperature, the mean skin temperature should be 33-34.5ºC for men and 32-35.5ºC for females, and the local skin temperature between 32-35.5ºC (Fan, 2009b). A person lying down produces heat of approximately 30 W/m^2, whereas a person doing physical activity produces 600 W/m^2 (Fan, 2009b and Qian, 2005). When the external environment becomes too hot or too cold, the human body may suffer due to the inability to regulate the thermal balance with the environment, therefore clothing enables the resistance or facilitation of heat and moisture exchange between the wearer and the environment (Boguslwska-Bączek and Hes, 2013 and Qian, 2005). The inability to maintain the core temperature of the human body could result in discomfort, such as hyperthermia, due to an increase in the temperature, or hypothermia, due to a reduction in the temperature (Fan, 2009b). According to Dominiak and Frydrych (2013), if the body temperature rises above 42ºC, or falls below 30ºC, it can have life threatening consequences, such as fainting or severe shivering. Comfort is therefore directly related to the ability of the body to maintain a constant core temperature, for example through the evaporation of sweat that cools the human body during different levels of work rate in different environmental conditions (Keighley, 1985).

Choudhury *et al.* (2011) distinguish between three aspects of clothing comfort. Firstly, thermal comfort, which refers to the transport of heat and moisture through fabric and clothing. Secondly, sensorial comfort, which involves the physical sensation that a fabric provides to the wearer. Thirdly, body movement comfort refers to the ability of a fabric to enable freedom of movement.

It is evident that the complexity of comfort makes it difficult for it to be defined quantitatively (Ravandi and Valizadeh, 2011); although, Li (2001) identifies elements which contribute to comfort, see Figure 1:

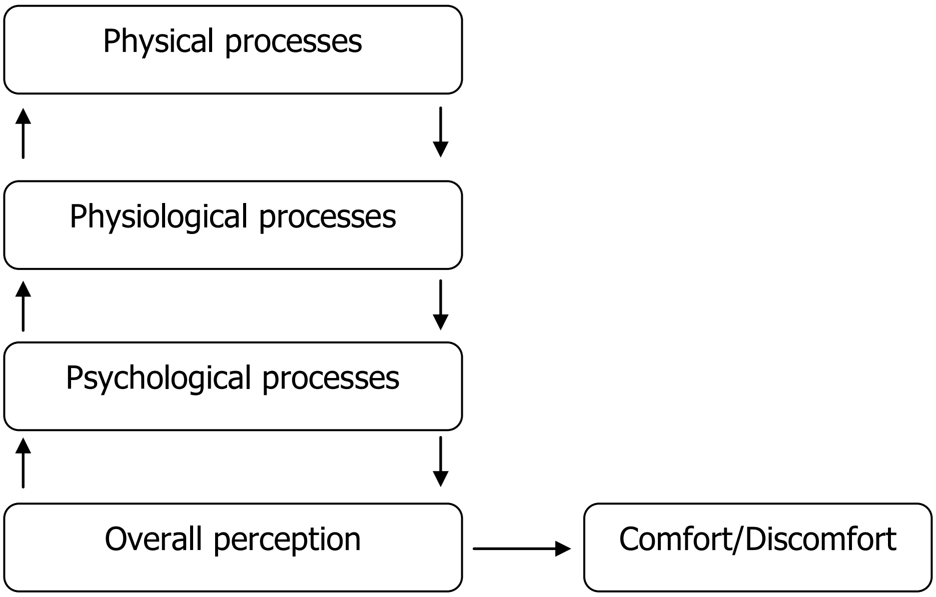


Figure 1: Subjective perception of overall comfort

(Source: Li, 2001)

From the information provided in Figure 1, it is clear that comfort is a multidimensional concept that is influenced by several variables. According to Li (2001), it is crucial to understand the individual processes that contribute to overall comfort, as well as how these processes interact with one another, in order to gain knowledge about the essence of comfort.

2.1.1.1 Physical comfort

According to Fan (2009b) and Li (2001), tactile or physical comfort relates to the contact that occurs between the fabric and the skin, and how sensory receptors on the human body are triggered. There are three types of skin-sensory receptors that convey information, namely touch, thermal and pain (Fan, 2009b and Li, 2001). Tactile comfort focuses on the feel of the fabric, and is therefore directly related to fabric handle (Nayak *et al.*, 2009). Elements, such as the roughness, smoothness, harshness, pliability and thickness of fabrics, are all concerned with the handle of fabric (Nayak *et al.*, 2009). The texture of a fabric is a complex sensation that includes visual (seeing a garment or fabric), auditory (the sound of interaction between the fabric and skin) and tactile perceptions (touching a fabric or garment), all of which contribute towards determining the overall perception of comfort (Li, 2001).

Fan (2009b) identifies the following range of different types of tactile comfort parameters:

1. Allergies: When fabric is uncomfortable to wear next to the skin it can cause an allergic reaction, due to physiological, psychological or physical reasons.
2. Skin and nasal irritation: Discomfort, such as nasal irritation or a tickling sensation on the skin, occurs as a result of fibres released from the fabric.
3. Local irritation: The edges of sewn-in labels and seams result in tactile discomfort due to the level of abrasion that occurs. Furthermore, a label that hangs outside the garment leads to psychological discomfort, as it is not appealing to the eye, except if it is intentionally done to display a special brand or product.
4. Abrasion: Abrasion between the skin of the wearer and the fabric during physical activity triggers sensations related to the softness and roughness of the fabric; although the level of skin moisture and perspiration also contributes to the level of discomfort during friction.
5. Tickle: Fabric hairiness, garment fit, and the frequency with which the fabric moves on the skin will determine the tickling sensations.
6. Clinging to the skin: There are three types of clinging to the skin, namely clinging due to wetness, tacky clinging due to skin dampness, and clinging due to static charge.
7. Prickle: Coarse and stiff fibres result in a prickly sensation by triggering skin pain sensory receptors.
8. Initial warm/cool feeling: When a garment is put on, or the fabric is touched for the first time, there will be an initial warm or cool feeling which will be influenced by the heat transfer between the skin and the fabric.
9. Dampness perception: Dampness in clothing is a result of liquid or moisture on the skin, or moisture in the clothing.

Slater (1991) states that physical discomfort will occur when a human is subjected to frictional contact outside a reasonable range, and which could result in pain or the development of open sores. On the other hand, the contact with the surface might be a tickling sensation which results in a different kind of discomfort (Slater, 1991). Even though textiles generally have acceptable levels of frictional properties, discomfort could occur, for example when wearing uncomfortable shoes that do not fit, or the shoe material does not follow the movement of the feet (Slater, 1991). Furthermore, the tactile sensation of textiles can range from a mild tickle sensation to severe discomfort that even extends to an allergic reaction (Fan, 2009b).

2.1.1.2 Physiological comfort

Choudhury *et al.* (2011) define physiological comfort as "the achievement of thermal equilibrium at normal body temperature with the minimum amount of bodily regulation". Malik and Sinha (2012) state that physiological comfort is the ability of the human body to maintain life. Thermal comfort is recognised in clothing items that provide comfort to the wearer in the widest possible range of environments and activities (Qian, 2005). Therefore, clothing is a crucial element that contributes to the comfort of a human. Ravandi and Valizadeh (2011) state that physiological comfort refers to the relationship between thermal and moisture management of the human body. Thermal comfort, which is a sub-section of total comfort, is a complex sensation (Havenith, n.d.). Thermal neutrality is described by Fanger (1970) as a state where a person prefers neither a warmer nor a cooler environment. An example of physiological comfort is a person in a cold environment that stays warm to prevent shivering but not too warm to trigger sensible perspiration that could result in wet clothing that clings to the body (Slater, 1991).

According to Fanger (1970), there are six major factors that influence human response to the thermal environment:

1. Air temperature
2. Mean radiant temperature
3. Air velocity
4. Relative humidity

5. Physical activity
6. Clothing thermal resistance (clo value)

Thermal comfort is achieved by a variety of combinations of these variables (Fanger, 1970). Therefore, it is not possible to examine the effect of one variable on thermal comfort independently, as the variables are interrelated with one another (Fanger, 1970).

According to Fan (2009b), thermal comfort can also be referred to as thermophysiological comfort. According to Broega *et al.* (n.d.), thermophysiological comfort refers to the ability of fabric to transfer perspiration produced by the body in order to maintain the required skin temperature of the human body. Therefore, thermophysiological comfort is achieved through satisfactory thermal resistance, moisture permeability and liquid transport in clothing (Fan, 2009b and Nayak *et al.* 2009). Factors, such as fabric material, design and construction, will influence the thermal insulation, moisture vapour resistance, water resistance and static charge build-up properties of clothing (Qian, 2005 and Kothari, 2006).

Fluctuations in temperature, from warm to cold, and changes in the humidity of the environment all have an influence on the comfort of clothing (Havenith, n.d.). The thermal comfort parameters of clothing are important to both consumers and manufacturers, as it provides not only indoor comfort, but can be vital in the survival of wearers in extreme conditions, for example on high mountains, in the deep ocean, or even in outer space (Qian, 2005). Therefore, it is essential for clothing to enable satisfactory heat exchange between the human body and the environment (Qian, 2005), so that the wearer feels comfortable. If the internal body temperature of the human body fluctuates beyond, or below, 37ºC it will have an impact on the rate of heat loss and heat production (Choudhury *et al.*, 2011). Table 1 provides an overview of the physiological responses that the body has in relation to an increase or decrease in body temperature from the 'normal' core temperature of 37°C.

Table 1: Physiological responses at different body temperatures

Body temperature (ºC)	Physiological response
43.3	Brain damage, fainting, nausea
37.8	Sweating
37	Normal
<37	Shivering and goose bumps
<32.2	Speechless
26.5	Stiff and deformed body
<26.5	Irreversible body cooling

(Source: Choudhury *et al.,* 2011)

According to Fan (2009b), one of the most important ways to maintain comfort of the human body is through evaporative heat loss. If moisture cannot escape through the clothing or fabric there will be a build-up of moisture on the skin and within the clothing which will result in discomfort (Fan, 2009b and Havenith, n.d.). Sport and leisure activities lead to the sweating of the body, which results in clothing becoming wet. In order to prevent the problem of wet clothing and improve comfort, Havenith (n.d.) recommends the use of natural fibres that have a high absorption rate, hydrophilic treatments, special fibre structures and special fabric construction methods to prevent the build-up of moisture in clothing. This is supported by Li (2001) who notes that hygroscopic fibres, such as wool and cotton, which are able to absorb moisture vapour when humidity rises, and release moisture when the humidity falls, is essential for the passage of heat between the body and the environment. There is, however, also a school of thought, and some supporting evidence, that a fast wicking hydrophobic fibre against the skin, with a hydrophilic fibre as the next (outer) layer, can also provide comfort, particularly in the case of active sportswear (Firgo *et al.*, 2006). The perspiration is pulled through the fabric by the hydrophilic fibre on the outside and as a result maximizes the area available for evaporation (Firgo *et* al., 2006). Clearly, therefore, it is possible for clothing to facilitate the thermoregulatory system of the body to maintain a constant body temperature, even during fluctuations in external environmental conditions or physical activities (Li, 2001).

2.1.1.3 Psychological comfort

According to Slater (1991), psychological comfort refers to the aesthetic elements of clothing, such as colour, design, fabric, style and fit. Consumers constantly base purchasing decisions for garments on these elements; therefore, psychological comfort has become increasingly important in garment and fabric product development (Fan, 2009a). Nayak *et al.* (2009) add that psychological comfort has nothing to do with the physical properties of the fabric. In other words, it focuses on the aesthetic properties of a garment as opposed to thermophysiological parameters.

Fan (2009a) identifies several aspects related to the psychological comfort of clothing (see Figure 2). From the elements shown in Figure 2, it appears that psychological comfort is a highly subjective matter and an individual choice (Fan, 2009a). If garment designers are able to consider these elements, and relate them to the choice in textile and garment design, they could meet the needs of the consumer more satisfactorily, for example improving the visual appearance of a garment (Fan, 2009a).

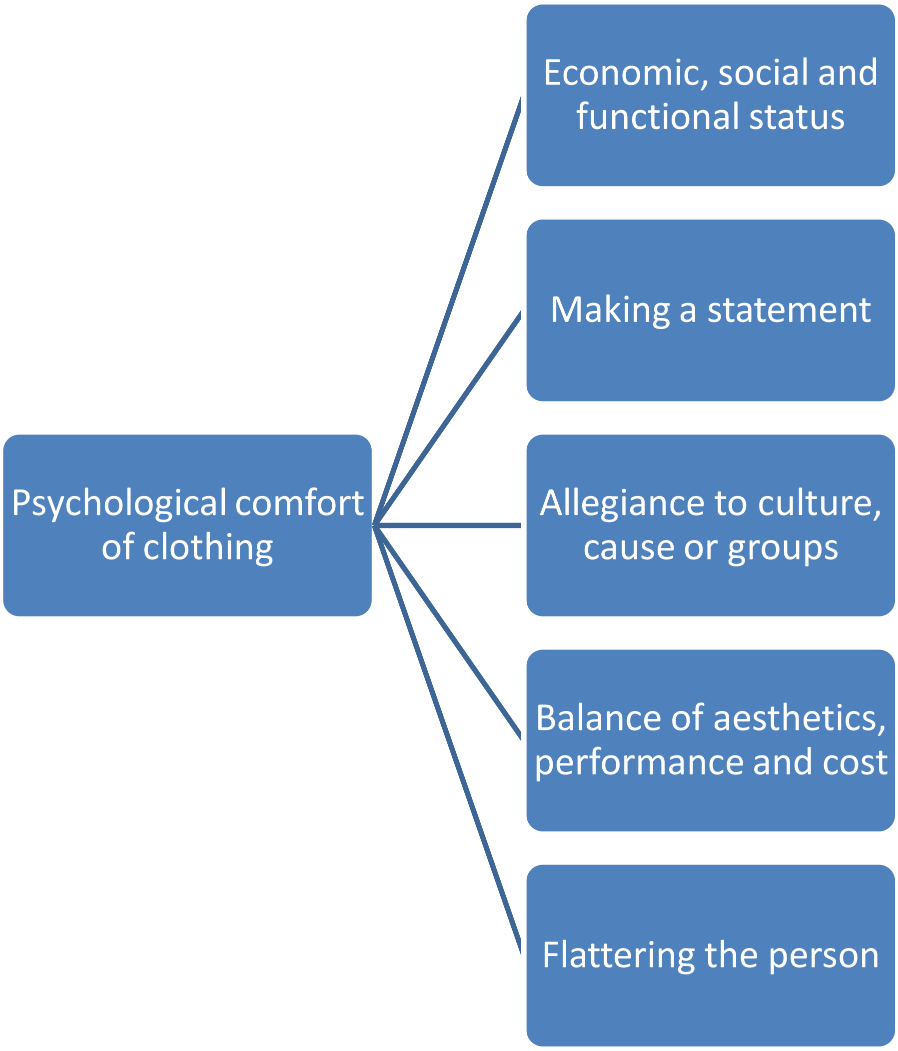


Figure 2: Factors that determine psychological comfort of clothing

(Source: Fan, 2009a)

Furthermore, Fan (2009a) identifies a range of factors that have an influence on psychological comfort, such as the effect of colour on the consumer, the texture of the fabric, and the design and fit of the garment. Colour not only influences human emotion and feelings but also influences perceptions regarding youthfulness, femininity, masculinity, and culture (Fan, 2009a). For example, a brightly coloured garment will generally appeal to a young group of consumers. The texture of a fabric also results in different psychological moods, for example, a soft fabric, such as flannel, will convey a feeling of softness; whereas a shiny fabric will suggest something more sophisticated (Fan, 2009a). Effective design of a garment will incorporate colour, texture, space, lines, pattern, silhouette, shape, proportion, balance, and harmony, in such a way that it will appeal to the consumer in a fashionable manner, or specific end use (Fan, 2009a).

2.1.1.4 Summary on comfort

Comfort is a difficult term to define due to the number of variables that are involved. According to Li (2001), clothing is constantly interacting with the human body during wear, which stimulates mechanical, thermal and visual sensations. Fan (2009b) states that humans are continuously trying to improve their level of comfort, and the importance of clothing and textiles in this regard is no exception. Although the need for comfort is always present, comfort needs differ due to different environmental and climatic conditions, and also throughout different life stages, from a baby to an elderly person (Fan, 2009b).

Fan (2009b) summarises the main features which determine whether a clothing ensemble can be deemed comfortable. Firstly, the body core and skin temperature must be regulated through adequate thermal insulation. Secondly, the skin of the body must remain dry, which requires the transmission of moisture and transfer of liquid through the clothing. Thirdly, the fabric should not cause physical discomfort and should not inflict pressure on the body, but rather allow ease of movement.

According to Li (2001), research in the field of clothing comfort can be applied in a range of industries. Industrial applications include the development of highly technical apparel products which focus specifically on the comfort of the product. Consumer research enables the design and development of products which better conform to the needs of the consumer. The ability of businesses to identify, research and develop new products, which satisfy the needs of consumers, is crucial to maintain a competitive advantage in the market.

2.1.2 The transfer of heat

The human body strives to maintain a constant temperature of 37ºC; although, it can vary slightly from person to person (Malik and Sinha, 2012). Davenport (2003) and Havenith (1999) state that the human body generates heat, through metabolic activity, which is lost through radiation, convection, conduction, evaporation and respiration, in order to maintain a constant body temperature, see Figure 3. The release of dry heat occurs through radiation, convection and conduction (Harnett, 1981, Kothari, 2006 and Matusiak, 2010). Kothari (2006) estimates that up to 75% of the metabolic heat of a person, wearing light clothing doing light activity in a temperate environment, is lost through dry heat. On the other hand, the rest of the heat is lost through the evaporation of water from the skin and through the lungs (Kothari, 2006). Latent heat transfer occurs as a result of moisture transmission related to water vapour pressure between the skin of the body and the environment (Kothari, 2006).

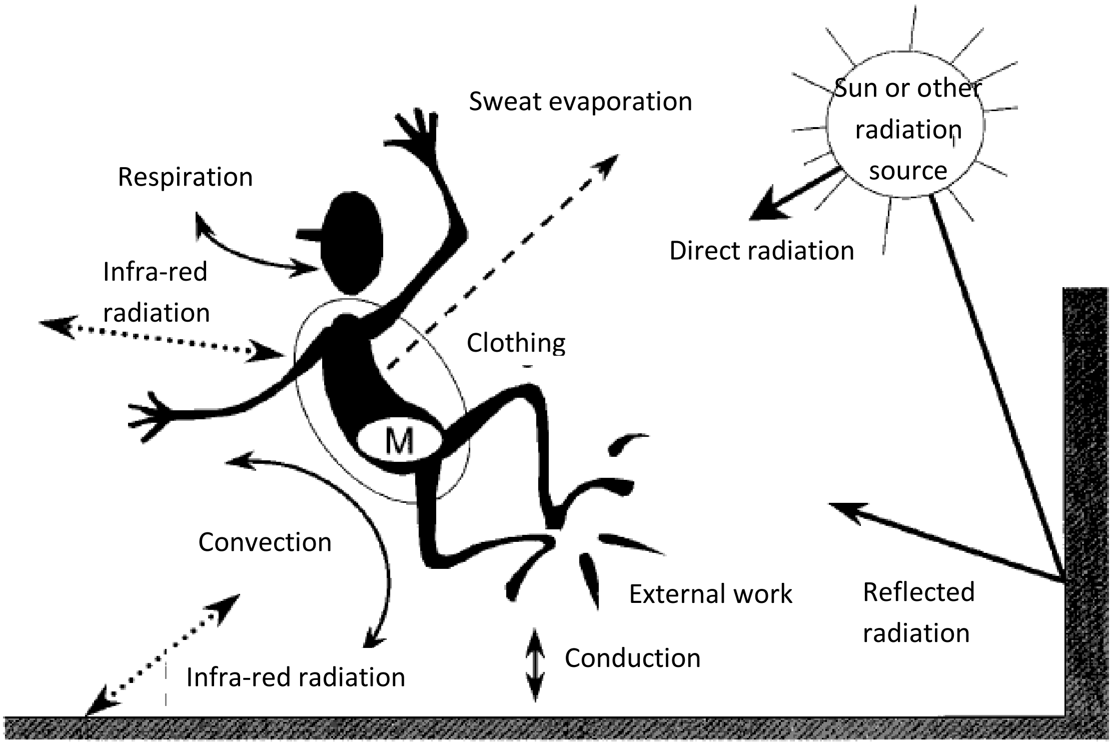


Figure 3: Schematic representation of the loss of heat from the human body

M= metabolic rate

(Source: Havenith, 1999)

2.1.2.1 Radiation

Radiation is the transfer of heat by electromagnetic waves from a warmer surface to a cooler surface (Coutant, 1998), or when heat is gained from a warmer surface (Choudhury *et al.*, 2011). It occurs when heat transfers from the human body to the outside and surrounding environment (Davenport, 2003 and Oğulata, 2007), without an intermediate substance or material being involved. According to Mehta and Harnett (1981), radiation is not affected by the movement of air, and therefore depends only on surface temperatures. The distance from the body and the nature of the surface will determine the amount of radiation that occurs (Mehta and Harnett, 1981). For example, light coloured garments are generally cooler than dark coloured garments, due to the fact that their surface reflects light from the sun, which can influence the regulation of radiation (Mehta and Harnett, 1981). According to Choudhury *et al.* (2011), three things happen when radiation comes in contact with a mass:

1. It continues its journey unchanged.
2. It is reflected or deflected from its course, or
3. It is absorbed.

The rate at which radiation occurs depends on the differences in temperature, the thermal absorptivity of the objects, as well as the distance between the objects (Choudhury *et al.*, 2011). Furthermore, the radiation qualities of a material include its temperature, emissivity, absorptivity, reflectivity and degree of transmission to allow radiation to pass through (Choudhury *et al.*, 2011).

2.1.2.2 Convection

Convection is defined by Mehta and Harnett (1981) as 'the method of transferring energy through a medium which itself is moving'. According to Choudhury *et al.* (2011), convection is a method of heat loss due to cooler air, or heat gain as a result of warmer air.

Mehta and Harnett (1981) distinguish between two types of convection, namely 'forced' convection and 'natural' convection. Forced convection occurs as a result of physical activity, where air and heat exchange occurs between the clothing and the external air; whereas natural convection occurs due to fluctuations in the density, temperature and humidity of the air (Mehta and Harnett, 1981). It is also important to note that air mobility is affected by the properties of textile fibres and the construction method of the fabric (Mehta and Harnett, 1981). For example, wool can limit the mobility of air in the fabric due to the scales on the fibre which trap air, and a tightly woven fabric can restrict penetration of wind, or air movement, due to the reduced spaces between warp and weft yarns in such a fabric (Mehta and Harnett, 1981). According to Coutant (1998), one of the ways in which clothing manufacturers reduce convection cooling is through the use of closures, for example draw cords to keep out cold air.

2.1.2.3 Conduction

According to Coutant (1998), conduction is the exchange of heat when objects are in contact with one another. When the body comes in contact with a cold item, for example a wet piece of clothing, heat will be lost through conduction, as the cooler object will conduct the heat away from the warmer item (Davenport, 2003). Clothing protects the wearer from direct contact with warm or cold surfaces (Choudhury *et al.,* 2011). The more physical contact there is with another medium or material, i.e. the greater surface area in contact, the more conduction will take place (Starr, 2010), with different objects having different rates of thermal conductivity (Coutant, 1998).

Heat loss through conduction can be minimised or even prevented, by wearing multi-layered garments, to provide insulation, as the air from the human body moves slower through the layers of the materials and any entrapped air to the surrounding air (Davenport, 2003). This is due to the fact that the insulation capability of fabric and garments depend on the air entrapped within it (Mehta and Harnett, 1981). In addition to multi-layered garments, the entrapment of air can be increased by using bulky types of fabrics, where the density of the yarns, fibre crimp, yarn twist, and closeness of the yarns will determine the amount of air trapped, and therefore the insulation value (Mehta and Harnett, 1981). Furthermore, the use of pile fabrics, with dense and easily compressible piles, as opposed to long piles of low density, will improve the conduction of heat due to the entrapment of more air (Mehta and Harnett, 1981).

2.1.2.4 Evaporation

Evaporation, due to sweat forming on the skin of a body, results in the loss of heat (Davenport, 2003 and Oğulata, 2007). According to Coutant (1998), this is referred to as 'latent heat of evaporation'. Starr (2010) comments that heat loss through evaporation can be essential for maintaining the equilibrium in body temperature during hot conditions or when exercising. Nevertheless, when the relative humidity of the environment is high it prevents the loss of heat, due to the inability of the air to absorb additional moisture from the skin of the body, i.e. prevents evaporation. On the other hand, if the relative humidity is low there will be a faster rate at which the air absorbs the moisture because the air is drier and therefore absorbs more moisture (Starr, 2010), i.e. a faster evaporation and rate of heat loss.

Heat is also lost through the process of breathing or respiration (Davenport, 2003). Oğulata (2007) divides heat loss through respiration into evaporative heat loss (latent heat) and sensible heat loss. According to Choudhury *et al*. (2011), latent heat loss consists of latent respiration heat loss, water diffusion through the skin and evaporation of sweat. Sweat on the skin of the human body occurs as a result of a moderately high temperature of the environment (Choudhury *et al.,* 2011).

2.1.2.5 Heat balance

Coutant (1998) is of the opinion that it is very difficult to combat both evaporative and convective heat loss simultaneously. For example, when there is no barrier to wind, the evaporative rate of the body will be excellent; whereas, when clothing is worn, it impacts on the effect of wind and the loss of heat through convection, and the rate of evaporation slows down (Coutant, 1998). As a result, there will be an increase in moisture vapour within the clothing layers (Coutant, 1998).

Mehta and Harnett (1981) state that a person wearing summer clothing doing light activity in a moderate environment, will generally lose 40% of heat through conduction and convection, 40% through radiation, and 20% through evaporation.

The loss of heat will increase in a dry atmosphere or decrease in a humid environment. In an environment with strong air movement, convective and evaporative heat loss will also increase; whereas, in an environment with little air movement, radiation will be the primary mode of heat loss (Mehta and Harnett, 1981).

Matusiak (2010) identifies the following three factors which influence the loss of heat between the human body and its environment:

1. The human organism (age, gender, weight, metabolic rate)
2. Climatic conditions (temperature, humidity, wind)
3. Clothing (fibre properties, layers of clothing, finishes, textile construction)

Havenith (1999) states that, in order for the human body to maintain a constant comfortable temperature, the amount of heat loss must even out heat production. If there is not an equilibrium, the body temperature will either increase, resulting in positive storage, or decrease, which results in negative storage (Havenith, 1999). Therefore, the equilibrium equation (2-1) can be formulated as follows:

Heat storage = heat production – heat loss________________________________(2-1)

= (metabolic rate – external work) –

(conduction + radiation + convection + evaporation + respiration)

Malik and Sinha (2012) also confirm that a thermal balance of the human body is achieved when the metabolic heat of the body and the heat from external sources evens out the loss of heat of the body. In other words, if there is no equilibrium between heat loss and heat gain, the temperature of the body will increase or decrease, which could potentially have life threatening results. Therefore, clothing is crucial for achieving thermal balance, as it influences the heat loss and moisture loss from the skin surface (Malik and Sinha, 2012). Nevertheless, climatic conditions also play a role, due to the fact that clothing suitable for a particular environment will not necessarily be suitable for a completely different environment. For example, ski clothing provides sufficient protection against the cold weather, but it will not keep the human body cool in warmer conditions.

2.1.3 Thermophysiological comfort

2.1.3.1 Introduction

Thermophysiological comfort encompasses all the aforementioned elements of heat transfer. Malik and Sinha (2012) state that thermophysiological comfort is achieved when the wearer experiences comfort in terms of their thermal and wetness state. In order to achieve thermophysiological comfort, efficient transport of heat and moisture is required (Malik and Sinha, 2012). According to Benisek *et al.* (1987), thermophysiological comfort is influenced by three elements, namely heat transfer, moisture vapour transfer, and liquid moisture transfer. Heat transfer from the human body to the environment, as well as thermal insulation in cold conditions, depends on the thickness and construction of the fabric (Benisek *et al.,* 1987). Moisture vapour transfer, the removal of insensible perspiration from the microclimate between the skin and the fabric, is improved through the use of hygroscopic fibres as well as open garment and fabric constructions (Benisek *et al.,* 1987). Liquid moisture transfer, the removal of liquid perspiration from the skin, is influenced by the type of fibre and fabric construction chosen for a textile (Benisek *et al.,* 1987).

Heat produced by the human body is released through the skin by dry heat and evaporation (Voelker *et al.,* 2009). The transfer of moisture, which is centered around the evaporation of sweat on the skin to remove heat from the human body, depends on three factors, namely the thermoregulatory system of clothing, the permeability of the textile, and the water vapour pressure of the surrounding air (Voelker *et al.*, 2009). Dry heat loss depends on the insulation properties of the garment (Voelker, *et al.,* 2009). Thermal insulation and vapour resistance of fabrics and garments generally determine the minimum and maximum temperatures at which an activity can be carried out while maintaining comfort (Mehta and Harnett, 1981).

According to Lotens (n.d.), clothing insulation refers to the air that is trapped in, and on, the clothing and is influenced by various factors, such as the construction of the fabric and the properties of the fibres. The absorption and reflection of heat radiation, absorption of water vapour, and the wicking rate of moisture of the fibres will influence the thermal insulation and vapour resistance of the textile (Lotens, n.d. and Havenith, n.d.).

Fanger (1970) states that the thermoregulatory system of the body aims to maintain a constant body core temperature, in other words, achieving a heat balance for the body where heat production equals heat dissipation. Fanger (1970) provides the following equation (2-2) to describe the heat balance of a human body:

$$H - E_d - E_{sw} - E_{re} - L = K = R + C \qquad \text{(2-2)}$$

Where:

H = internal heat production of body

E_d = heat loss through water vapour diffusion

E_{sw} = heat loss by evaporation of sweat

E_{re} = latent respiration heat loss

L = dry respiration heat loss

K = conduction through clothing

R = heat loss by radiation, and

C = heat loss by convection

Qian (2005) simplifies this equation as follows:

$$S = M - W_k - H_d - H_e - E_r \quad (\mathrm{W/m^2}) \qquad \text{(2-3)}$$

Where:

S = the rate of body heat storage (which will be 0 under thermal equilibrium)

M = the metabolic rate

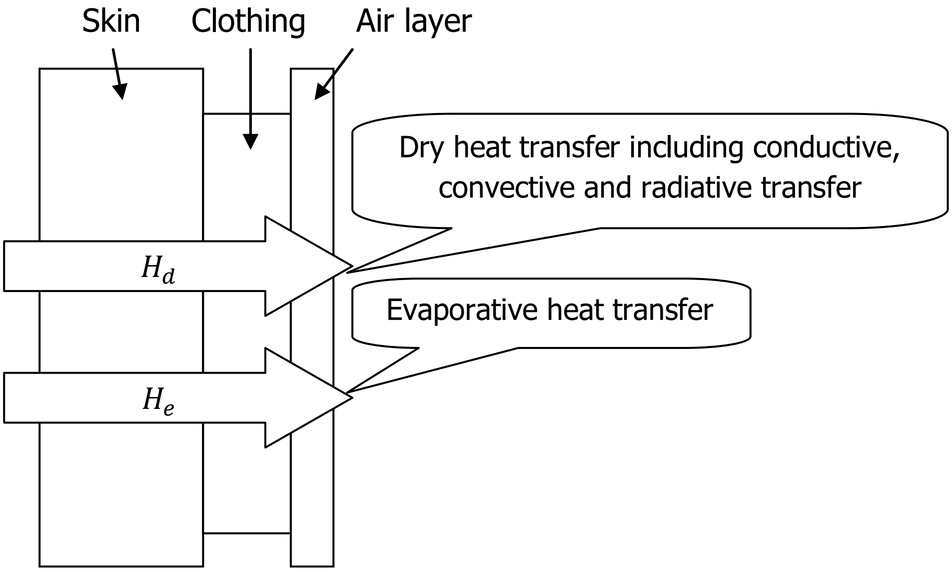
W_k = external work

H_d = dry heat loss from the skin, through conduction, convection and radiation

H_e = evaporative heat loss, and

E_r = the sum of the latent and sensible respiration heat loss.

Qian (2005) provides a diagram that illustrates the transfer of heat of a clothed person standing in still air, see Figure 4. Qian (2005) and Voelker *et al.,* (2009) comment that the metabolic system of the human body generates heat which is transferred through clothing by conduction, convection and radiation. These three methods of transmission are known as dry heat transfer H_d (W/m²); whereas evaporative heat transfer (latent heat) is achieved through moisture transmission H_e (W/m²).



$$H_t = H_d + H_e$$

Figure 4: Clothing system for heat and mass transfer

(Source: Qian, 2005)

According to Fan (2009b), thermal insulation of textile fabrics can be measured in terms of thermal conductivity (W/mK) or thermal resistance (Km²/W: Kelvin metres-square per Watt). Holcombe (1984) defines thermal resistance of fabrics as "the ratio of the temperature difference between the two faces of the material to the rate of heat transfer per unit area of the material normal to the faces". In other words, thermal resistance measures the resistance of the conductor to heat flow per unit area. The clothing and thermal insulation measurement (clo unit), which was introduced in the 1940s, focuses on the thermal insulation of clothing to maintain the comfort of a resting person in an environment of 21°C (Holcombe, 1984 and Fan, 2009b). It is also important to note that the clo unit reflects the insulation of a clothing ensemble, as opposed to a single garment (Fan, 2009b). One clo is equal to a thermal resistance of 0.155 Km^{2}W (Fan, 2009b). In addition, the unit of measure for water vapour resistance is m^{2}Pa/W (Konarska *et al.*, 2006).

According to Woodcock (1962), the formula (2-4) for establishing the rate of heat transfer through clothing H_t (W/m^2), where direct heat loss and evaporative heat loss are measured independently, is as follows (see Figure 4):

$$H_t = H_d + H_e \qquad \text{(2-4)}$$

According to Woodcock (1962) and Fan (2009b), dry heat transfer (H_d) and latent heat transfer (H_e) of a clothed body can be determined by the following formulae:

$$H_d = \frac{(T_s - T_a)}{I_t} \qquad \text{(W/m}^2\text{)} \qquad \text{(2-5)}$$

$$H_e = \frac{(P_s - P_a)}{R_t} \qquad \text{(W/m}^2\text{)} \qquad \text{(2-6)}$$

The thermal insulation and water vapour resistance are indicated by I_t and R_t respectively, and $(T_s - T_a)$ and $(P_s - P_a)$ reflect the temperature difference and difference in water vapour pressure between the skin and environment, respectively (Fan, 2009b). T_s is the area weighted mean skin temperature (°C); T_a is the mean environmental temperature (°C); P_s is the water vapour pressure at the skin (Pa); and P_a is the water vapour pressure at the environment (Pa). These two formulae and the formula of Fanger (1970), are crucial for examining the thermal comfort of a human being as they are not constant figures, and will be influenced by several variables, such as body posture, body movement and environmental conditions (Fan, 2009b).

Thermal insulation (I_t) and water vapour resistance (R_t) are calculated using the following formulae (Qian, 2005): A_s

$$I_t = \frac{A_s(T_s - T_a)}{H_d} \qquad \text{(m}^2\text{K/W)} \qquad \text{(2-7)}$$

$$R_t = \frac{A_S(P_S - P_a)}{H_e} \quad (\text{m}^2\text{Pa/W}) \qquad (2\text{-}8)$$

In the afore mentioned equations, A_s indicates the body surface area (m²), and $(T_s - T_a)$ and $(P_s - P_a)$ are the temperature difference and difference in water vapour pressure between the skin and the environment, respectively (Qian, 2005).

In terms of vapour transfer, Mehta and Harnett (1981) state that clothing acts as a barrier to the flow of vapour. If vapour cannot escape through the clothing, the skin of the body will not be dry and will result in discomfort (Mehta and Harnett, 1981). This is supported by Prahsarn *et al.* (2005) who state that humidity in the microclimate between the clothing and the human skin results in dampness and clamminess, especially during the period after a particular activity has been stopped. Therefore, it is essential to keep vapour resistance as low as possible to ensure comfort (Mehta and Harnett, 1981).

Another important factor, which influences comfort, is the permeability index (i_m), which was introduced by Woodcock in 1962 (Qian, 2005). According to Sitvjenkins, *et al.* (2011), the water vapour permeability index is determined through the following equation (2-9):

$$i_m = \frac{60.6\, R_{ct}}{R_t} \qquad (2\text{-}9)$$

Where: R_{ct} is thermal resistance, and R_t is water vapour resistance.

The permeability index changes the concept that clothing should keep the wearer warm to one that clothing should maintain a level of thermal equilibrium (Woodcock, 1962). According to Mehta and Harnett (1981), the ratio of thermal resistance to vapour resistance refers to the moisture permeability index. Verdu *et al.* (2009) state that i_m is dimensionless and has values between 0 and 1. Verdu *et al.* (2009) and Qian (2005) state that a fabric that is completely water vapour impermeable will have a value of 0. A fabric with a value of 1 has both the thermal resistance and water vapour resistance of an air layer of the same thickness (Verdu *et al.,* 2009). Frydrych *et al.* (2002) comment that air permeability, which is influenced by fabric porosity and the cross-section and shape of the textile, will ultimately determine the thermal properties of a garment. Therefore, the moisture permeability index focuses on the thermophysiological comfort of clothing and fabrics.

Fan and Chen (2002) propose the accumulation of moisture within clothing as an additional parameter of thermal insulation. The moisture accumulation within clothing can be measured, for example on a sweating manikin, by weighing the garment before it is placed on the manikin and after 24 hours (Fan and Chen, 2002). Qian, (2005) gives the following equation (2-10) for the measurement of moisture accumulation:

$$M_a = \frac{W_b - W_a}{W_a} \text{ x } 100\% \qquad (2\text{-}10)$$

In the above equation, M_a is the moisture accumulation in the clothing which builds up during the test, and W_a and W_b reflect the original and final weight of the clothing in grams, respectively.

From the above discussion, it is evident that the purpose of clothing is to support the thermoregulation of the body (Rossi, 2005), with several factors affecting the thermal and moisture transport through textiles, as summarised by Rossi (2005):

1. Dry heat transfer: Conductive, convective and radiant heat transfer occurs between the body, the environment and the atmosphere, being influenced by factors, such as wind speed and thermal resistance of fabric layers.

2. Thermal energy stored within clothing: Clothing items, such as heat protective clothing, have the ability to store large amounts of heat.

3. Diffusion of water vapour molecules through a textile: The permeability of a textile contributes to the breathability of a garment.

4. Adsorption and movement of water vapour molecules and liquid water along fibre surfaces and the open spaces between fibres and yarns.

5. Absorption and desorption of water vapour

6. Evaporation of liquid

2.1.3.2 Air permeability and porosity

Porosity and permeability are identified by Dayal (1980) as key elements that contribute to comfort in fabrics and clothing. Porosity is defined by Dayal (1980) as "the total volume of void space obtained within the boundaries of a textile". Air permeability is defined by Ho *et al.* (2011) as "the rate of air flow through a fabric when there is a different air pressure on either surface of the fabric". Furthermore, it is important to note that air permeability is affected by the porosity of a fabric (Ho *et al.,* 2011). The porosity of a textile is defined by the following equation (Özdil *et al.*, 2007):

$$P_1 = (1 - m/\rho . h)100 \quad \text{(2-11)}$$

Where: P_1 is porosity, m is fabric weight (g/cm^{-2}), ρ is fibre density (g/cm^{-3}), and h is fabric thickness (cm).

All textile fibres, whether natural or synthetic, are impermeable to air and the passage of air through a textile fabric is achieved due to the pores within the construction of the fabric, in other words between the fibres and yarns (Kothari, 2006). The type of fibre has no influence on the air permeability of a fabric, the latter depending rather on the structure of the fabric, fibres and yarns, in terms of fibre fineness and shape, and the type and compactness of the fabric and yarns structure (Dayal 1980 and Kothari, 2006). Yarn twist is particularly important in woven fabrics, because an increase in the twist will result in an increase in yarn density and circularity, reducing yarn diameter and cover factor, which increases the air permeability (Ding, 2008), all other factors remaining constant. According to Ding (2008), it is also important to consider the finishing techniques of fabrics and their impact on air permeability. For example, hot calendering can flatten fabrics, which reduces its air permeability due to the reduction in pore size (Ding, 2008). Therefore, yarn characteristics and fabric construction largely determine the air permeability of a fabric (Dayal, 1980).

According to Choudhury *et al.* (2011), a fabric that is air permeable is usually permeable to water vapour or liquid as well. This statement indicates the relationship between water vapour permeability, liquid moisture transmission, and air permeability of fabrics. Furthermore, Choudhury *et al.* (2011) state that it is not only important to consider the entrapment of air and air permeability of textiles in terms of water vapour permeability, but also in terms of the impact on the thermal resistance of the fabric.

Figure 5 illustrates the pores (void spaces) between the fibres and yarns in a plain weave fabric, through which air passes.

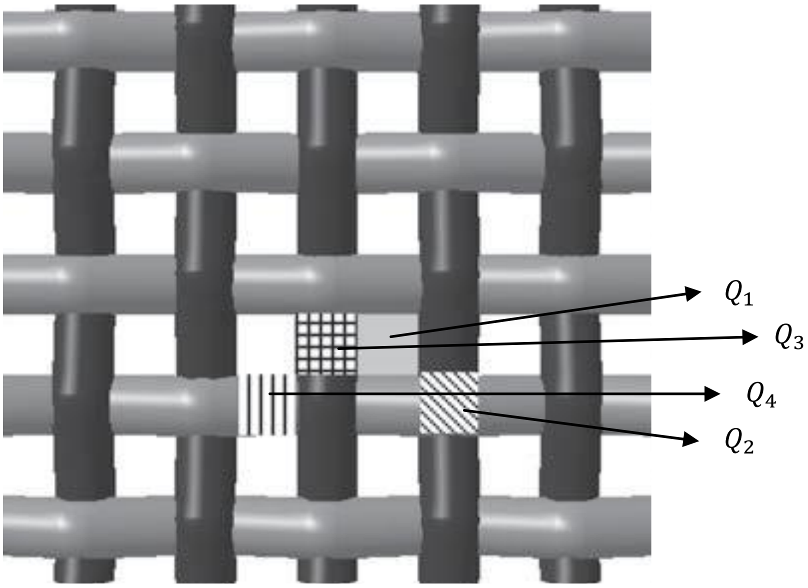


Figure 5: Pores in plain woven fabric

(Source: Ogulata and Mezarcioz, 2012).

Ogulata and Mezarcioz (2012) identify four airflow regions in Figure 5 as follows:

1. Flow rate between warp and weft yarns (Q_1)
2. Flow rate through the fibres at the intersection of warp and weft yarns (Q_2)
3. Flow rate through the fibres of warp yarns (Q_3)
4. Flow rate through the fibres of weft yarns (Q_4)

Therefore, the air permeability (Q_{total}) of a woven fabric can be defined as follows:

$$Q_{total} = Q_1 + Q_2 + Q_3 + Q_4 \qquad (2\text{-}12)$$

Havlová (2013) simplifies the aforementioned airflow regions by distinguishing between two types of porosity:

1. Micro porosity (void spaces between fibres in yarns).
2. Macro porosity (void spaces between yarns).

Havlová (2013) is of the opinion that the air permeability of a textile is determined mainly by the macro porosity of the fabric. Therefore, two fabrics that appear similar in construction may vary significantly in terms of air permeability, due to the macro porosity of each fabric in terms of size, shape, texture and compactness of the yarns (Havlová, 2013). However, the type of weave or knit structure will also have an impact on the air permeability of a fabric (Havlová, 2013).

In terms of apparel and clothing ensembles, Ho *et al.* (2011) state that the air permeability of clothing ensembles is influenced by the walking speed and rhythm of human beings. Activities, such as walking, result in air penetration in and out of the clothing and between the fabric layers; although, the extent of this penetration will still depend on the fabric's pore size (Ho *et al.,* 2011). For example, using a mesh fabric in sportswear improves the ventilation of the clothing, due to the fact that the pores enable air and moisture transfer (Ho *et al.,* 2011).

2.1.3.3 Water vapour permeability and resistance

Mehta (1984) states that the human body loses approximately one litre of water per day through the skin, through insensible perspiration (water vapour). Heat is required to evaporate water, and it is estimated that a quarter of heat produced by the body is lost in this way (Mehta, 1984). Nevertheless, at high levels of activity a great deal of heat is produced; and this mechanism is then incapable of cooling the body adequately. Therefore, sensible perspiration is produced on the skin surface in order to lose more heat and to cool the body through the evaporation of the perspiration (Mehta, 1984).

The transport of water vapour through a fabric is important as it determines the physiological comfort of a fabric (Mehta, 1984). This refers to the ability of a fabric to transfer perspiration from the body to the fabric surface to maintain comfort (Lee and Obendorf, 2012). A fabric is comfortable if it is able to transmit moisture vapour when the body perspires, and release moisture vapour to the external environment once perspiration has stopped, to reduce the humidity on the skin (Supuren *et al.,* 2011). If the clothing provides a considerable resistance to the evaporation of perspiration, not all of the perspiration will evaporate from the skin surface, which will ultimately determine the rate at which the body is cooled (Mehta, 1984). In addition, the perspiration may even wet the garment, due to the insufficient transmission of water vapour of the textile, resulting in severe discomfort (Mehta, 1984). Therefore, Mehta (1984) recommends that, in order for a garment to be classified 'breathable', and to transmit perspiration vapour, the water vapour resistance of the fabric should be as low as possible.

Water vapour transmission through a fabric occurs as a result of diffusion, through openings or pores in the fabric, and is influenced by various factors, such as fabric structure, fabric thickness and pore size and concentration (Lee and Obendorf, 2012 and Mehta and Harnett, 1981). According to Mehta (1984), the water vapour resistance of a textile is mainly determined by the thickness of the fabric, although the tighter the fibres are packed in a fabric, the greater the vapour resistance will also be. On the other hand, water vapour transmission can also occur through diffusion through individual fibres, which depend on the hydrophilic or hydrophobic nature of the fibres (Lee and Obendorf, 2012). According to Mehta (1984), protein and cellulosic fibres, that are hygroscopic, transmit vapour absorbed by the fibre much more rapidly compared to non-hygroscopic synthetics. Therefore, hygroscopic fibres, such as wool and cotton, transmit water vapour more rapidly than non-hygroscopic fibres, such as polyamide and polyethylene (Mehta, 1984). Fabrics made from synthetic fibres, such as polyamide, of similar tightness of construction, will therefore have much higher water vapour resistance values, compared to wool or cotton fabrics (Mehta, 1984). This statement highlights the impact that they hygroscopic nature of a fibre has on the water vapour transmission ability of the fabric.

A study conducted by Lee and Obendorf (2012), established that water vapour transmission in woven fabrics, with a fabric thickness between 0.206 and 1.000 mm, decreased with an increase in fabric thickness, fabric cover factor, yarn twist factor, yarn packing factor, moisture regain of fibre, and solid volume fraction, but, increased with an increase in the pore diameter of the fabric. These fabric parameters are interrelated, and Lee and Obendorf (2012) developed the following equation (2-13) to predict the water vapour transmission through woven fabrics:

$$\mathrm{WVT} = -0.05 - T - 0.2B - 0.06D + 0.002Y + 11B^2 + 0.025D^2 - 0.0017Y^2 \_\_\_\_(2\text{-}13)$$

Where; WVT is water vapour transmission, T is fabric thickness (mm), B is the fabric cover factor, D is the moisture regain of the fibre (%), and Y is the mean flow pore diameter (μm). Yarn twist and yarn packing factor were not included in the equation, since they found in their study that these two parameters to be insignificant.

According to Kothari (2006), to ensure comfort of a human being wearing clothing, the water vapour permeability of the fabric should be as high as possible to allow the escape of water vapour, which is constantly being released from the skin (insensible perspiration). If water vapour is unable to escape through the textile, the condensation of water vapour, due to an increase in the humidity at skin level, will result in a clammy sensation (Kothari, 2006). The type of fibre used in a fabric will influence the water vapour permeability of the textile to some extent, due to the ability of fibres to absorb a certain amount of moisture from the surrounding air (Kothari, 2006). However, the rate at which water vapour is transferred through a fibre, depending on the nature of the fibre, whether hydrophobic or hydrophilic (Kothari, 2006).

Another important aspect is highlighted by Benisek *et al.* (1987), namely the design of a textile product that has an influence on the perspiration removal of a garment. For example, a garment designed with an open fabric construction and loose fit, will allow the removal of perspiration much better than a tight fitting garment, made from a tightly constructed or thick material (Benisek *et al.,* 1987). A loosely fitting garment, made from an open constructed fabric will also improve the air permeability of the product (Benisek *et al.,* 1987). External factors could also influence the level of comfort that a human being experiences, for example, when sitting on plastic chairs, the movement of perspiration vapour through the clothing is prevented, which results in discomfort (Mehta and Harnett, 1981). It is, therefore, recommended by Mehta and Harnett (1981), that fibres, such as wool and cotton, should be used in clothing, due to their hygroscopic nature.

Fabric manufacturers have the difficult task of finding a compromise between high water vapour permeability, and high thermal and air flow resistance, as these parameters are incompatible to some extent (Kothari, 2006). Nevertheless, the introduction of breathable coatings have enabled the production of water vapour permeable clothing that restrict air permeability and penetration of liquid water, at the same time (Kothari, 2006). For example, GORE-TEX is a material that contains a membrane that provides wind and water protection, while allowing water vapour to pass through the material (Ho *et al.*, 2011).

2.1.3.4 Thermal resistance

Heat transfer through textiles and clothing involve conduction through air and fibres, radiation (both direct and from fibre to fibre), as well as convection (Ukponmwan, 1993). In a homogenous solid, the mechanism of heat transfer is through conduction, and the temperature profile is linear (Ukponmwan, 1993). The total heat transferred increases with the presence of radiation, but the temperature profile will depart from linearity due to the interaction between conduction and infra-red radiation (Ukponmwan, 1993).

According to Ukponmwan (1993), the transmission of heat through clothing and textiles occur in three forms:

1. Dry transmission (also referred to as conduction and includes a radiation element).
2. Diffusion of insensible perspiration.
3. Diffusion of liquid perspiration.

It is important to note that only the first two forms of transmission will operate under conditions of comfort. The presence of liquid, in the form of perspiration on the human skin, is associated with discomfort. Therefore, Ukponmwan (1993) states that the total rate of heat transfer (Q) consists of a conductive (Q_c) and an evaporative component (Q_e):

$$Q = Q_c + Q_e \qquad (2\text{-}14)$$

The resistance that a fabric provides against the movement of heat is crucial as it determines thermal comfort (Matusiak, 2013 and Ukponmwan, 1993). The air that is trapped within the structure of a fabric between the fibres and yarns, largely determines the thermal resistance of a textile (Matusiak, 2013). Thermal resistance is defined by the following equation (Matusiak, 2013):

$$R_{ct} = \frac{h}{\lambda} \qquad (2\text{-}15)$$

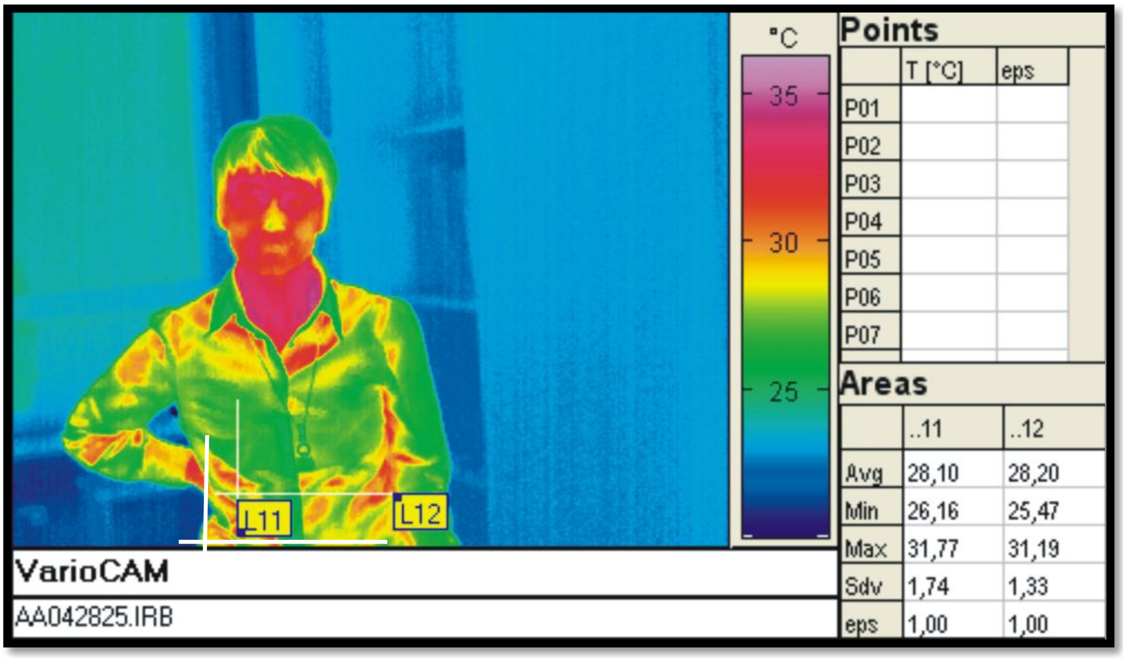
Where: R_{ct} is the thermal resistance (m^2K/W), h is the fabric thickness (m), and λ is the thermal conductivity (W/mK).

The thermal resistance of fabrics, made from the same fibres, depend on the thickness and compactness (such as weave and density of threads) of the particular textile (Matusiak, 2013). This is supported by Ho *et al.* (2011) and Ukponmwan (1993), who comment that thermal resistance is determined by fabric thickness, as opposed to the type of fibre used in the fabric. This is due to the fact that the volume of air enclosed in clothing materials are generally more than the volume of the fibres (Havenith, n.d.). In addition, when two fabrics are placed on top of each other, the thermal insulation will be higher compared to the individual fabrics due to the entrapment of more air between these two layers (Ho *et al.*, 2011).

Starr (2002) confirms that the open spaces within a textile fabric largely determine thermal insulation, with the physical structure and size of fibres and yarns also influencing the overall insulating capacity. For example, a fibre, such as wool, has a crimp that provides more voids, pores and surface area for air, which increase the insulation of the fabric (Harnett, 1984 and Starr, 2002). In other words, the warmest fibre is usually the one that produces the thickest or bulkiest fabric (Ukponmwan, 1993). Furthermore, Harnett (1984) states that a fabric with an uneven or textured surface will have the ability to trap more air and provide more insulation than a fabric with a very smooth surface. For example, the brushing of a fabric surface to increase its thickness and bluk will result in a higher thermal insulation due to the entrapment of air. This is particularly important when producing underwear, as it also increases the apparent warmth to touch (Holcombe, 1984).

As mentioned previously, external factors also play a significant role in the comfort of clothing. Qian (2005) and Ukponmwan (1993) state that external factors, such as wind penetration, can influence the level of thermal resistance of a clothing ensemble. For example, when a garment flaps due to wind, warm air is lost in the microclimate (the air gap between the skin and the garment assembly) and replaced with cold air, which reduces the thermal insulation of the garment ensemble as a whole (Qian, 2005). The design of a garment should also be considered, due to the fact that the transfer of air occurs through the openings of a garment, which influences thermal insulation (Qian, 2005).

Qian (2005) highlights the fact that the air gaps that exist between the skin, clothing, and clothing layers, determine the flow of air in the microclimate, due to the change in the size of the air gaps when the wearer moves. According to Matusiak (2010), this will have a major influence on heat exchange. Figure 6 illustrates the temperature distribution of a single shirt, to highlight the importance of garment fit. It is evident from Figure 6 that there are differences in temperature at different parts of the human body, mainly due to fabric folds at different distances from the body (Matusiak, 2010). The temperature along the perpendicular line L1, ranges between 26.16 and 31.77°C; whereas along the horizontal line, L12, it ranges between 25.47 and 31.19°C (Matusiak, 2010). The most important aspect highlighted by Figure 6, is that the difference in temperature between the extreme points of the shirt is higher than 5°C, even though the shirt is made from the same fabric (Matusiak, 2010).



Points

	T [°C]	eps
P01		
P02		
P03		
P04		
P05		
P06		
P07		

Areas

	..11	..12
Avg	28,10	28,20
Min	26,16	25,47
Max	31,77	31,19
Sdv	1,74	1,33
eps	1,00	1,00

Figure 6: Thermogram illustrating temperature distribution of a shirt

(Source: Matusiak, 2010)

Ukponmwan (1993) summarises the main factors that must be considered when studying the thermal properties of a textile as follows:

1. Thermal conductivity of fibres and the air contained within the fabric.
2. Specific heat of the fibre substance.
3. Textile thickness.
4. Textile density.
5. Textile surface in terms of fibre used, fabric construction, and finishing.
6. Area of contact between fabric and surfaces.
7. Heat loss by conduction from skin to fabric.
8. Heat loss by convection from skin through the fabric and from the fabric surface.
9. Heat loss by radiation.
10. Heat loss by evaporation of water from skin or fabric.
11. Heat gain due to water absorption by fabric.
12. External factors, such as temperature, relative humidity, or movement of surrounding air.

Ukponmwan (1993) states that the most important aspect to consider, from the factors listed above, is the ability of a textile to hold as large an amount of still air as possible, and then to retain this during use. Therefore, the linear relationship that exists between fabric thickness and thermal resistance is not significantly influenced by the type or blend of fibres (Ukponmwan, 1993).

2.1.4 Objective testing of thermal comfort and associated standards

The first section of the literature review highlighted the fact that comfort is a multidimensional concept which is influenced by several variables, while the last section examined the importance of air permeability, water vapour transmission and thermal insulation with regard to thermophysiological comfort of textiles and clothing. This following section identifies and discusses some of the methods and equipment that are used in order to measure these parameters.

According to Rossi (2005), the test methods, used for analysing thermophysiological properties of textiles, aim to mimic heat and mass transfer from the human skin to the environment through textiles. Unfortunately, many of the results produced by the different methods are not comparable due to the different test conditions employed (Rossi, 2005).

2.1.4.1 Air permeability

According to Ding (2008), the air permeability of textiles is tested to determine the rate of air flowing perpendicularly through a specific area of fabric at given pressure differences, across the fabric test area, over a given period. Ultimately, the main purpose for testing the air permeability of textiles and clothing is to assess the 'breathability' and comfort of the particular item (Ding, 2008). Air permeability tests are also important, however, for certain textiles, such as parachutes, sail cloths, and industrial filter fabrics, which require a specific amount of air to permeate through the textile (Ding, 2008).

Air permeability testers usually consist of the following components (Ding,2008):

1. A clamping device to secure the testing sample (tensionless).
2. A guard ring to prevent air leaking from the edges of the test area.

3. A pressure gauge to measure the pressure drop from one side of the sample to the other.
4. An air pump providing a steady flow of air through the sample.
5. A means of adjusting the rate of airflow.
6. A flow meter that measures the rate of air flow through the sample

One example of an air permeability tester, is the SDL Atlas Air Permeability tester in Figure 7, which is used to test the resistance of fabrics (whether woven, knitted, or nonwoven), to the passage of air flow (SDL Atlas, n.d.). The sample is clamped by the clamping arm of the device, and the vacuum pump draws air through the test head (SDL Atlas, n.d.). The test pressure is selected before the test commences, and is automatically maintained by the device. Once the test is completed, the air permeability of the sample is digitally displayed according to the selected unit of measure (SDL Atlas, n.d.). The TEXTEST FX 3300 Air Permeability tester in Figure 8 is another example of an air permeability tester. It also has a clamping device for securing the sample, and automatically controls the air pressure, which ranges from 20 to 2 000 Pa (TEXTEST Instruments, n.d.).

Figure 7: Atlas Air Permeability Tester

(Source: SDL Atlas, n.d.)

Figure 8: FX3300 Air Permeability Tester

(Source: TEXTEST Instruments, n.d.)

Ding (2008), provides a range of standard test methods used for testing the air permeability of textiles. A selection is provided below as follows:

1. ASTM D737-2004: Test method for air permeability of textile fabrics.
2. BS EN ISO 9237-1995: Determination of the permeability of fabrics to air.
3. BS 5636-1990: Determination of permeability of fabrics to air.
4. BS EN ISO 4638-1995: Polymeric materials, cellular flexible – Determination of air flow permeability
5. ISO 9237:1995: Determination of the permeability of fabrics to air.

Air permeability test methods, such as ASTM D737-04 and BS EN ISO 9237:1995, are used extensively in the industry, since they apply to most fabrics, including woven fabrics, non-woven fabrics, air bags, blankets, napped fabrics, knitted fabrics, layered fabrics and pile fabrics (Ding, 2008). Furthermore, the fabrics can be untreated, heavily sized, coated, resin treated, or otherwise treated (Ding, 2008).

2.1.4.2 Water vapour permeability and resistance

Although a range of test conditions and testing devices exist in order to measure the water vapour permeability of textiles, a major problem is that the results obtained are not always comparable between the various techniques and testing devices (Arabuli *et al.,* 2010). Therefore, it is crucial that the appropriate device and test conditions are chosen for a particular research purpose (Arabuli *et al.*, 2010), and that care is taken when comparing the results obtained by different test instruments and/or methods.

Arabuli *et al.* (2010) lists a range of standard methods used across the globe for testing the water vapour permeability of textiles:

1. ASTM E96: Standard test methods for water vapour transmission of materials.
2. ISO 15496: Measurement of water vapour permeability of textiles for the purpose of quality control.
3. ISO 2528: Sheet materials – Determination of water vapour transmission rate – (Gravimetric dish method).

4. ISO 11092 (EN 31092): Physiological effects – Measurement of thermal and water vapour resistance under steady state conditions.
5. ASTM 1868: Standard test method for thermal and evaporative resistance of clothing materials using a sweating hot plate.

Arabuli *et al*. (2010) divide these test methods into two categories:

1. Gravimetric methods.
2. Sweating hot plate methods.

The gravimetric methods are also known as the 'cup methods' or 'dish methods', and are the most simple methods for testing water vapour transmission (Arabuli *et al*., 2010). Due to the simplicity of the cup method, Ding (2008) suggests that it is the most suitable method for manufacturers to test the water vapour permeability of their textiles for quality control purposes. Figures 9 to 11 illustrate the cup method as outlined by the ASTM E96 method. Figure 9 illustrates the 'desiccant method', where vapour transport is passed from the outside an environment to the inside of the cup. According to Ding (2008) and Rossi (2005), the rate of water vapour movement is determined through periodic weighings. Figure 10 illustrates the 'water method', where water vapour is passed from the inside of the cup to the environment. Finally, Figure 11 illustrates the 'inverted water method', which is similar to the water method, except that the cup is inverted. According to Arabuli *et al.* (2010), gravimetric methods provide the following measurements:

1. Water vapour transmission rate: the water vapour flow in unit time through unit area of a body, normal to specific parallel surfaces.
2. Water vapour permeance: the time rate of water vapour transmission through unit area of flat material, brought about by unit vapour pressure difference between two specific surfaces.
3. Water vapour permeability: the time rate of water vapour transmission through unit area of flat material of unit thickness brought about by unit vapour pressure difference between two specific surfaces.
4. Relative water vapour permeability: water vapour which has evaporated through a textile.

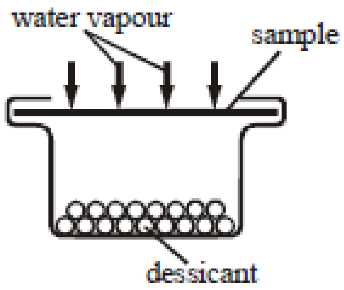


Figure 9: Desiccant “cup” method

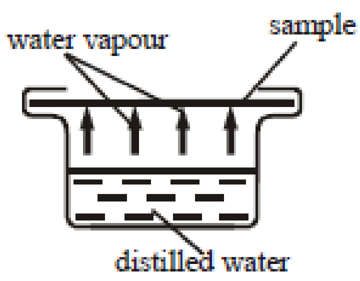


Figure 10: Water “cup” method

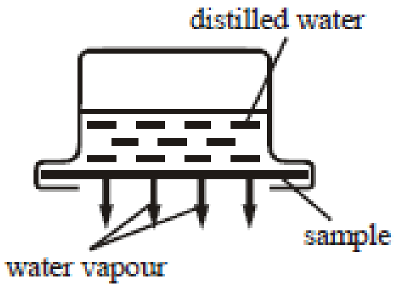


Figure 11: Inverted “cup method

(Source: Arabuli *et al.*, 2010)

Rossi (2005) states that the main disadvantage of gravimetric methods is that some of the moisture will evaporate during the weighing process. In addition, these methods do not consider other dynamics, such as wicking processes (Rossi, 2005).

The sweating hot plate methods are a new generation of methods, where the textile is tested while in intimate contact with a wet plate or sweating plate (Arabuli *et al.*, 2010). According to Rossi (2005), the sweating hot plate devices have the ability to measure both thermal insulation and water vapour resistance of one or several textiles, and comply with the ISO 11092 or EN 31092 standards. Examples of such devices include, the SGHP-8.2 in Figure 12, and the Permetest described in detail later (Section 2.1.4.6). Sweating hot plate devices have a heated plate maintained at 35°C, on which the fabric sample is placed, with air, at a defined temperature, relative humidity and velocity, being blown over the sample (Rossi, 2005). The plate is covered with a water vapour permeable foil, with the heating power, required to compensate for evaporative cooling and for maintaining the plate at 35°C, being proportional to the water vapour permeability of the fabric (Rossi, 2005).

Figure 12: Sweating hot plate SGHP-8.2

(Source: Measurement Technology Northwest, n.d.)

The sweating hot plate method, using the SGHP-8.2, requires a sample to be placed on the surface of a heated sweating plate (see Figure 13), covered with a vapour permeable membrane (Arabuli *et al.*, 2010). Water is passed through the plate and membrane, and evaporates, while the temperature of the plate is kept constant. Finally, the energy used for maintaining a constant temperature is measured and provides a measure of water vapour resistance (Arabuli *et al.*, 2010). The disadvantage of the SGHP-8.2 is cost, complexity of service, time consuming testing, and the large number of samples required (Arabuli *et al.,* 2010).

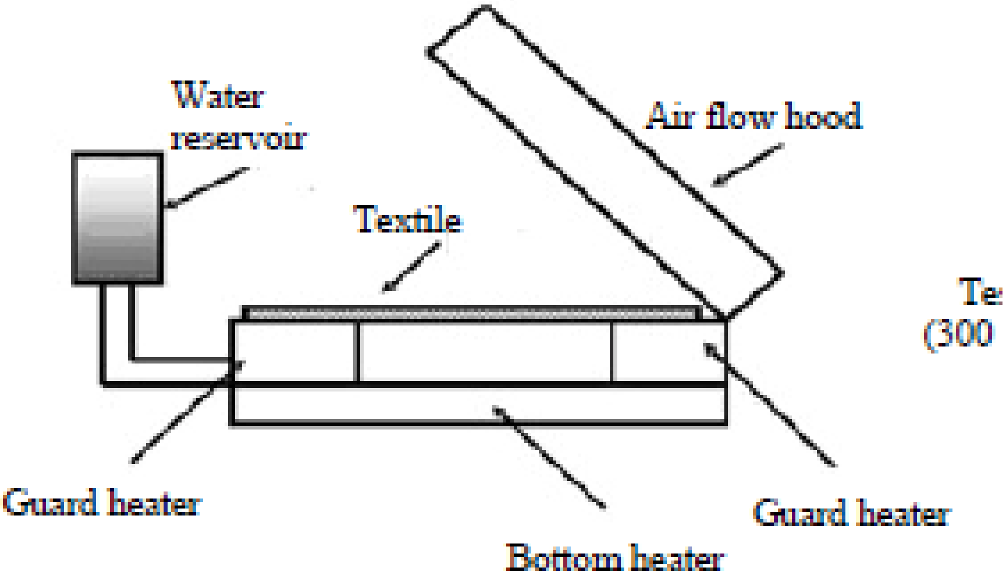


Figure 13: Sweating hot plate method using SGHP-8.2

(Source: Arabuli *et al.,* 2010)

2.1.4.3 Thermal resistance

The measurement of the rate of heat flow in a specific direction is difficult, even if the heater is supplied with a known amount of power, because it releases the heat in all directions (Uttam, 2012). Nevertheless, several devices such as the Togmeter, guarded hot plate and Alambeta instrument, have been developed over the years in order to measure heat transport (Uttam, 2012).

The Togmeter measures the thermal resistance of textile fabrics, by means of a thermostatically controlled heating plate (standard plate), covered with an insulating board of known thermal resistance (Uttam, 2012). The temperature is measured at both faces of the standard plate, the upper face of the standard plate is maintained between 31-35°C, and a small air flow is maintained over the apparatus (Uttam, 2012). Figure 14 illustrates the functioning of the Togmeter using the single plate method (a two plate method is also possible). The sample is placed on the heated standard plate and is left uncovered, the temperature being measured at the heater (T1), and between the standard plate and test fabric (T2) (Uttam, 2012). The top plate is used to measure the air temperature (T3). Uttam (2012) states that the device measures both thermal resistance and the resistance of the air, because the air above the specimen has thermal resistance itself.

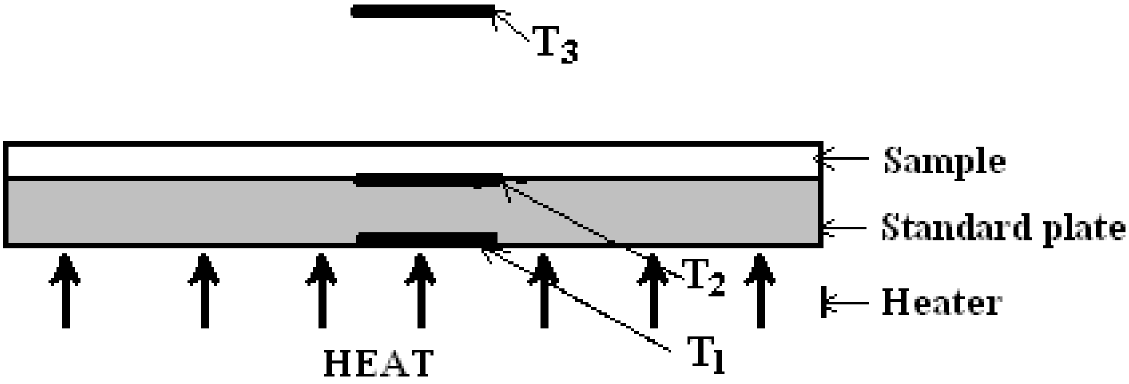


Figure 14: Single plate method on Togmeter

(Source: Uttam, 2012)

The guarded hot plate method, previously discussed in terms of water vapour permeability, is also used to measure the thermal transmittance of textiles, see

Figure 15. The device consists of a test plate, a guard ring, and a bottom plate, all of which have heating elements to maintain a temperature between 33-36°C (Uttam, 2012). The device measures the amount of heat that passes through the fabric, which is placed on top of the hotplate, from the power consumption of the test plate heater (Uttam, 2012). The measured thermal transmittance represents a combination of the thermal transmittance of the fabric and that of the air layer above the fabric (Uttam, 2012).

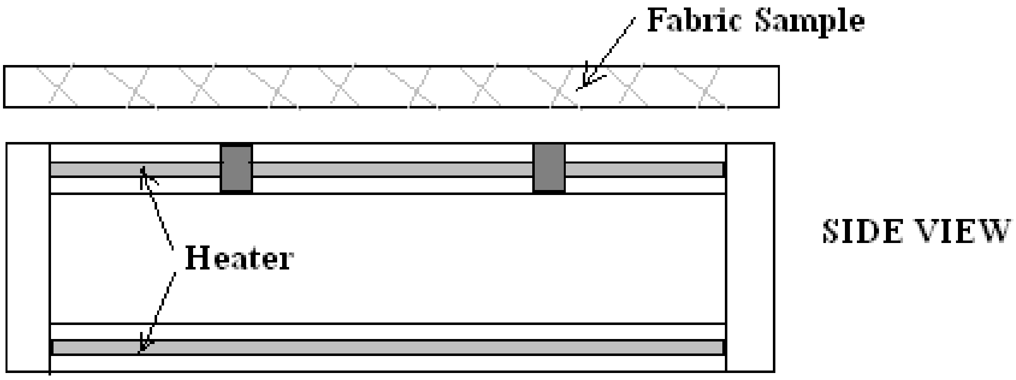
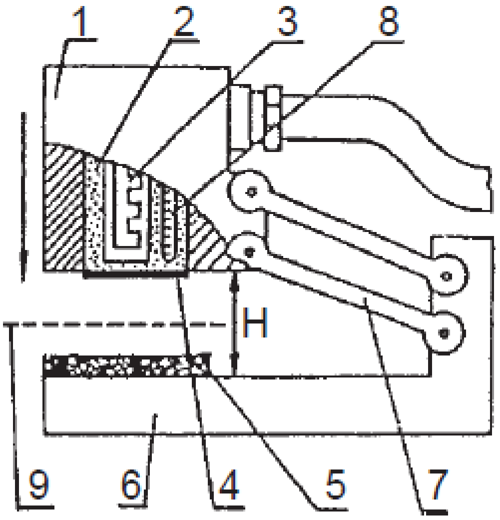


Figure 15: Guarded hot plate

(Source: Uttam, 2012).

Uttam (2012) is of the opinion that the guarded hot plate and Togmeter have several disadvantages, such as length of time for testing, size of samples, and awkward insertion of the sample into the devices. In addition, these two devices only measure steady-state thermal insulation properties (Uttam, 2012). On the other hand, the Alambeta device measures transient and steady-state thermal insulation properties, such as thermal insulation and thermal contact properties (Uttam, 2012). The Alambeta device, as seen in Figure 16, consists of upper and lower measuring heads fitted with heat flow sensors. When the upper measuring head is lowered onto the sample, the heat flow at the upper surface and the underside of the sample is measured (Hes and Loghin, 2009). One of the main advantages of the Alamabeta is that it requires less than three minutes to complete a test (Hes, 1999).



1. Measuring head
2. Copper block
3. Electric heater
4. Heat flow sensor
5. Measured sample
6. Instrument base
7. Head lifting mechanism
8. Resistance thermometer
9. Wetted textile interface simulating sweat discharge

Figure 16: Alambeta device

(Source: Hes, 1999)

According to Uttam (2012), the Alambeta measures seven parameters:

1. Thermal conductivity.
2. Thermal diffusion.
3. Thermal absorption.
4. Thermal resistance.
5. The ratio of maximal to stationary heat flow density.
6. Stationary heat flow density at the contact point.
7. Fabric thickness.

According to Gericke and Van der Pol (2010), Hes (1999), and Oğlakcioğlu and Marmarali (2007), the Alambeta device also evaluates the thermal absorptivity of the fabric, which is an indication of the warm-cool feeling that the wearer will experience upon touch .

The Permetest, used in this study, and discussed in detail later, is another testing device that can be used for testing thermal resistance.

2.1.4.4 Thermal manikins

2.1.4.4.1 The history of thermal manikins

An important, and relatively recent, advancement relating to the more meaningful and realistic measurement of comfort related properties of textiles, particularly of clothing, was the development of thermal manikins. According to Holmér (2004), the first thermal manikin was developed in the early 1940s in the United States of America. It was a one segment copper manikin, designed first and foremost for use with specialised apparel within the army. Before the development of the manikin, there was no method for testing the thermal heat transfer properties of military clothing or any other clothing ensembles (Endrusick *et al.,* n.d.). According to Bogdan and Zwolińska (2012) and Nilsson (2004), the one segment manikin was further developed in subsequent years to represent a more realistic human, by increasing the number of segments of the manikin, designing the manikin to move, and simulating the process of human perspiration.

In 1941, the clo unit was introduced by Gagge *et al.* (1941), providing a standard measure for the thermal insulation of clothing (Endrusick *et al.,* n.d. and Matusiak, 2010). A unit of one clo represented the thermal insulation of a business suit; whereas two clo represented a garment providing twice the amount of insulation (Endrusick *et al.*, n.d.). During the 1950s, research scientists established that the curves of the human body created a complex microclimate between the surface of the skin and the textile (Endrusick *et al.*, n.d.). Therefore, thermal manikins improved scientists understanding of the localised variations in thermal conductivity when a garment covers a human body (Endrusick *et al.*, n.d.). During the 1960s, sweating manikins were introduced for the purpose of improving the breathability of apparel (Endrusick *et al.*, n.d.). In 1962, the moisture permeability index was introduced by Woodcock to characterise the water vapour permeability of clothing materials (Endrusick *et al.*, n.d.). The introduction of the moisture permeability index extended the clo formula, which relates dry heat loss to clothing insulation, to include heat losses from the evaporation of perspiration (Woodcock, 1962).

In 1984, the Army Research Institute of Environmental Medicine (USARIEM) in the USA started using a thermal manikin that simulated walking and running motions inside a climatic chamber in which different air velocities could be directed at the manikin in order to test moisture transfer properties under such conditions (Endrusick *et al.,* n.d.). A significant advancement was made when the control of thermal manikins was computerised (Bogdan and Zwolińska, 2012 and Nilsson, 2004). As a result, it was possible to set accurate temperature values on the surface of each manikin segment in order to obtain more reliable and realistic results (Bogdan and Zwolińska, 2012).

One of the major developments was the introduction of Walter, the sweating manikin, covered in a breathable fabric skin, by the Hong Kong Polytechnic University in 1991. Walter, a one segment manikin that simulates human walking motions, has an automated water supply system with a real time water loss measurement system, where the temperature of the manikin surface is controlled by the pumps inside the manikin (Nilsson, 2004). Walter will be discussed in more detail under section 2.1.4.5.

Scientific and technological advancements continue to improve the development of thermal manikins and to make them more multifunctional for research purposes (Wang, 2008 and Zhang *et al.,* 2009). Since the 1940s, the use of thermal manikins has increased substantially, and it is estimated that there are more than 100 manikins in use across the world (Wang, 2008). Furthermore, the fact that thermal manikins are developed and improved by universities, companies and researchers across the world, leads to an increase in the technical features, shapes, number of segments and structure of the manikins (Konarska *et al.* 2006).

2.1.4.4.2 Functioning of a thermal manikin

According to Holmér (2006), a thermal manikin usually consists of a number of segments which cover the manikin, and which can be controlled and heated individually. Tamura (2006) identifies the following seven elements that a thermal manikin should have in order to accurately simulate the human body; although, not all thermal manikins have all of these capabilities:

1. Accurate body shape and size.
2. Controlled heat emission.
3. Control over the distribution of heat over the skin of the body.
4. Emission of the skin.
5. Control over the distribution of perspiration.
6. Control in terms of body movement.
7. Control of the core and shell, in order to simulate human physiological responses.

In terms of a sweating manikin, Fan and Keighley (1990) identify the following features that are important in the functioning of the manikin:

1. The manikin is similar in physical appearance and size to that of a human.
2. The simulated skin on the manikin is made of coated fabric.
3. The water circulation system simulates the blood circulation system of a human body. It therefore produces a temperature profile over the entire manikin which is similar to that of a human body.
4. The core temperature of the manikin is maintained at 37ºC, through a body temperature control and heat supply system. This also relates to measuring the amount of heat that is supplied to the body and the amount of heat that is lost.
5. The surface temperature acquisition system measures the temperature of the skin as well as that of the surface of the clothing over the entire body.
6. The manikin simulates walking motions by moving the arms and legs.
7. Finally, a tube is used, not only to transport water to the rest of the body, but also to measure the amount of perspiration through the breathable fabric.

2.1.4.4.3 The application of thermal manikins

Fan and Keighley (1990) state that, although it is possible to test the thermal comfort of clothing using human wearer trials, these tests are usually inconsistent, inaccurate, costly, and may even threaten the safety of humans under extreme testing conditions. Therefore, thermal manikins are crucial in testing how environmental stress impacts clothed persons in different thermal environments (Fan and Keighley, 1990).

Although manikins are complex and very expensive, they are a useful piece of equipment, since they enable convective, radiative and conductive heat loss in all directions over the entire body of the manikin to be measured (Holmér, 2004). Therefore, Holmér (2004) identifies two application areas for thermal manikins:

1. Determining the heat transfer properties of clothing.
2. Examining the impact of thermal environments on the human body.

Starr (2010) states that thermal manikins are used to test two factors, namely dry thermal resistance and water vapour resistance. Furthermore, Nilsson (2004) states that thermal manikins are used to measure convective, radiative and conductive heat loss. There are two different types of studies that use thermal manikins: those that require technologically advanced manikins, which simulate sweating, in order to study the thermal environment of closed spaces, for example vehicles, and those that require simple manikins which have only the basic functions required to study thermal insulation of clothing (Bogdan and Zwolińska, 2012, Holmér, 2004, and Starr, 2010). The basic types of manikin usually provide a heating function, and are used in particular by sport and protective clothing companies (Bogdan and Zwolińska, 2012). Thermal manikins have also been introduced into the research field of phase transformation compounds in order to test the cooling characteristics of clothing developed for hot conditions (Bogdan and Zwolińska, 2012).

Thermal manikins are utilised in the following range of industries and research fields (Nilsson, 2004):

1. HVAC (heating, ventilation and air-conditioning) systems.
2. Control and production of buildings, vehicles, incubators.
3. Assessing indoor air quality.
4. Simulation of human occupancy.
5. Measuring thermal properties.
6. Testing protective gear.
7. Assessing clothing design.

8. Physiological simulations.

From the foregoing information it is evident that thermal manikins are crucial for the better development, design and improvement of clothing in terms of comfort for the wearer.

2.1.4.4.4 Standards

Thermal manikins are used for both industrial and research purposes, which necessitate the use of standard methods to control the calculation and evaluation of thermal conditions (Holmér, 2006). The use of standards not only benefits customers when choosing garments, but also benefits manufacturers in terms of manufacturing clothing items which meet the demands of the consumers (Holmér, 2006).

Some international standards, applying to the use of thermal manikins, have been identified by Fan (n.d.) and Holmér (2006) as Nordic, European, US, and International Standards.

Holmér (2006) states that, in 1986, Nordic countries introduced the following four standards for the thermal insulation measurement of cold protective clothing:

1. INSTA 352 (Definitions, units and symbols)
2. INSTA 353 (Form, construction and measurement of a thermal manikin)
3. INSTA 354 (Procedure to measure a single garment)
4. INSTA 355 (Procedure to measure a clothing ensemble)

In 1989, a European Union standard was developed (presently known as ENV-342) which described the procedure to test protective clothing against the cold, using a thermal manikin (Holmér, 2006). Similar to ENV-342, another standard, EN-511, sets out the procedure for testing protective gloves on a thermal model of a hand (Holmér, 2006).

Holmér (2006) identifies two standards by the American Society for Testing and Materials (ASTM), namely F1291, which describe the use of a heated thermal manikin for testing thermal insulation of clothing, and F1720, which is used for testing the thermal insulation of sleeping bags. In addition, Psikuta (2009) identifies ASTM F2370 as a standard used to test the evaporative resistance of clothing by means of a sweating manikin. One International Organisation for Standardisation (ISO) standard for thermal manikins, ISO-15831, focuses on the functions of a thermal manikin and the measurement of thermal insulation (Holmér, 2006 and Psikuta, 2009).

Holmér (2006) comments that, in ISO-15831 and EN-342, two different methods of determining thermal insulation are provided, namely a "serial" and a "parallel" method. He is of the opinion that both methods are actually 'parallel', as they describe a heat flow from a uniform, warm surface that passes through layers of clothing covering different segments of the surface, lying side by side. He goes on to state that the two ASTM standards, referred to previously, are also based on the parallel method. He also states that the serial method usually provides an insulation value that is higher than that provided by the parallel method.

2.1.4.5 Walter the sweating manikin

Walter, a one segment perspiring thermal manikin, was developed in 2001 by the Hong Kong Polytechnic University (Wang, 2008). Figure 17 illustrates the front view of Walter. The 'skin' of Walter consists of a waterproof, but moisture permeable (i.e. breathable) fabric, which enables the simulation of human perspiration, by allowing moisture to pass through the skin, while keeping the water inside the body (Fan, 2006 and Wang, 2008). The manikin maintains a temperature of 37ºC, similar to that of a human body, by pumping warm water from the centre of the manikin body out to all of the extremities of the manikin (Fan, 2006 and Fan and Qian, 2004).

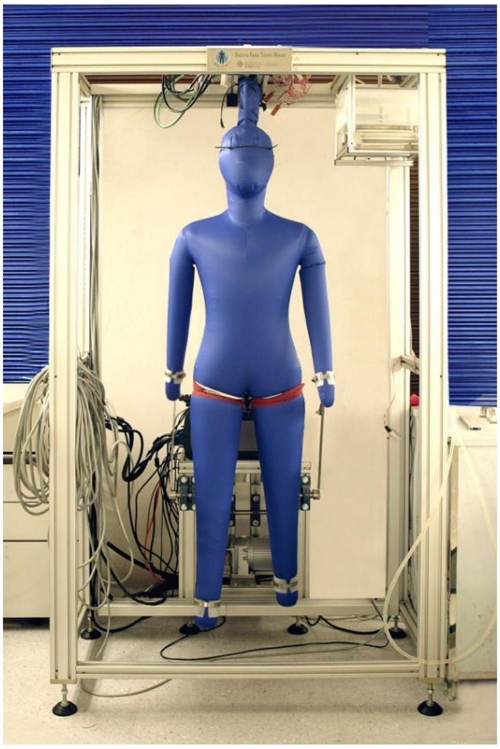


Figure 17: Walter sweating manikin

(Source: Fan, n.d.)

According to Fan (2006), different kinds of breathable fabrics can be used on Walter in order to simulate different rates of perspiration. The legs and arms of the manikin can also be moved for the purpose of simulating human walking movement (Qian, 2005 and Wang, 2008).

Fan (2006) identifies the main features of Walter, as the water circulation system, the walking motion system, online water supply system, and the control and measurement system. Figure 18 illustrates the location of pumps and valves on Walter used to regulate the temperature distribution over its skin (Fan and Chen, 2002). The automatic water supply system of the manikin compensates for the loss of water, and the real-time measurement of water loss is necessary for the accurate measurement of the dynamic responses of the manikin (Fan and Qian, 2004).

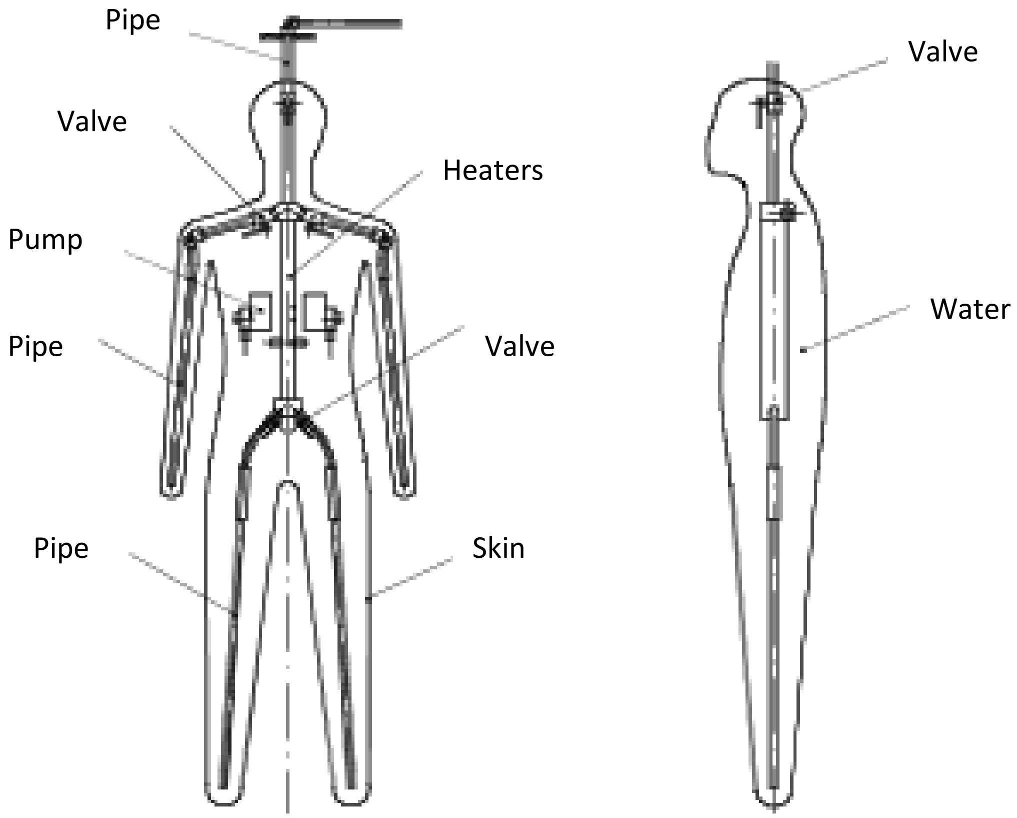


Figure 18: Inner construction of Walter

(Source: Fan and Chen, 2002)

According to Qian (2005) and Starr (2010), the most crucial parameters tested by the manikin are thermal insulation and moisture vapour resistance. Fan and Qian (2004) add that the moisture accumulation can also be calculated for the clothing, for example, after a period of 24 hours. Another comfort parameter, measured by the manikin, is the moisture permeability index (Gericke and Van der Pol, 2010). Walter software is used to determine the moisture permeability index, which explains the relationship between water vapour resistance and thermal resistance (Gericke and Van der Pol, 2010). The importance of the moisture permeability index was previously discussed under section 2.1.3.1. According to Fan and Chen (2002), thermal insulation and water vapour resistance is calculated by measuring the heat supply to the manikin, the temperature at the skin, the temperature and humidity of the environment, as well as the perspiration rate of the manikin.

2.1.4.5.1 Application of Walter

Fan (2006) identified five examples, where Walter had been utilised for a specific purpose. A manufacturer of T-shirts used the manikin for the purpose of comparing the comfort properties of T-shirts made from different materials and finishes, and established that T-shirts with a Teflon finish have lower moisture vapour resistance than cotton T-shirts. Walter has been used by a manufacturer to compare two firemen suits having the same design but different insulation layers. It was found that one suit became significantly wetter on the inside, and it was assumed that this suit would therefore be more uncomfortable to wear than the other one. Walter has also been used to compare army suits made from different fibres, to establish the water vapour permeability of the suits. Tests have also been conducted on Personal Cooling Garments which contain Phase Changing Materials. Finally, Walter has also been used in the medical industry to test the water vapour permeability of surgical gowns made from different non-wovens.

In addition to the above examples, Walter has also been used for product development purposes, in the fields of sportswear, protective clothing, army uniforms and HVAC systems for more comfortable living (Fan, n.d.).

2.1.4.6 Permetest

The Permetest was developed by Dr. Hes from the Technical University Liberec in the Czech Republic and is manufactured by the Sensora Company. According to Hes (2009), tests on the Permetest are completed within 2-3 minutes and usually provide results with a CV of 3%, thereby ensuring good repeatability. Samples are very small, usually 12x12cm. It is, however, not necessary to actually cut fabric samples, as garments can also be tested on the instrument (Hes, 2009). According to Arabuli *et al*. (2010), the Permetest provides measurements that are similar to the ISO Standard 11092.

According to Gericke and Van der Pol (2010), the Permetest, see Figure 19, is a semi-automated computer controlled device.

Figure 19: Permetest instrument

(Source: Sitvjenkins *et al.,* 2011)

The Permetest is designed to test three comfort parameters, namely water vapour permeability, water vapour resistance and thermal resistance (Gericke and Van der Pol, 2010). According to Hes and Loghin (2009), the Permetest simulates the human skin in either a dry or wet state. The device measures the amount of water vapour transmitted through the test sample and automatically calculates the average water vapour permeability and resistance (Gericke and Van der Pol, 2010).

The Permetest consists of the following four key parts (Hes, 2009):

1. The wind channel which is attached to a suction part of 2 axial fans.
2. A measuring head, where the porous surface is covered in a semi-permeable foil.
3. A dosing syringe that supplies liquid to the measuring head.
4. An electronic box.

Figure 20 illustrates the functioning of the Permetest instrument. Arabuli *et al.* (2010) and Das *et al.* (2009) state that the Permetest functions on the principle of heat flux sensing. According to Hes and Loghin (2009), the measuring head of the Permetest is covered with a semi-permeable foil. A sample is mounted on the measuring head, where sensors distinguish small changes in the amount of water absorbed by the fabric during unsteady state of diffusion, which are then recorded by the computer (Gericke and Van der Pol, 2010). Tests on the Permetest are conducted under isothermal conditions, and the temperature of the measuring head is maintained at room temperature (Gericke and Van der Pol, 2010). According to Chidambaram *et al.* (2012) and Das *et al.* (2009), when water flows into the measuring head, some heat is lost due to evaporation, and the device measures the evaporation when the measuring head is covered with a sample, as well as when uncovered. The test is completed once the transfer of water from the measuring head to the atmosphere reaches steady-state (Gericke and Van der Pol, 2010).

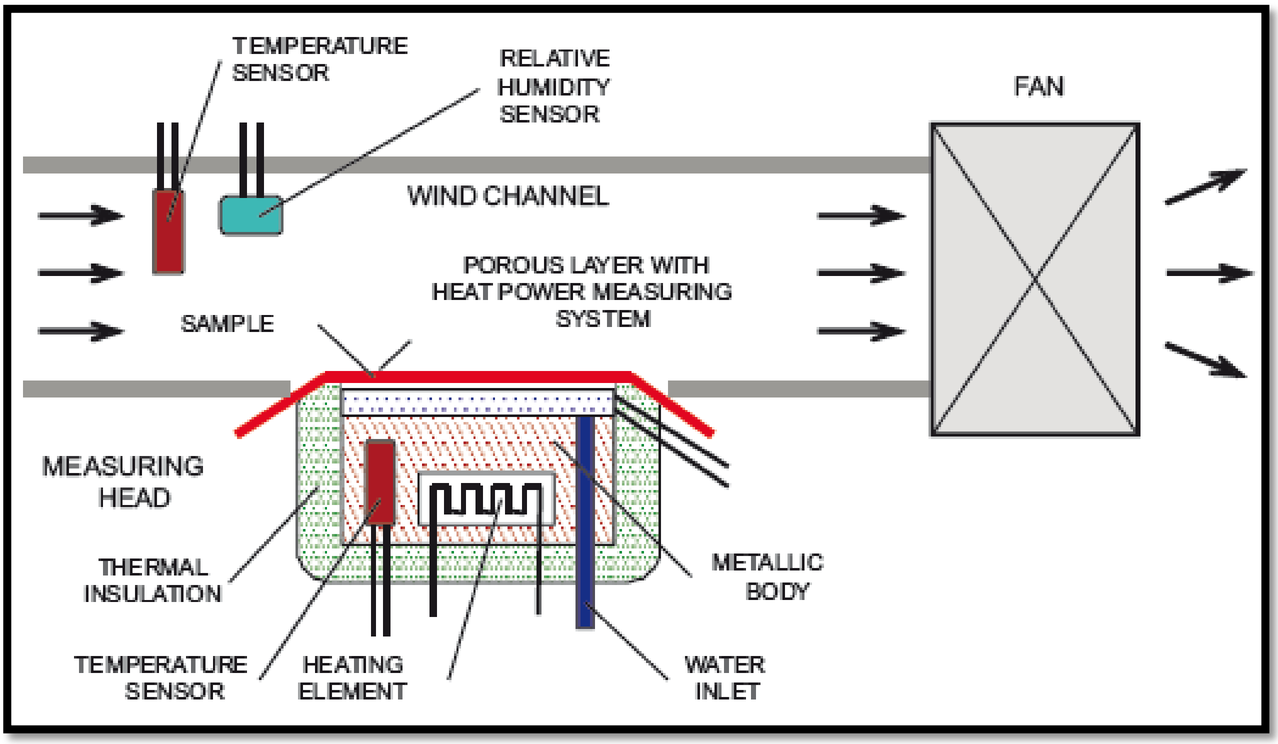


Figure 20: Functioning of Permetest

(Source: Hes and Ursache, 2011)

In order to calculate the water vapour permeability (P) of a textile, the ratio of heat loss from the measuring head, with fabric (q_s) to that without fabric (q_0) is used (Hes, 2009):

$$P(\%) = 100\, q_s \,/\, q_0 \quad \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_}(2\text{-}16)$$

(P=100% indicates the permeability of the free measuring surface (i.e. uncovered).

The equation used to determine the water vapour resistance (R_t) of a textile is as follows (Hes, 2009):

$$R_t\ (\mathrm{m^2Pa/W}) = (P_{wsat} - P_{wo})(1/q_s - 1/q_o) \quad \text{\_\_\_\_\_\_\_\_\_\_\_}(2\text{-}17)$$

$$= \mathrm{K}\ (100 - \varphi)(1/q_s - 1/q_o)$$

Where; P_{wsat} and P_{wo} are the saturated water vapour partial pressure, in Pascal, valid for the temperature (t_0) of the air in the laboratory, and the partial water vapour pressure in the air, respectively. The relative humidity, φ, is kept between 45-60%, and the constant, K, is determined by the calibration procedure.

The Permetest is also able to measure the thermal resistance of fabrics. The measuring head of the Permetest is kept dry when thermal resistance is measured. Thermal resistance is measured in m²K/W on the Permetest, with the equation used for determining the thermal resistance as follows (Hes, 2009):

$$R_{ct} = \mathrm{K}\ (t_H - t_0)(1/\mathrm{U}_1 - 1/\mathrm{U}_0) \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_}(2\text{-}18)$$

The sensitivity constant, K, is determined by the calibration procedure. The measuring head is maintained at the temperature t_H, where $t_H = t_0 + 10^{\circ}\mathrm{C}$. U_1 and U_0 represents the steady state electrical voltages shown on the digital display of the Permetest (with and without the sample, respectively). According to Senthilkumar *et al.* (2010), when testing the thermal resistance, the sensors measure the heat that is required to be supplied to the measuring head to maintain a 10°C temperature gradient. This is measured by the Permetest in order to calculate the thermal resistance.

Considerable research has been conducted on the Permetest to gain a better understanding of water vapour permeability and thermal resistance of textiles and the variables that influence these parameters. Some of these studies, where the Permetest was used for some, or all of the tests, are mentioned below, the findings where relevant will be discussed in Section 2.2.2.

Das *et al.* (2009) examined the moisture transmission properties of plain woven fabrics made from polyester and viscose blended yarns. The impact of blend proportion, yarn count and twist level on air permeability, water vapour permeability, in-plane wicking, and vertical wicking was investigated. Das and Kothari (2012) studied the moisture vapour transmission behaviour of 100% cotton plain weave fabrics, with five different pick densities and two different weft counts. Gericke and Van der Pol (2010) investigated the comfort related properties of knitted bamboo, cotton and viscose fabrics, with similar construction, weight and finishing treatment. Oğlakcioğlu and Marmarali (2007) tested various knitted structures containing either 100% cotton or 100% polyester fibres to determine the factors which affect the thermophysiological comfort of the fabrics. Chidambaram *et al.* (2011) investigated the effect of yarn linear density and loop length on the thermal comfort related properties of 100% bamboo knitted fabrics. Singh and Nigam (2013) studied the effect of yarn type (combed, carded, and compact spun yarns), the pick density ranging from 88 to 108 filling yarns per inch for each of the three fabrics, on the comfort related properties of 100% cotton plain weave fabrics. Senthilkumar *et al.* (2010) examined the air permeability, water absorbency, thermal resistance and wickability of plain weave fabrics produced from polyester/viscose and polyester/cotton blends, and which varied in fabric thickness.

2.2 Comfort related properties of fibres, textiles and clothing

2.2.1 Introduction

According to Broega *et al.* (n.d.), comfort is a very important aspect of clothing which depends significantly on the tactile and thermophysiological properties of the fabrics. Fan (2009b) states that the fabric chosen for a garment will always have an impact on the thermal insulation and other properties of the garment, due to the influence of various factors, such as fabric thickness and density of the knit or weave. Fibre, yarn and fabric parameters, and finishes all have an influence on the physical and comfort related properties of the resultant fabric (Slater, 1991). Therefore, the proper engineering of a fabric is crucial, in terms of its thermal, mechanical and physical properties, in order to ensure satisfactory comfort (Broega *et al.,* n.d.). As previously mentioned, several instruments have been developed to examine the thermal insulation properties of fabrics, including the guarded hot plate and the Alambeta instrument (Fan, 2009b).

Li (2001) found that comfort is one of the primary clothing requirements of consumers, see Figure 21. The study included population groups from Europe, Asia and Australia. From Figure 21 it is apparent that the most important requirements include the comfort, fit, style, colour and quality of the garment. Thiry (2003) confirmed that comfort is the main requirement of consumers, especially due to the significant increase in the demand for comfortable clothing. Some of the primary comfort variables of clothing include fabric handle, moisture management, and thermal management (Thiry, 2003). Fabric hand relates to the tactile comfort of clothing. Moisture management is one of most widely tested comfort parameters, due to its significant contribution for improving performance, athletic and outdoor apparel, in terms of fabric and garment design (Thiry, 2003). Furthermore, thermal management is crucial in garments, for example skiwear, where the wearer must be protected from the environment, while still maintaining comfort (Thiry, 2003).

Figure 21: Clothing requirements of consumers

(Source: Li, 2001)

Clothing provides a barrier against heat and moisture transfer between the skin of the body and the external environment (Havenith, 1999). The cooling mechanism of the human body is through perspiration; although, if the moisture vapour cannot escape to the external environment, the microclimate of the air in the clothing could result in hyperthermia of the body (Haghi, 2011). On the other hand, hypothermia can occur when the body loses more heat than it produces (Haghi, 2011). Voelker *et al.* (2009) describe clothing made from textiles as the 'second skin' of the body, which influences the physiological operations of the body in ensuring thermal comfort, as already discussed. According to Fan (2009ab), thermal manikins are used in order to test the thermal insulation properties of clothing.

The appropriate selection of fibres, fabrics and design of garments can improve the convective cooling, heat retention, moisture vapour resistance, and liquid water resistance of the product (Slater, 1991). Nevertheless, according to Tyagi *et al.* (2004), there have been numerous studies focusing on clothing comfort, but not enough attention has been given to the connection between clothing comfort and the fibres utilised. According to Malik and Sinha (2012), natural and synthetic fibre manufacturers have realised that consumers are not only interested in the visual appearance of clothing, but are increasingly concerned with the comfort that the textile materials and clothing provide.

Textiles, and clothing products are constructed from the following raw materials; fibres, yarns, fabrics and films (Starr, 2010). Potluri and Needham (2005) gave an overview of the construction of textile materials, and the various procedures and methods that are utilised, see Figure 22. Although the fabric thickness has the main effect on the insulation properties of clothing, the type of fibre can influence properties, such as air permeability and moisture absorption, which, in turn, will affect comfort related properties, such as thermal insulation and water vapour resistance (Havenith, 1999). An example of this is wool, which is hygroscopic, absorbing moisture in the form of vapour but repelling liquid moisture (water), due to the hydrophilic nature of the scales on the cuticle (Zhou *et al.* 2007). Furthermore, the crimp of wool fibres prevents the fibres from being aligned too close to one another, causing the structure to be bulky, which results in the entrapment of air in air pockets, for improved insulation (Ghosh, 2004).

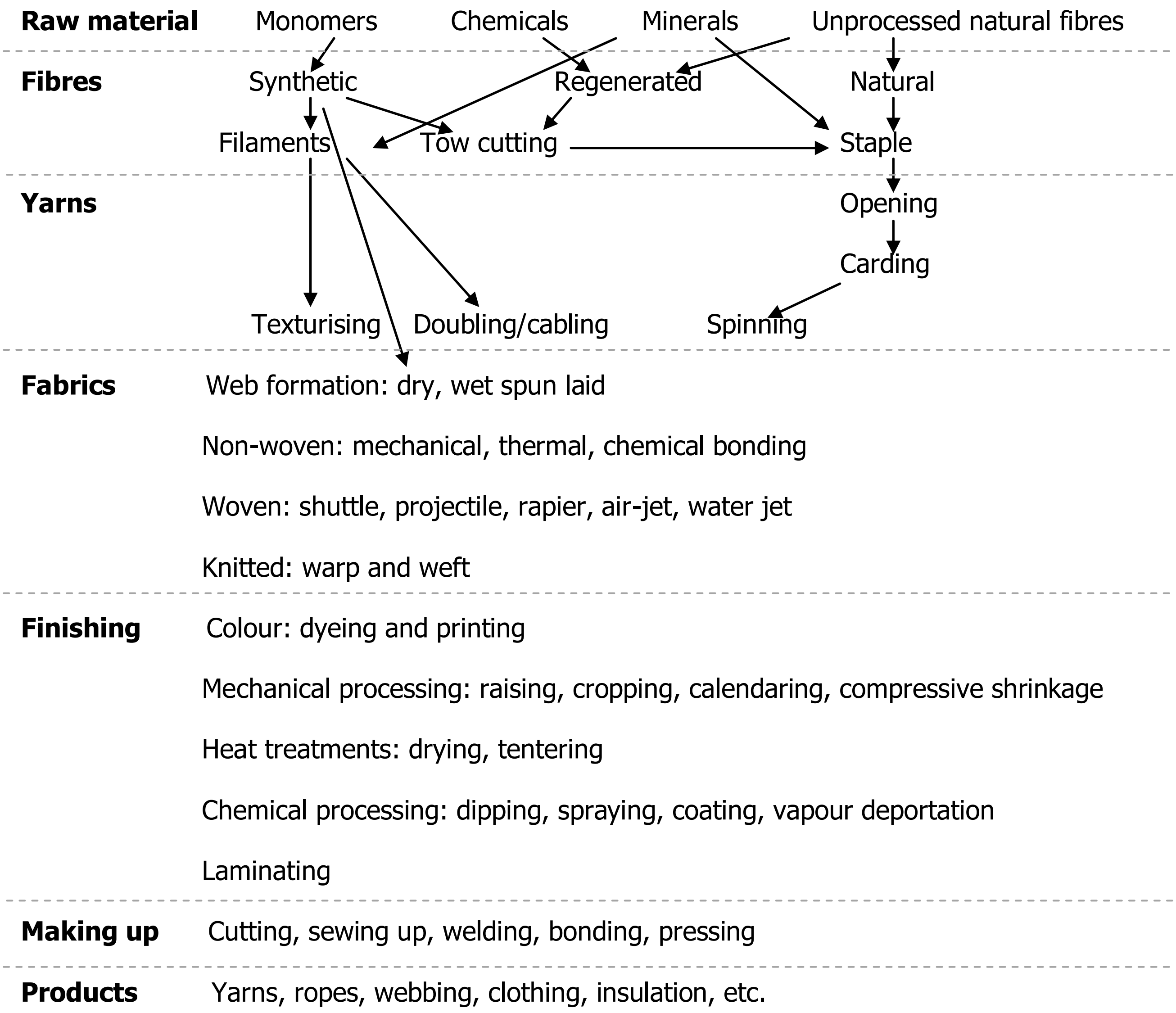


Figure 22: The construction of textiles

(Source: Potluri and Needham 2005)

According to Matusiak and Sikorski (2011), the raw materials, as well as the structure of the fabric, will determine the comfort properties of a garment, due to the thermal properties of the fibres. This is supported by Frydrych *et al.* (2002), who state that the final properties of clothing depend on the physical and structural design of the chosen textile, as well as the choice of fibre, whether it is natural or man-made. The choice of fibre will also determine the moisture absorption and transmission and related properties of the fabric, for example, a hygroscopic fibre, such as wool, absorbs moisture and releases heat of absorption at the same time

(Fan, 2009b). On the other hand, polyester fibres have a low ability to absorb moisture (Barnett, 1997).

Slater (1991) distinguishes between three important fibre properties, when developing a fabric, namely fibre type, length and fineness. The type of fibre will influence both physical and psychological comfort parameters, such as the absorbency of the fabric, thermal capabilities, permeability, electrostatic propensity and launderability (Slater, 1991). Fibre length will determine strength, lustre, evenness and hairiness; whereas fibre fineness will determine the drape and softness of the fabric or garment (Slater, 1991). Kothari (2006) added additional factors, such as fibre cross sectional-shape, crimp and surface properties, as parameters which affect the comfort of fibres.

Chattopadhyay (2008) provided an overview of important fibre, yarn and fabric parameters which must be considered in order to control the microclimate of a garment, see Table 2.

Table 2: Fibre, yarn and fabric parameters for microclimate control

Functional attribute	Fibre parameters	Yarn parameters	Fabric parameters
Warmness/coolness	Fineness	Low twist, count, bulk	Thread density, fabric thickness
Reduction in sweaty humidity and stickiness	Finer fibre	Fibre orientation, pore size	End and pick density, type of weave
Waterproof	Fineness, cross sectional shape	Twist	End and pick density, type of weave

(Source: Chattopadhyay, 2008)

In terms of the air and water vapour permeability of a textile material, Chattopadhyay (2008) states that these two factors depend on the number and distribution of pores in the fabric. This is supported by Kothari (2006), who states that the passage of air through a textile material depends on the pores (spaces between fibres) in the fabric, as opposed to the fibre itself. This is due to the fact that all fibres are impermeable to air (Kothari, 2006). However, in terms of water vapour permeability, Kothari (2006) states that most textile fibres have the ability to absorb a certain amount of moisture. The rate at which the water vapour passes through the fibre will depend on the nature of the fibre and whether it is hydrophobic or hydrophilic (Kothari, 2006). Ho *et al.* (2011) state that hydrophilic fibres not only reduce heat strain during exercise and rest, but also determine the thermal comfort of the clothing, in terms of the dryness of the skin. Moisture absorbency also refers to the moisture regain of a fibre, for example, wool and cotton have very high moisture regain, and therefore absorb more moisture and heat from the body (Ho *et al.*, 2011).

2.2.2 Properties of natural and man-made fibres

2.2.2.1 Introduction

Kothari (2006) stated that consumers require clothing to be light weight, comfortable, safe, elegant and easy to care for. Clothing and fibre manufacturers, however, are faced with the scenario that no one type of fibre can meet all of these requirements satisfactorily.

Mishra (2000) distinguished between two types of fibres, namely natural and man-made fibres, see Figures 23 and 24. Natural fibres are present in nature, and are obtained from animals, vegetables or minerals. Man-made fibres include three main types of fibres, namely regenerated, synthetic, and inorganic fibres.

The commercial suiting fabrics used in the present study and tested on the Permetest consist of wool, cotton, viscose, and polyester fibres, and some of their blends. It is therefore important to examine each fibre in detail to determine their advantages and disadvantages, and how the fibre could potentially impact on the comfort of the resultant textile material.

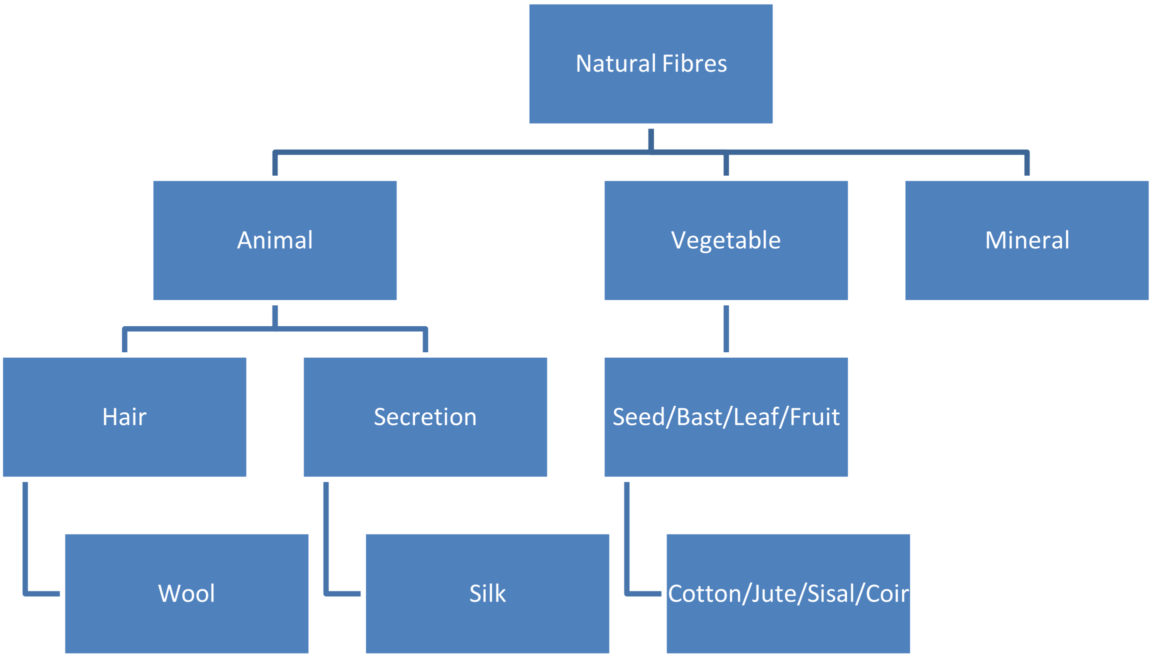


Figure 23: Natural Fibres

(Source: Mishar, 2000)

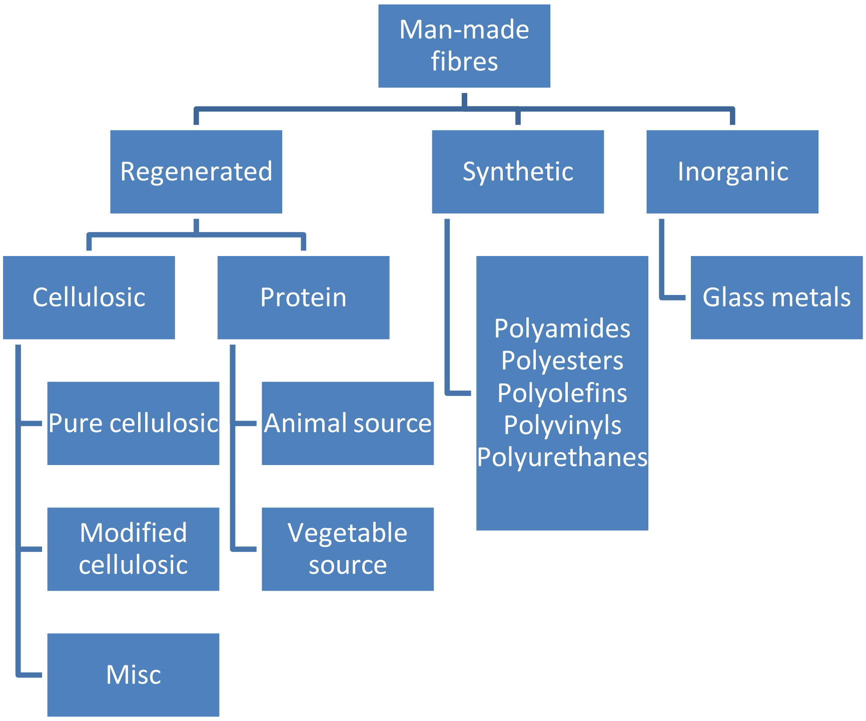


Figure 24: Man-made fibres

(Soure: Mishar, 2000)

Zimniewska (2010) stated that, since natural fibres have been used in clothing, they have been one of the main methods of protecting humans against environmental and climatic conditions. Not only do they protect the wearer, but they also provide excellent comfort and have a positive influence on the body (Zimniewska, 2010). This is confirmed by a study conducted by Zimniewska (2010), in collaboration with the Nara Women University in Japan and Karol Marcinkowski University of Medical Sciences in Poland, in which a comparison was made between bedding made from 100% linen, 100% cotton and 100% polyester. It was found that the people who participated in the study experienced a deeper sleep with quicker human body regeneration when sleeping in the natural fibre bedding than those who slept in the synthetic bedding (Zimniewska, 2010). Ravandi and Valizadeh (2011) also expressed the opinion that natural fibres provide better comfort than man-made fibres.

2.2.2.2 Properties of wool

Wulfhorst *et al.* (2006) stated that wool is one of the most commonly used fibres in clothing, and has been in existence since the second half of the second millennium B.C. Some of the major wool producing countries in the world include Australia, New Zealand, Russia, Argentina, South Africa, Uruguay, UK, USA, Turkey, India, Brazil and Bulgaria (Ghosh, 2004).

Figure 25 illustrates the structure of a wool fibre (Wulfhorst *et al.* 2006). Wool fibres generally have a natural crimp, which results in bulky fabrics for improved insulation (IWTO, n.d.). The diameter of wool fibres vary from about 16 microns in superfine Merino wool, to more than 40 microns in coarse hairy wool (IWTO, n.d.). The broad range in wool fibre diameter, fineness, or grade, makes the fibre suitable for a range of products, whether clothing, household or technical textiles (IWTO, n.d. and Kott, n.d.). There are different methods used across the world for grading wool, such as the American system, the Spinning Count system, or the Micron system; however, all three systems relate to the fibre diameter, which largely determines the price and value of the wool (Kott, n.d.). In addition, the more uniform the fibres are within a particular quantity of wool, the higher the value (Kott, n.d.). The colour of the wool fibre also contributes to the value of the fibre. If off-colour fibres are found in white wool fibres, the value of the wool reduces (Chappell, n.d.). Foreign material, such as seeds, reduce the value of the fibre, and in some cases might even require the wool to be discarded (Chappell, n.d.). Other factors which have an impact on the price of wool, include length, strength and medullation.

Wool fibres are hygroscopic, which indicates that they absorb moisture in the form of vapour (Zhou *et al.*, 2007). In contrast to this, they repel liquid moisture, due to the scales on the cuticle which are hydrophobic (Zhou *et al.*, 2007). Kadolph *et al.* (1993) add that, due to the hygroscopic nature of wool fibres, they can absorb a great deal of moisture without feeling wet. Wool has the ability to absorb up to 30% of its own weight in moisture without feeling wet (Zhou *et al.,* 2007). Therefore, wool has the highest moisture absorption rate of any natural fibre or general synthetic fibre (Ghosh, 2004 and Zhou *et al.*, 2007). As a result, wool clothing will generally keep the wearer dry, as it will take a while for water or rain to penetrate the fabric (Zhou *et al.,* 2007). According to Ghosh (2004), the epicuticle, which is the outer layer of the cuticle, is the only non-protein part of the fibre that protects the fibre by acting as a water-repellent membrane, see Figure 25. Water vapour, as opposed to liquid water, however, can transfer from the external environment into the fibre, and *vice versa* through microscopic pores located on the epicuticle (Ghosh, 2004 and Zhou *et al.*, 2007). As a result, wool fabrics have the ability to absorb perspiration in the form of vapour, without feeling wet or having a wet appearance, and will release the absorbed water vapour into the air for the purpose of maintaining a balance in moisture (Ghosh, 2004).

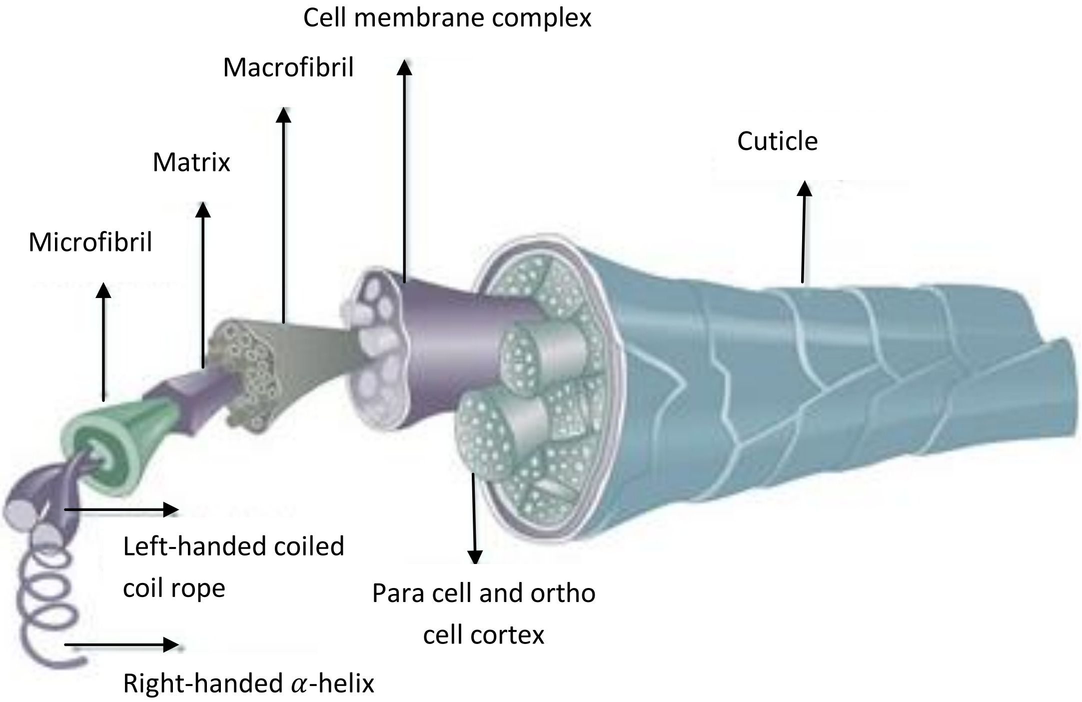


Figure 25: The structure of a wool fibre

(Source: The Woolmark Company, 2012)

The crimp of wool fibres prevent them from being aligned too close to one another which results in the entrapment of air in the air pockets (Ghosh, 2004). The insulation capability of wool fabrics is essentially due to these air pockets, as opposed to the properties of the wool fibre per sé (Ghosh, 2004). Mishra (2002) mentions that the crimp and cross-sectional shape of wool fibres will differ according to the different wool breeds and types.

Zhou *et al.* (2007) commented that wool fabric is versatile, being worn in both cold and warm environments. Mehta and Harnett (1981) state that the thermal insulation of a fibre decreases when it takes up moisture, as is the case with wool fibres. Nevertheless, it is important to note that this will not necessarily have a major impact on the thermal insulation of a garment, since the thermal insulation of a fabric or garment depends on the air trapped in the fabric (Mehta and Harnett, 1981).

Garments containing wool act as a buffer between the wearer and the external environment, due to their high heat releasing and heat absorption properties, which protect the wearer from sudden changes in climatic conditions (Mehta and Harnett, 1981 and Zhou *et al.,* 2007). According to Mehta and Harnett (1981), the evaporation of perspiration absorbed by wool fibres is relatively slow, due to the fact that wool does not wick water readily. Therefore, heat loss is spread out over an extended period, which allows enough time for the regulatory system of the human body to adapt (Mehta and Harnett, 1981).

Mehta and Harnett (1981) summarised the main reasons for using wool to ensure comfort in both summer and winter clothing, as follows. Firstly, wool prevents damp sensations of clothing during hot summer days, due to the moisture absorbency of the fibre. In addition, the fabric removes perspiration and ensures cooling of the body by its evaporation at the skin. During winter months, thick wool fabrics, with a tightly woven construction, provide not only insulation, but wind protection as well. Furthermore, the hygroscopic nature of the wool fibre facilitates the escape of perspiration. One of the major advantages of wool garments is that it protects the wearer during sudden changes in climatic conditions.

2.2.2.3 Properties of cotton

According to Mishra (2000), the cotton fibre is one of the oldest fibres used for textile related purposes; although, the exact date of the origin of cotton is not known. Cotton fibres are derived from the Gossypium plant which has many variations (Mishra, 2000). Cotton is a hygroscopic fibre (Wingate, 1970) and consists of five morphological structures, see Figure 26:

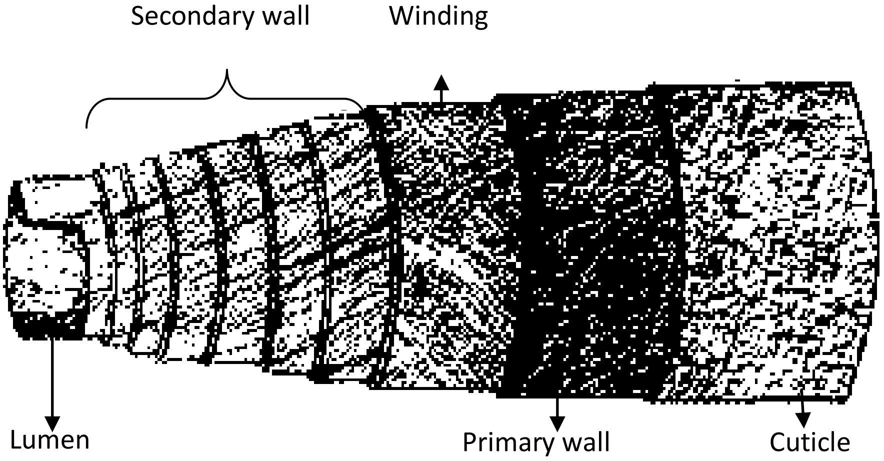


Figure 26: The structure of a cotton fibre

(Source: Cotton Incorporated, n.d.)

1. Cuticle: The outside layer that protects the fibre from mechanical and chemical damage.
2. Primary wall: Situated below the cuticle and made up of cellulose.
3. Winding: The first layer of secondary thickening.
4. Secondary wall: Contributes to the weight of the fibre and consists of cellulose.
5. Lumen: The centre of the fibre.

Cotton fibres are classified according to their quality, in terms of colour, trash content, strength, micronaire and length, which ultimately determines the pricing system for cotton (Cotton Incorporated, n.d.). Micronaire is a measure of the fineness of cotton fibres, and is related to cotton variety (Cotton Incorporated, n.d.). It is actually a composite measure of both fibre fineness and maturity, when different cotton varieties are involved. The cotton fibre length will also vary genetically, and there is usually a range of different fibre lengths in one sample of cotton fibre (Cotton Incorporated, n.d.). The strength of cotton fibres is determined by measuring the force required to break the fibres, which are usually in bundle form, which is then reported as tenacity, in grams per tex, or grams per denier (Cotton Incorporated, n.d.). Other important factors include the colour of the fibre, in terms of brightness and the degree of yellowness (pigmentation); extraneous matter, which is the material other than fibre; and the amount of neps, which are small tangled fibre knots, usually caused by processing (Hedge *et al.,* 2004). These elements, namely colour, foreign matter and preparation, determine the grade of cotton fibres, and contribute to the quality classification of cotton fibres (Calhoun and Bowman, 1999). Previously, grade was determined subjectively by human classers, but specialised equipment has been introduced to assess these elements more objectively (Calhoun and Bowman, 1999).

Kadolph *et al.* (1993) stated that cotton is suitable for year-round use, particularly due to the acceptance of cotton by consumers as a comfortable fibre, due to its excellent softness and moisture absorption properties. The excellent ability of cotton fibres to absorb moisture is due to the imperfect assembly of fibrils in the fibre (Mishra, 2000), fibre strength increasing with increasing moisture content (Kadolph *et al.,* 1993 and Mishra, 2000). The drape, lustre, texture and handle of cotton fabrics are mainly determined by the yarn thickness and type, and the structure and finish of the fabric (Kadolph *et al.*, 1993).

One of the major problems associated with cotton is its tendency to crease (Kadolph *et al.*, 1993). If cotton fibres are not given a durable press or easy care finish, or if the fabric is not blended with polyester, the cotton fabric will crease easily (Kadolph *et al.*, 1993). In addition, cotton fabrics can also be dimensionally unstable; a durable press or consolidation treatment being essential to improve dimensional stability (Kadolph *et al.*, 1993).

According to Ravandi and Valizadeh (2011), cotton has both positive and negative properties. Positive properties include its good durability, excellent liquid and moisture absorption, easy to care for, and comfort that is provided to the wearer due to its softness and breathability. Its negative properties include poor crease performance and dimensional instability. Therefore, Ravandi and Valizadeh (2011) emphasised the importance of blending fibres. For example, blending cotton with polyester improves the crease resistance of the fabric, while retaining the comfort of the cotton fibres. Cotton is also generally blended with fibres, such as polyamide, linen and wool, in order to combine the best properties of each fibre (Ravandi and Valizadeh, 2011).

2.2.2.4 Properties of viscose

Viscose rayon is a manufactured fibre, made from regenerated cellulose (Wardiningsih, 2001). Wood pulp (short-fibre cellulose) is converted, through various procedures and chemicals, to a spinnable solution, which is then extruded as long filaments that can be adapted in terms of length, denier, physical properties, and cross-sectional shape (Wilkes, 2001). The filaments are basically formed when the viscose solution is extruded through a spinneret, with different hole sizes and shapes, which determine the cross-sectional size and shape of the filaments (Wilkes, 2001). In addition, the filaments are stretched on a rotating wheel as the filaments leave the spinneret, which determines the diameter of the filaments (Ghosh, 2004) Although viscose is a 100% cellulose fibre, as is cotton, with the same density as cotton fibres, it has a lower molecular chain length (degree of polymerisation) and a higher proportion of amorphous material, making it more absorbent (Wardiningsih, 2001). Therefore, viscose is a hydrophilic fibre, with a moisture content between 11-13% (Mishra and 2000 and Wardiningsih, 2001). The elasticity of viscose is poor, and the filament does not return to its original length after it has been stretched and released (Mishra, 2000). According to Ghosh (2004), viscose does not have the excellent wet-stability and washability of cotton, it tends to deform and shrink with use.

According to Mishra (2000), viscose is suitable for general textile applications, including clothing, although, due to its hydrophilic nature, the fibres are not usually suitable for insulation purposes.

2.2.2.5 Properties of polyester

Barnett (1997) and Down (1999) stated that polyester is one of the most widely used fibres due to its versatility. Polymer chips are melted and extruded to produce polyester filaments that are finely drawn, sometimes textured to produce a bulkier type of yarn, or cut into short lengths to produce staple yarns (Down, 1999). Figure 27 illustrates the difference between flat (untextured) and textured filaments.

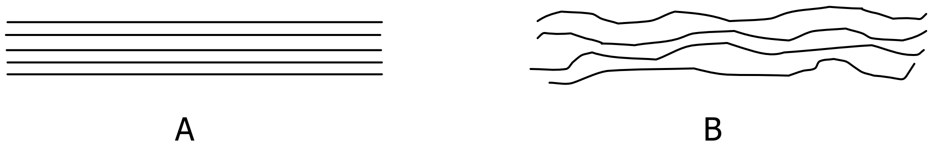


Figure 27: Flat (A) and textured (B) polyester filaments

(Source: Down, 1999)

According to Barnett (1997), the insulating properties of polyester fabrics will depend on the type of yarn that is used, whether flat filament or textured. A textured yarn will be able to trap much more air, for insulation purposes, compared to a flat filament yarn (Down, 1999). Polyester has a very low ability to absorb moisture (Barnett, 1997), although the capillaries formed in textured yarns will improve the absorption of water into the yarn, i.e. between filaments (Down, 1999). In addition to these elements, Wulfhorst *et al.* (2006) identified other outstanding properties of polyester, such as tear strength, abrasion resistance, high elasticity, and light fastness. According to Chattopadhyay (2008), polyester also has good care properties, such as crease resistance and wear resistance, which make it suitable for both apparel and home furnishings. This is supported by Kadolph *et al.* (1993), who stated that polyester fibres also blend well with natural fibres, since it maintains a good appearance.

According to Kadolph *et al.* (1993), the strength and abrasion resistance of polyester fibres are excellent; whereas, its absorbency is poor, at less than one percent of its own weight. Therefore, clothing made from polyester fibres will be uncomfortable to wear during hot and humid conditions, due to the inability of moisture to escape (Kadolph *et al.*, 1993). The low moisture absorbency of polyester fibres has both advantages and disadvantages. On the one hand, garments made from polyester fabrics have a quick drying rate after washing; whereas, on the other hand, polyester fabrics are incapable of absorbing perspiration and cannot conduct it in that way to the exterior for evaporation, although it can wick the perspiration away (Ludewig, 1971). In addition, the hydrophobic nature of polyester fibres can result in electrostatic charges (Ludewig, 1971), although this can be counteracted by an antistatic.

2.2.3 Comparative fibre comfort related properties

Research has shown that synthetic fibres provide good durability and easy care properties, while natural fibres provide good moisture absorbency, which provides comfort to the wearer (Kothari, 2006). When natural and synthetic yarns are combined into one textile, it is possible to produce yarns and fabrics with all round desirable properties (Kothari, 2006). One such example is shown in Table 3, whereby the combination of polyester and cotton/viscose reduced the negative properties of polyester, and *vice versa.* Kothari (2006) distinguished between three reasons for blending fibres: firstly, to combine the positive properties of the fibres; secondly, to produce coloured effects; and thirdly, to reduce cost, by utilising a cheaper fibre.

Table 3: Positive and negative properties of polyester and cotton/viscose

Polyester	Cotton/Viscose
Good crease retention	Poor crease retention
Good wrinkle recovery	Poor wrinkle recovery
Good tenacity	Poor tenacity
Better abrasion resistance	Lower abrasion resistance
Lower staining tendency	Higher staining tendency
Ease of washing	Difficulty of washing
Higher colour fastness	Lower colour fastness
Poor moisture absorption	Good moisture absorption
Poor static dissipation	Good static dissipation
Poor moisture vapour transmission	Good moisture vapour transmission
Poor feel	Good feel
Warm, crisp hand	Cool, silky hand
Lower comfort	Higher comfort
Non bio-degradable	Bio-degradable

(Source: Kothari, 2006)

According to Kothari (2006), natural fibres have a lower thermal conductivity than synthetic fibres in a dry state; although they absorb 8-13% moisture, which increases their conductivity, Sampath *et al.* (2011) stating that thermal conductivity indicated the ability of a textile material to conduct heat from one point to another point. Figure 28 provides an indication of the thermal conductivity of both natural and synthetic fibres. It is apparent that, for synthetic fibres, polyester and polypropylene have a relatively low thermal conductivity, while for natural fibres, silk has the lowest thermal conductivity (Kothari, 2006). Wool and cotton also have a low thermal conductivity compared to the synthetic fibres. The fibre with the highest thermal conductivity is Rayon (viscose), followed by nylon.

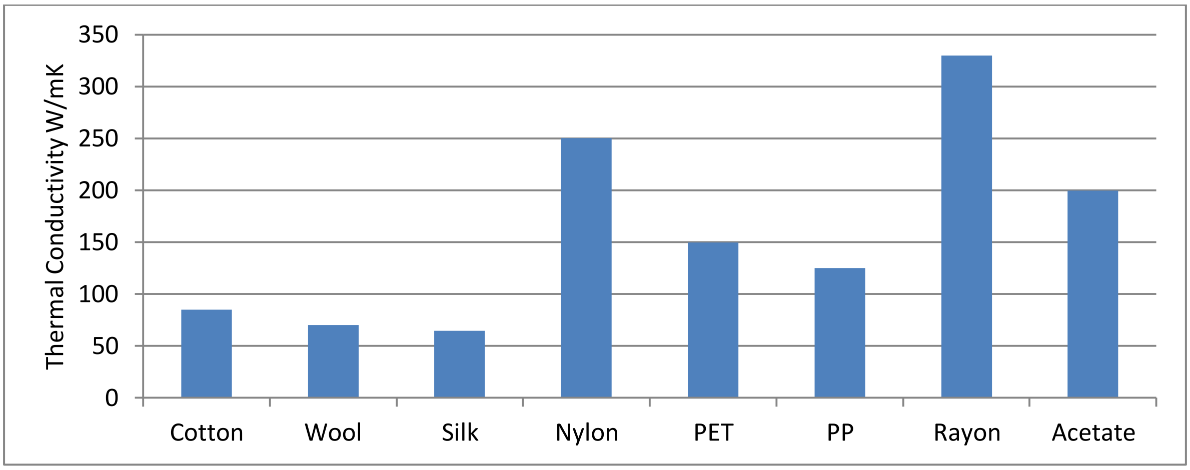


Figure 28: Thermal conductivity of natural and synthetic fibres

(Source: Kothari, 2006)

In terms of moisture absorption of fibres and textile materials, Kothari (2006) commented that it is one of the key elements which protects the body against sudden changes in the climate and external environment. Natural fibres, such as cotton, hemp, jute, silk and wool, all have high absorption regain compared to man-made fibres, such as polyester, polyamide, polyacrylic and polyvinylchloride (Kothari, 2006).

Table 4 lists some of the performance properties of wool and polyester fibres, as identified by Wulfhorst *et al.* (2006). From the information provided in Table 4, it is important to note that wool has a higher heat insulation and moisture absorbency capability than polyester. It is also important to note, from Table 4, that the air permeability of wool is rated lower than that of polyester, probably due to the more crimpy nature of wool.

Table 4: Properties of wool and polyester

Fibre	Material properties			Properties of utility value							
	Strength	Elongation	Moisture absorbency	Wrinkle tendency	Permeability	Heat insulation	Light fastness	Weathering fastness	Fastness against microorganisms	Dirt susceptibility	Price
Wool	-	+	++	0	0	++	-	--	0	+	+
Polyester	++	0	--	-	+/++	--	++	+	++	+	0

++ very high + high 0 medium - low -- very low

(Source: Wulfhorst *et al.*, 2006)

According to Kadolph *et al.* (1993), some of the most important comfort properties of a fibre, whether natural or man-made, include absorbency, heat retention, density and elongation. Table 5 provides a comparison between wool, cotton, polyester, and viscose in terms of these related comfort properties.

Table 5: Comparison of comfort related properties of wool, cotton, polyester and viscose

Fibre	Absorbency (Moisture regain %)	Heat retention	Density (g/cc)	Elongation (%)
Wool	13-18	Excellent	1.32	25
Cotton	7-11	Poor	1.52	3-7
Polyester	0.4	Good	1.34-1.38	12-55
Viscose	11.5-12.5	Poor	1.5	9-18

(Source: Kadolph *et al.,* 1993)

From the information provided in Table 5, it is evident that cotton has good absorbency, very low elongation, and reasonable heat retention. Kadolph *et al.* (1993) stated that cotton is a very comfortable skin-contact fabric; although, cotton fabrics tend to absorb considerable moisture in damp conditions, which can result in wet clinging clothing and discomfort. As mentioned previously, wool is a hygroscopic fibre with very high moisture regain, excellent heat insulation and medium density. Compared to cotton, wool has a lower density; therefore, a cotton blanket will, for example, be heavier than a wool blanket of the same thickness, but not as warm as the wool blanket, due to the excellent heat insulation of wool fibres (Kadolph *et al.,* 1993). Polyester has the lowest absorbency of the fibres, with reasonable heat insulation. According to Kadolph *et al.* (1993), the low absorbency of polyester reduces its comfort factor when used in skin-contact apparel, and increases its electrostatic characteristics. Viscose has good absorbency, reasonable elongation, but very poor heat insulation.

Kothari (2006) emphasised the need to consider additional comfort parameters when the comfort properties of the various types of fibres are compared. For example, cotton and viscose fibres have good wicking properties, whereas polyester has poor wicking properties (Kothari, 2006). Fabrics made from viscose fibres generally have a smooth handle, which appeals to the wearer and potentially improves comfort (Kothari, 2006). As mentioned previously, fabrics made from polyester fibres have the tendency for static charge build up, which can ultimately reduce the comfort of the wearer (Kothari, 2006).

It is evident that a range of comfort parameters must be considered when comparing the various types of fibres. The comparison of the fibres highlights the strengths and weaknesses of the natural and synthetic fibres, and emphasises the need for blending fibres for optimal comfort performance. Kothari (2006) stated that no fibre has all of the desirable attributes. Knowledge of the positive and negative properties of each fibre can enables manufacturers to combine fibres to take advantage of the positive attributes of each fibre, reducing, possibly even eliminating, the poor attributes.

2.2.4 Effect of fibre properties on comfort

Natural fibres are generally accepted as hydrophilic, whereas synthetic fibres are considered hydrophobic (Starr, 2010). The amorphous areas (open areas) within a fibre contribute to the absorbency of a textile material, due to the high amount of open spaces within the fibre which can be filled with moisture (Starr, 2010). Although the type of fibre will not have a major impact on the comfort related properties of clothing, it is the responsibility of fibre manufacturers to explore how fibre properties impact on fabric and garment properties, and ultimately comfort (Mehta and Harnett, 1981).

Considerable research has been conducted focussing on the comfort related properties of fabrics. Some of these studies examined the impact that fibre type and blend has on comfort related properties. In addition, several of these studies used the Permetest to gain a better understanding of water vapour permeability and thermal resistance of fabrics, as well as the variables that influence these parameters, some of which are summarised below.

Although the structure, chemical composition and diameter of the fibres, selected for a textile material, influence thermal insulation, the air trapped within the textile material, which is a function of the thickness and porosity of the material, is the main determinant of its thermal insulation properties (Fan, 2009b, Havenith, 1999, Slater, 1991 and Starr, 2010).

According to Mehta (1984), the water vapour resistance of a fabric is determined by its thickness, rather than by the fibre type. Figure 29 illustrates the linear dependence of water vapour resistance on the thickness of loosely constructed underwear fabrics containing various types of natural and synthetic fibres (Mehta, 1984), from which it is apparent that the different fibre types essentially behave similarly, in that none lie consistently above or below the regression line, which would have been the case had fibre type had an effect.

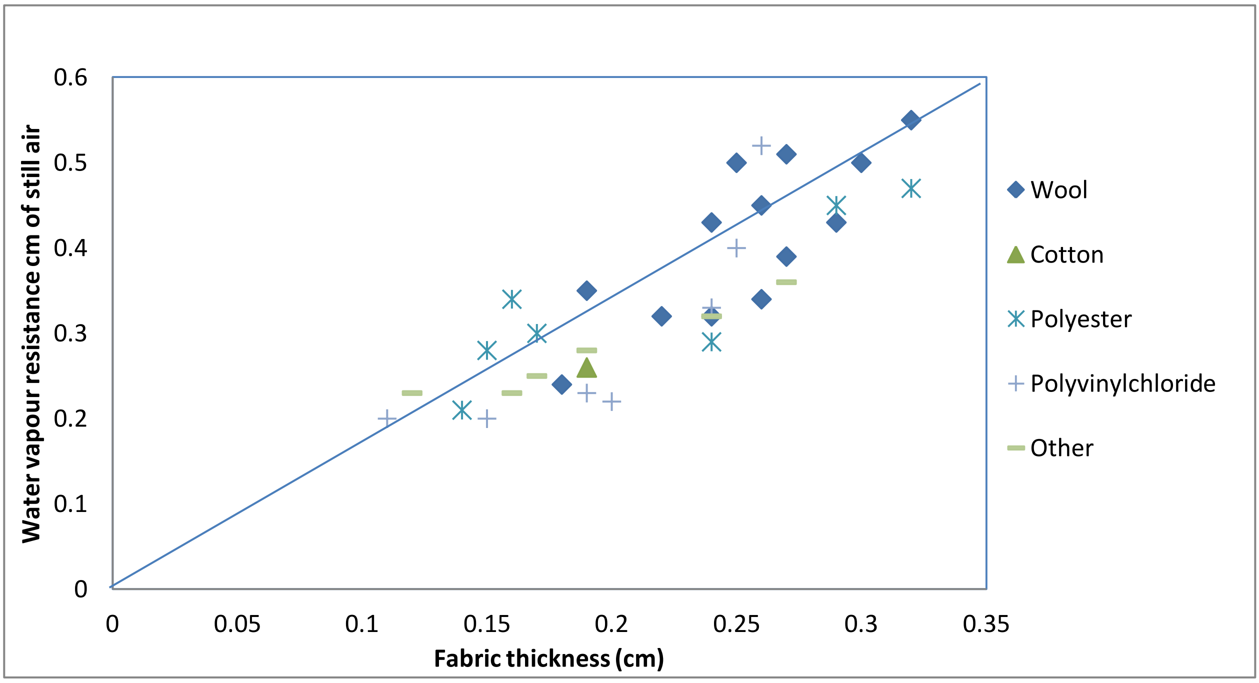


Figure 29: Dependence of water vapour resistance on underwear fabric thickness

(Source: Mehta, 1984)

Das *et al.* (2009) examined the moisture transmission properties of plain woven fabrics made from polyester and viscose blended yarns. The impact of blend proportion, yarn count and twist level on air permeability, water vapour permeability, in-plane wicking, and vertical wicking was investigated. The Permetest was used to test the water vapour permeability of the fabrics. It was found that the blend proportion and yarn count had a significant effect on the breathability. An increase in polyester content reduced the water vapour permeability, while the air permeability of the fabrics decreased as the yarns became finer, while the water vapour permeability decreased with a decrease in yarn twist (Das *et al.,* 2009). Nevertheless, it is not clear whether or not possible blend associated changes in fabric thickness and mass played a role.

Gericke and Van der Pol (2010) investigated the comfort related properties of knitted bamboo, cotton and viscose fabrics, with similar construction, weight and finishing treatment. The comfort related properties were tested by means of the Permetest, Alambeta, Walter (the sweating manikin) and SEM images. They found that there were no significant differences in the thermal insulation and moisture management properties of the different fibre types (Gericke and Van der Pol, 2010). In other words, the research indicated that bamboo fibres cannot necessarily be marketed as being more comfortable than cotton or viscose fibres.

In a study, conducted by Tyagi *et al.* (2004), it was found that the thermal comfort properties of woven polyester-viscose fabrics were influenced by the properties of the fibres as well as by the weave construction. Coarse polyester fibres, with non-round cross section, produced good absorbency and thermal insulation; but, reduced the air-permeability and water vapour transmission of the fabric (Tyagi *et al.*, 2004). In terms of fabric construction, the study established that the twill fabrics had better air permeability, water vapour transmission, wickability, absorbency and thermal insulation than the plain weave fabrics (Tyagi *et al.*, 2004).

In a study, where polyester and viscose blended suiting fabrics were compared in terms of comfort properties, it was found that (Nayak *et al.,* 2009):

1. The air permeability of the fabrics decreased with an increase in polyester content.
2. The fabric thermal insulation increased with an increase in polyester content.
3. The fabric moisture vapour transfer decreased with an increase in polyester content.

A study, using an Alambeta device to compare the thermal properties of cotton and regenerated cellulose (Tencel) yarns, showed that the choice of raw material for a particular garment should be based on a subjective selection of which property is more important for the user (Frydrych *et al.,* 2002). For example, cotton should be selected over Tencel yarns if the fabric was to be used for summer clothing as the cotton has satisfactory thermal conductivity; whereas, Tencel yarns should be selected when better air permeability is desired (Frydrych *et al.*, 2002).

2.2.5 Effect of yarn properties on comfort

It is important to consider the impact of the yarn structure, such as twist, compactness, hairiness, and linear density, independently of its fibre components, on the comfort of a textile material. According to Ravandi and Valizadeh (2011), the spinning technique, yarn linear density and the pore size, and distribution of pores, in the yarn determine the strength, evenness, frictional characteristics, thermal insulation, liquid vapour permeability, and air permeability of a textile. Essentially, therefore, the yarn structural parameters will influence the comfort related properties of the fabric and garment, insofar as they influence the air trapped within and between the yarns. This in turn, is a function of yarn bulk, hairiness, and linear density.

Although the structure, chemical composition and diameter of the fibres, selected for a textile material, influence thermal insulation, the air trapped within the textile material, which is a function of the thickness and porosity of the material, is the main determinant of its thermal insulation properties (Fan, 2009b, Havenith, 1999, Slater, 1991 and Starr, 2010). For example, wool or textured filaments, will have superior insulation properties, as they provide a greater surface area for the entrapment of air due to the crimp of the fibre (Starr, 2010). Furthermore, the number of plies and the level of twist in a yarn can affect the insulating capabilities of the resultant textiles in as much as they influence the amount of air trapped (Starr, 2010 and Slater, 1991). In other words, yarns that have a smooth surface and a high twist will have poorer insulating properties, due to the more compact nature of such yarns and the lack of open spaces between the yarns (low cover); although, such yarns would improve the strength and lustre of the fabric (Slater, 1991).

Chidambaram *et al.* (2011) investigated the effect of yarn linear density and loop length on the thermal comfort related properties of 100% bamboo knitted fabrics. Various comfort related parameters were tested in the study, the water vapour permeability being tested with the Permetest. It was found that the water vapour permeability increased with an increase in the linear density of the bamboo yarn, and that the water vapour permeability was higher for fabrics containing finer yarns. (Chidambaram *et al.*, 2011).

Singh and Nigam (2013) investigated the effect of yarn type (combed, carded, and compact spun yarns), the pick density ranging from 88 to 108 filling yarns per inch for each of the three fabrics, on the comfort related properties of 100% cotton plain weave fabrics. The water vapour permeability was tested using the Permetest. It was found that the water vapour permeability of the fabrics produced from the compact weft yarns, was slightly higher than that of the fabrics containing the combed and carded weft yarn fabrics, most likely due to the more compact and less hairy nature of the compact yarns (Singh and Nigam, 2013).

2.2.6 Effect of fabric properties on comfort

Starr (2010) states that a thin fabric will not provide as much insulation as a thick fabric, due to the inability of the former to trap air. Fan (2009b) adds that surface hairiness and loose construction of a textile contribute to the entrapment of air, which improves insulation.

The three ways in which water can move through a textile fabric is identified by Starr (2010), as sorption, diffusion and wicking. Sorption consists of the following three processes as identified by Starr (2010); adsorption, where water is taken up and held near, or on, the surface of the textile; absorption, where moisture is distributed throughout and in the textile fabric; and desorption, which consists of the release of the moisture from the textile. In terms of diffusion, the moisture in a textile material will disperse more quickly when the fabric has a low mass, an open weave, or is made from bulky yarns (Mehta and Harnett 1981 and Starr, 2010). The ability of a textile material to wick moisture away from the body will depend on fibre wettability as well as the structure of the yarn and fabric (Starr, 2010). According to Mehta and Harnett (1981), wicking not only depends on the properties of fibres and surface finishes, but also on the capillaries in the fabric which facilitate the wicking process.

In terms of finishes used on textiles, Slater (1991) and Ravandi and Valizadeh (2011) state that both mechanical and chemical finishes could result in changes that affect the comfort of the fabric. Mechanical finishes, such as brushing, could increase the bulk of the fabric and trap more air, which influences physiological comfort, whereas chemical finishes and dyeing will generally mainly determine visual and psychological comfort of a garment in terms of the aesthetic appearance of the garment (Slater, 1991). Additional examples of chemical finishes, include crease resistance, stain resistance, antistatic performance, flame resistance and water resistance, all of which contribute to both psychological and physiological comfort parameters (Slater, 1991). Havenith (1999) stated that coatings and membranes on fabrics could also have an influence on the vapour resistance of the fabric. In the final analysis therefore, it is the ability of the fabric to entrap air, together with its mass and thickness and wetting and wicking ability which will determine its comfort. Of great importance in this respect, is the fabric bulkiness (compactness) and the surface tension and other relevant properties of its fibres and yarns.

As mentioned previously (see Figure 29), the thickness of a fabric largely determines the thermal insulation of the fabric or garment, there being a linear relationship between these two parameters (Chidambaram *et al.,* 2011, Kothari, 2006 and Mehta, 1984).

In a study, conducted by Tyagi *et al*. (2004), it was found that the thermal comfort properties of woven polyester-viscose fabrics were influenced by the properties of the fibres as well as by the weave construction. The study established that the twill fabrics had better air permeability, water vapour transmission, wickability, absorbency and thermal insulation than the plain weave fabrics (Tyagi *et al*., 2004).

Das and Kothari (2012) studied the moisture vapour transmission behaviour of 100% cotton plain weave fabrics, with five different pick densities and two different weft counts. Three different methods were used to test the water vapour permeability of the fabrics, namely the Permetest, the cup method and the MVTR cell method. Although the three methods produced different water vapour permeability values, all three methods gave the same trends, the water vapour permeability decreasing with an increase in fabric cover factor (Das and Kothari, 2012). An increase in fabric cover factor reduced the open spaces in the fabric, which ultimately reduced the diffusivity of the fabrics (Das and Kothari, 2012). In addition, the results indicated that the thinner fabrics had higher water vapour permeability than the thicker fabrics (Das and Kothari, 2012).

Oğlakcioğlu and Marmarali (2007) tested various knitted structures containing either 100% cotton or 100% polyester fibres to determine the factors which affect the thermophysiological comfort of the fabrics. Both the Alambeta and the Permetest were used in the study. According to the results obtained on the Permetest, the water vapour permeability of both the cotton and polyester fabrics showed a decrease in value from single jersey (with the highest value), to 1x1 rib (intermediate value), to interlock (lowest value). From their results, they concluded that the effect of knitted structure on water vapour permeability was statistically significant. It should also be noted, however, that the single jersey fabrics had the lowest fabric thickness, which facilitated the easy transportation of water vapour.

Singh and Nigam (2013) investigated the effect of yarn type (combed, carded, and compact spun yarns), the pick density ranging from 88 to 108 filling yarns per inch for each of the three fabrics, on the comfort related properties of 100% cotton plain weave fabrics. The water vapour permeability was tested using the Permetest. The results of the research indicated that the water vapour permeability decreased when the number of picks (weft density) increased from 88 to 108 for all the fabrics (Singh and Nigam, 2013). This was ascribed to the fact that, when the number of filling yarns increased, the fabric cover factor (i.e. fabric compactness) also increased, which reduced the ability of water vapour to pass through the fabric (Singh and Nigam, 2013).

Senthilkumar *et al*. (2010) studied the air permeability, water absorbency, thermal resistance and wickability of plain weave fabrics produced from polyester/viscose and polyester/cotton blends, and which varied in fabric thickness. The Permetest was used for testing the thermal resistance of the samples. It was found that the fabric with the highest thermal resistance had the highest fabric thickness and fabric cover factor, which enabled more entrapment of air for insulation (Senthilkumar *et al.,* 2010). Senthilkumar *et al*. (2010) emphasised, however, that the air permeability of the fabric also affected its thermal resistance. In their case, the fabric with the lowest thickness did not have the lowest thermal resistance, which was ascribed to its higher air permeability.

A study conducted by Boguslawska-Bączek and Hes (2013) to test the water vapour permeability of wet wool fabrics, as well as of blended fabrics, using a Permetest, produced the following results:

1. An increase in the mass of a wool fabric resulted in a decrease in the water vapour permeability of the fabric, as well as an increase in its water vapour resistance.
2. An increase in the moisture content of wool or wool/viscose blended fabrics had an adverse effect on the ability of the fabric to transport water vapour.
3. The water vapour permeability of the wet fabrics was quite low.

In a study, conducted by Tyagi *et al*. (2004), it was found that the thermal comfort properties of woven polyester-viscose fabrics were influenced by the properties of the fibres as well as by the weave construction. Coarse polyester fibres, with a non-round cross section, produced good absorbency and thermal insulation; but, reduced the air-permeability and water vapour transmission of the fabric (Tyagi *et al.*, 2004). In terms of fabric construction, the study established that the twill fabrics had better air permeability, water vapour transmission, wickability, absorbency and thermal insulation than the plain weave fabrics (Tyagi *et al.*, 2004).

2.2.7 Effect of clothing design and structure on comfort

The preceding section established that the properties of fibres and textiles, in terms of fibre properties, yarn structure, fabric structure and textile finishes, influence the comfort of clothing items. However, it is also important to consider the influence that the design of a garment has on comfort.

Mehta and Harnett (1981) state that factors, such as the design of a garment, the number of layers and the weight, thickness and construction of the fabric, will influence the thermal comfort of clothing. Table 6 provides an overview of the thermal insulation values of individual clothing items, as identified by Holcombe (1984). The values in Table 6 are listed in order, from the clothing item with the lowest insulation to the clothing item with the highest insulation. Holcome (1984) suggested that the thermal insulation of clothing items predominantly depend on the thickness of the fabric and the amount of air that is trapped.

Table 6: Thermal insulation of clothing items

Clothing item	Thermal insulation (Km²/W)
Satin lining	0.01
Cotton shirting	0.01
Lightweight worsted suiting	0.02
Medium weight suiting	0.06
Melton overcoat	0.08
Heavyweight suiting	0.09
Wool pullover	0.11
Velour overcoat	0.11
Anorak lining	0.20
Sliver knit jacket	0.41

(Source: Holcombe, 1984)

According to Qian (2005), the transfer of heat through clothing depends on clothing parameters, body posture, activity and external environmental conditions. In addition to these factors, Lawson *et al.* (2004) identified the type of textile (weave construction, fabric mass and thickness, fibre type), the mechanism of heat transfer, and the presence of moisture, as factors which influence the thermal comfort of clothing. Havenith (1999) was of the opinion that the insulation capabilities of a clothing item depends more on the thickness of the material than on the type of fibre used. This was supported by Fan (2009b), who stated that the air entrapped in the fabric, as opposed to the type of fibre, determined the insulation of the garment. Therefore, factors, such as air movement, air permeability of clothing, the number of garment layers, and movement by the wearer, influence thermal insulation, due to, for example, the compression of the garment decreasing material thickness, or allowing air to enter through garment openings (Havenith, 1999). In addition, Fan (2009a) stated that there will be a decrease in the insulation property of a garment when there is an increase in wind or air movement. Haghi (2011) commented that, although material thickness largely determines insulation properties, the consumers still have their own perceptions of the comfort related properties of certain fibre types, such as preferring to wear wool in cold conditions.

Qian (2005) commented that, in order for clothing to be cool during summer, the thermal insulation (I_t) must be low; whereas during the winter it must be high, to keep the wearer warm. In order for clothing to be permeable, the moisture vapour resistance (R_t) must be as low as possible and the moisture permeability index (i_m) should be as high as possible (Qian, 2005). Finally, the moisture accumulation (M_a) of any piece of clothing should be low to keep the wearer dry and comfortable (Qian, 2005).

In order to achieve the aforementioned comfort targets, it is necessary to critically examine the design of clothing. Aspects of garment design, such as the amount of body surface area that the garment covers, the fit of the clothing, in terms of tightness or looseness, and openings in the garment, that allow wind and air to penetrate the garment, influence moisture transmission and therefore ultimately comfort (Fan, 2009b). In cold environments, the clothing should be designed in such a way as to trap air between the body and the clothing, and to keep it there; whereas, in a warm environment, the design of the clothing should have open constructions and be loosely fitting, which will ensure sufficient loss of heat, through evaporation of perspiration (Mehta and Harnett, 1981). This is supported by Chen *et al.* (2004), who stated that loose fitting garments generally reduce thermal insulation and water vapour resistance, especially during windy conditions or body movement.

2.2.8 Effect of clothing ensembles on comfort

Holcombe (1984) stated that the thermal insulation of clothing ensembles is greater than the sum of the thermal resistances of the individual clothing items, due to the fact that additional air is trapped between the extra layers of fabric (Holcombe, 1984).

According to Ho *et al.* (2011), the number of layers in a clothing ensemble will influence the thermal insulation and moisture vapour resistance. The greater the number of layers, the higher thermal insulation and moisture vapour resistance the ensemble will have, due to the amount of air that is trapped (Ho *et al.,* 2011).

According to Keighley (1985), it is crucial that clothing and clothing ensembles must be designed in such a way that they allow water vapour from the skin to transfer through the clothing ensemble. For example, when a waterproof, vapour impermeable garment is worn together with a clothing ensemble, the loss of water vapour from the clothing will be reduced, and discomfort will occur as a result of condensation inside the clothing (Keighley, 1985). Several ‘breathable fabrics’ have been developed in order to improve the transfer of water vapour, while maintaining the water resistance of the fabric (Keighley, 1985). Therefore, the introduction of breathable fabrics has facilitated the design of clothing ensembles that will provide protection against rain, reduce condensation, while allowing the transfer of water vapour to improve comfort (Keighley, 1985).

A study was conducted by Fan and Chen (2002) in which the thermal comfort properties of nine different clothing ensembles were compared using a perspiring thermal manikin (Walter). Table 7 shows the various different clothing ensembles that were covered in their study. The clothing ensemble with the highest thermal insulation was H, which consisted of ensemble A and B, covered with a cotton jacket and trousers (C). The clothing ensemble, with the lowest moisture vapour resistance, was ensemble B, which consisted of a long sleeve underwear top and long bottom made of a thick knitted fabric. The study also found that ensemble I, which consisted of inner garments and rainwear jacket and trousers, exhibited the most moisture accumulation. Even though the knitted underwear was made from an absorbent fabric, the outer rainwear jacket was not permeable, which resulted in a build up of moisture (Fan and Chen, 2002).

Table 7: Details of clothing ensembles

Code	Weight (g)	Description of ensemble
A	248	Long sleeve underwear top and long bottom made of a thin knitted fabric
B	806	Long sleeve underwear top and long bottom made of a thick knitted fabric
C	1185	Cotton jacket and trousers
D	900	GORE-TEX rainwear jacket and trousers
E	1054	Ensemble A+B
F	1433	Ensemble A covered with C
G	1148	Ensemble A covered with D
H	2239	Ensemble A + B, then covered with C
I	1954	Ensemble A + B, then covered with D

(Source: Fan and Chen, 2002)

2.3 Summary of literature review

The literature review discussed the importance of comfort in terms of fabrics and garments. Comfort is a multidimensional concept influenced by a range of variables. Several equipment for testing the comfort related properties of fabrics and garments was examined. Various fabric properties in terms of fibre type, yarn type, fabric thickness, density, air permeability and porosity were discussed in order to gain a better understanding regarding the importance of these factors in terms of comfort related properties, namely water vapour permeability, water vapour resistance, and thermal resistance. The literature review also examined the use and importance of the Permetest for testing comfort related properties on fabrics.

The literature review also provided results obtained from previous research studies, focussing on comfort related properties that were tested using the Permetest. Several of these studies observed that the dominant factor determining thermal resistance is fabric thickness, also highlighting the important role of entrapped air. The more air that a fabric is able to trap, the higher the thermal resistance will be. In terms of relative water vapour permeability and water vapour resistance, some of the significant factors identified in previous studies include fabric thickness, fabric mass, fabric cover factor, as well as fabric structure. Another important piece of evidence examined in the literature review is that the importance of fibre type or blend, in terms of its influence on water vapour transmission and thermal resistance, is relatively small. Even though some of the studies found that fibre type has an influence on the comfort related properties of fabrics, many of these results would perhaps be explained by associated changes in fabric mass and thickness, rather than by the fibre type, or even by differences in the fineness, crimp and cross-section of the fibres. Furthermore, the majority of the studies highlighted the major influence of fabric parameters, such as thickness, mass, air permeability, and cover factor, rather than fibre type or blend, on the fabric comfort related properties.

CHAPTER 3: RESEARCH METHODOLOGY

This chapter provides an overview of the methods and procedures used to answer the research questions outlined in Chapter 1.

3.1 Methodology

The methodology used for this study consisted of the following three procedures:

1. Selecting commercial suiting fabrics, made from both natural and man-made fibres, ranging in fabric mass, and consequently also in thickness.
2. Conducting laboratory tests on all the fabrics to determine the physical fabric properties and comfort related properties.
3. Analysing and interpreting the results through multiple regression analysis.

Firstly, the commercial men's suiting fabrics were sourced from two large and important clothing factories located in Cape Town. A group of 26 commercial fabrics, covering both natural and synthetic fibres and blends, over a range of fabric mass, were selected. The majority of the fabrics selected for the study consisted of wool, polyester, viscose, and cotton fibres, or a combination of these fibres, these representing the most popular mens suiting fabrics here. The fabrics consisted of plain weave, 2x1 twill weave, and 2x2 twill weave.

A summary regarding the selection of fabrics is as follows:

1. The fabrics selected for this study focused on both natural and man-made fibres, namely wool, polyester, viscose and cotton, in order to determine whether it was possible to assign comfort related properties to fibre type. All the fabrics were commercially produced fabrics and were not specifically manufactured for the research study.
2. The fabrics utilised in the study consisted of the three most popular weave structures used for suiting fabrics, namely plain, 2x1 twill, and 2x2 twill. These three weave structures were chosen to determine the role, if any, of fabric construction in thermal comfort and water vapour permeability.

3. The group of fabrics were selected so as to cover as wide a range of fabric mass, and therefore also of thickness, as possible, in order to evaluate the effect that these two parameters have on comfort related properties.

The second part of the methodology was to test the fabrics in terms of their physical and comfort related properties. The physical properties tested include mass, thickness, and air permeability. Fabric density was calculated by dividing the fabric mass by fabric thickness. The comfort related properties were tested using the Permetest. The three comfort related properties measured, were relative water vapour permeability, water vapour resistance and thermal resistance. The values of these comfort related properties were also used in order to calculate the fabric moisture permeability index, considered to represent an overall measure of fabric thermophysiological comfort.

Once all the tests had been completed, the results were analysed using the appropriate statistical techniques and multiple regression analysis, and graphically plotted in order to establish and illustrate the effects of the various fabric parameters and fibre type on the fabric comfort related properties. Ultimately, the most significant empirically derived relationships between the fabric parameters and the comfort related properties were determined by means of the multiple regression analysis.

A Pearson correlation matrix was used to determine the correlation coefficients between the different variables, independent and dependent. The Pearson correlation matrix provided an indication of the strength and direction of linear relationships between the variables. The multiple regression analysis was carried out using the stepwise forward regression procedure, with statistical significance being tested at the 95% confidence levels. Both multi-linear and multi-quadratic regression analyses were carried out, and the corresponding best fit regression equations were established for each dependent variable. The extent to which each significant independent variable contributed towards explaining changes in the dependent variable was established. In addition, graphs were presented for each dependent variable to illustrate the various trends and the role and importance of fabric parameters, and fibre type and blend, in terms of the fabric comfort related properties.

Figure 30 provides an overview of the methodology and procedure used to complete the study and ultimately, answer the research questions.

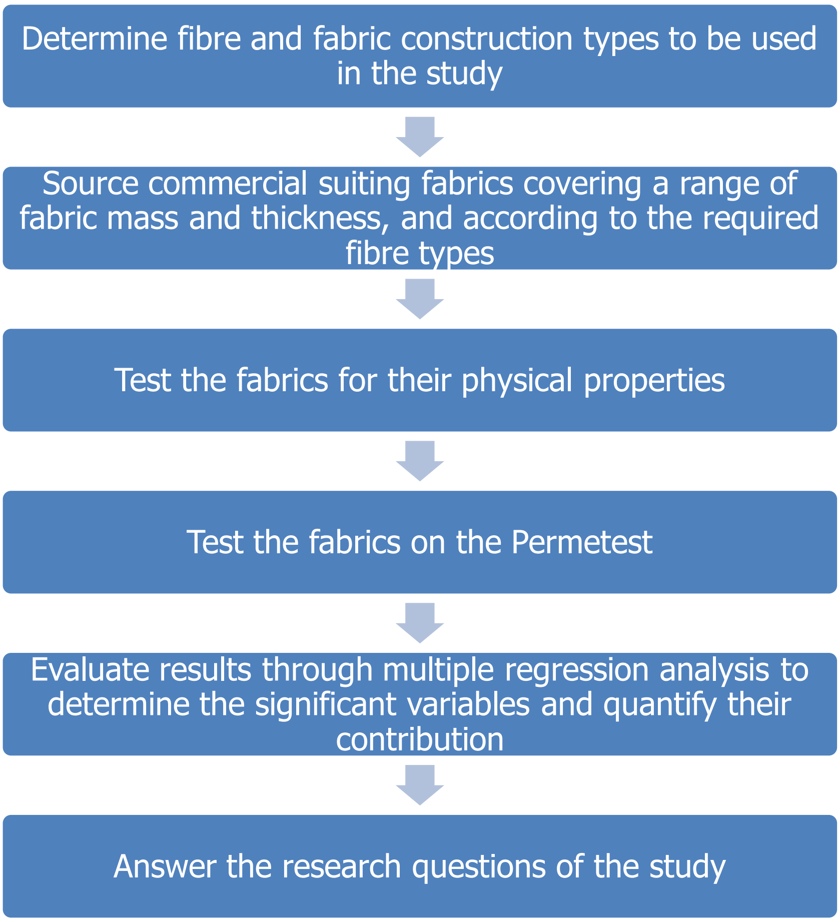


Figure 30: Research methodology

3.2 Methods

3.2.1 Materials and physical testing

The commercial fabrics that were used in the study are listed in Table 8, all the fabrics being woven. The fabrics were tested for mass, thickness, air permeability and structure. Fabrics were selected over a broad spectrum in mass, ranging from 145 to 250 g/m², the thickness of the fabrics ranging from 0.23 to 0.65 mm. Three different weave structures were chosen for the study, namely plain weave, 2x1 twill weave, and 2x2 twill weave, these being the most popular for men's suiting. All the fabrics were conditioned under standard atmospheric conditions, of 21°C (±2°C) and 65% (±2%) humidity, for 24 hours before testing.

Table 8: Properties of fabrics used in the study

Code	Composition	Mass (g/m²)	Thickness (mm)	Density (kg/m³)*	Air permeability (ml/s/cm²)	Structure
A	60/40 wool cotton	145	0.29	500.0	31.3	1x1 Plain Weave
B	100% wool	147	0.25	588.0	16.3	
C	100% wool	147	0.30	490.0	43.3	
D	55/45 polyester wool	150	0.27	555.6	67.3	
E	52/48 wool polyester	154	0.23	669.6	27.5	
F	70/30 wool polyester	154	0.30	513.3	29.9	
G	100% polyester	157	0.45	348.9	62.3	
H	100% wool	161	0.23	700.0	24.1	
I	100% polyester	169	0.45	375.6	34.8	
J	50/50 wool polyester	171	0.32	534.4	17.6	
K	65/35 polyester viscose	179	0.32	559.4	16.9	
L	100% wool	190	0.42	452.4	18.6	
M	100% polyester	200	0.50	400.0	42.8	
N	65/35% polyester viscose	200	0.34	588.2	10.3	
O	100% wool	162	0.30	540.0	22.5	2x1 Twill Weave
P	100% wool	173	0.40	432.5	19.0	
Q	80/20 wool polyester	174	0.31	561.3	12.5	
R	78/22 polyester viscose	187	0.33	566.7	6.4	
S	100% cotton	196	0.41	478.0	32.6	
T	65/35% polyester viscose	210	0.46	456.5	13.6	
U	100% cotton	225	0.43	523.3	15.4	
V	80/20 polyester wool	172	0.32	537.5	14.9	2x2 Twill Weave
W	65/35% polyester viscose	184	0.34	541.2	16.5	
X	65/35% polyester viscose	245	0.46	532.6	10.0	
Y	65/35% polyester viscose	245	0.55	445.5	10.5	
Z	90/10% polyester wool	250	0.65	384.6	20.5	

*Derived from the fabric mass and thickness

The fabric mass, thickness, density and air permeability represent the independent variables of this study, although air permeability is, to a large extent, itself dependent upon fabric mass and thickness, while fabric density is derived from fabric mass and thickness.

3.2.1.1 Fabric mass

Fabric mass was measured according to SANS 79:2004. Three samples were cut using a sample cutter (diameter of 11.3cm), and weighed on a digital scale, and the average of the three values taken, and the result given in grams per square metre (g/m^2).

3.2.1.2 Fabric thickness

Fabric thickness was tested according to ISO 5084:1996, using an Elastocon thickness gauge. Ten samples were taken from each fabric and tested for thickness. Thereafter, the average of the ten samples was calculated to obtain the thickness of each fabric, in millimetres.

3.2.1.3 Fabric density

Fabric density, in kg/m^3, was derived from the measured fabric mass (g/m^2) and thickness (mm) values, using the following formula:

$$\text{Fabric density} = \text{Fabric mass} / \text{Fabric thickness}$$

3.2.1.4 Air permeability

The air permeability of the fabrics was tested using the WIRA Air Permeameter, according to ASTM D737-04(2012). The WIRA Air Permeameter utilises a water manometer tube and three flow meters of different sizes. Each flow meter has an isolating valve. The appropriate valve is opened until the required pressure drop (1cm of water) is achieved. The flow rate was read directly from one of the flow tubes.

Five samples of each fabric were tested on the WIRA Air Permeameter, thereafter the average for the five tests was calculated and converted to ml/s/cm^2. The pressure differential used was 98 Pa.

3.2.2 Comfort related testing

3.2.2.1 Introduction

The Permetest was used in this study for measuring the comfort related properties of all of the fabrics. The literature review examined various pieces of equipment utilised for testing comfort related properties of fabrics. Even though thermal and sweating manikins are modern and advanced pieces of equipment, and probably the preferred method for testing comfort of garments and ensembles, the Permetest has the ability to test both the water vapour permeability and thermal resistance of fabrics, and is fairly widely used for research. According to Gericke and Van der Pol (2010), the debate regarding whether sweating manikins, or the Permetest and Alambeta are the most representative of actual wearing conditions, is an ongoing one. It is important to note that measurements on sweating manikins are carried out over a 10 hour period, whereas measurements on the Permetest are completed within a very short period, usually 3 minutes. Research conducted by Gericke and Van der Pol (2010) on three knitted fabrics made from different fibres, tested on Walter the sweating manikin, the Permetest, and the Alambeta, showed that the three test methods exhibited the same trends. It would therefore be expected that, if the commercial suiting fabrics used in this study, were tested on a sweating manikin, similar trends would be observed as those found with the Permetest. This can be the topic for further research.

3.2.2.2 Permetest

The Permetest, at the Department of Polymer Science at the University of Stellenbosch, was used to test the fabrics for three comfort related properties, namely water vapour permeability, water vapour resistance and thermal resistance. These three comfort related properties represent the dependent variables of this study.

Before testing commenced, samples were conditioned for 24 hours in a laboratory at a temperature of 21ºC (±2°C) and 65% (±2%) humidity.

Three measurements were taken per fabric (also used by Oğlakcioğlu and Marmarali, 2007). One measurement consisted of 5 repeats, each on a different fabric specimen. The average, standard deviation and coefficient of variation were determined for each set of measurements.

3.2.2.3 Testing procedure for water vapour permeability and resistance

Before testing the water vapour permeability and resistance of the fabrics, the water reservoir of the Permetest was filled with water, and the wind speed was set to 1m/s. The procedure that was followed for determining the relative water vapour permeability and water vapour resistance on the Permetest was according to the guidelines provided in the instrument testing manual (Hes, 2009). Under isothermal conditions, relative water vapour permeability and resistance were determined as follows:

Calibration procedure:

1. Without a sample on the Permetest, press Reference Start on the computer and wait until steady state is achieved.
2. Insert blue calibration sample, press Sample Start on computer, wait until steady state is achieved.
3. Repeat until the water vapour resistance value lies between 4.8 and 5.2. If not, then press Calibrate on the computer and repeat steps 1 and 2, until a value between 4.8 and 5.2 is obtained.

Test procedure:

1. Without a sample on the Permetest, press Reference Start on the computer and wait until steady state is achieved.
2. Place sample on the measuring head of the Permetest, press Sample Start on the computer and wait until steady state is achieved.
3. Write down the values for relative water vapour permeability and water vapour resistance.

4. Repeat steps 1 to 3 five times on different samples each time
5. Refill the water reservoir of the Permetest regularly.

As discussed previously in the literature review, the relative water vapour permeability refers to the ability of a fabric to transport water vapour to the external environment; whereas, water vapour resistance is the resistance that a fabric has against the transmission of water vapour. The water vapour permeability of a fabric is particularly important in clothing, because if a garment is unable to transmit moisture vapour when the body perspires, the perspiration will not evaporate from the skin surface and can even wet the garment, resulting in severe discomfort. Therefore, Mehta (1984) and Kothari (2006) recommend that, in order for a garment to be classified 'breathable', and to transmit perspiration vapour, the water vapour resistance of the fabric should be as low as possible, and the water vapour permeability should be as high as possible.

3.2.2.4 Testing procedure for thermal resistance

Before testing the thermal resistance of the fabrics, the temperature gradient was set to 10°C and the wind speed was set to 2 m/s. The procedure followed in order to test the thermal resistance was according to the guidelines provided in the instrument testing manual (Hes, 2009). The procedure was as follows:

Calibration procedure:

1. Deselect Isothermal Mode on the computer.
2. Without a sample on the Permetest, press Reference Start on the computer and wait until steady state is achieved.
3. Insert the black calibration sample, press Sample Start on the computer and wait until steady state is achieved.
4. Repeat until the thermal resistance value equals 59. If not, press Calibrate on the computer and repeat steps 3 and 4, until a value of 59 is obtained.

Test procedure:

1. Without a sample on the Permetest, press Reference Start on the computer and wait until steady state is achieved.

2. Place sample on the measuring head of the Permetest, press Sample Start and wait until steady state is achieved.
3. Write down the value for thermal resistance.
4. Repeat steps 1 to 3 five times on different samples each time.

Thermal resistance, which refers to the resistance a fabric provides against the movement of heat, is significant in terms of the comfort related properties of fabrics due to it determining thermal comfort. The literature review identified that the thermal insulation that a fabric provides depends, to a large extent, on the thickness of the particular textile and the volume of air that is provided for the entrapment of air. Other external factors influencing thermal resistance is the design of garments, whether the design includes openings that will increase air movement, and as a result reducing thermal resistance.

3.2.3 Moisture permeability index

The moisture permeability index (i_m) for each fabric was calculated according to the following formula:

$$i_m = \frac{60.6\ R_{ct}}{R_t} \text{-------------------------} (3.1)$$

Where: R_t is moisture vapour permeability, and R_{ct} is the thermal resistance.

The permeability index changes the concept that clothing should keep the wearer warm to one that clothing should maintain a level of thermal equilibrium (Woodcock, 1962). Theoretically, the index can vary from 0 to 1; a fabric with a value of 0 is vapour impermeable; whereas a fabric with a value of 1, has both the thermal resistance and water vapour resistance of an air layer of the same thickness (Verdu *et al.,* 2009). Frydrych *et al.* (2002) comment that air permeability, which is influenced by fabric porosity and the cross-section and shape of the textile, will ultimately determine the thermal properties of a garment. Therefore, the moisture permeability index focuses on the thermophysiological comfort of clothing and fabrics. The moisture permeability index is one of the dependent variables in this study.

CHAPTER 4 : RESULTS AND DISCUSSION

Chapter 4 provides the results of the comfort related properties obtained on the Permetest. The chapter focuses on analysing and comparing the results through the use of multiple regression analysis, in order to identify and quantify the relationships between the dependent and independent variables.

4.1 Permetest results

Table 9 provides the data obtained on the Permetest, in terms of relative water vapour permeability, absolute water vapour resistance, and the thermal resistance for all of the fabrics (also see Appendices A, B, and C). The last column in Table 9 provides the moisture permeability index calculated for each fabric.

Table 9: Results of comfort related tests

	RWVP (%) P	CV% RWVP	AWVR (m^2Pa/W) R_t	CV% AWVP	TR (m^2K/W) R_{ct}	CV% TR	MP index i_m
A	53.7	1.4	2.6	3.8	15.1	2.4	0.35
B	52.9	1.9	2.6	4.4	14.1	5.7	0.33
C	54.8	3.8	2.5	8.0	14.8	6.1	0.36
D	54.9	2.6	2.5	2.3	15.1	6.2	0.37
E	56.1	6.3	2.7	3.7	18.9	4.8	0.42
F	59.0	3.4	2.4	4.2	15.7	3.0	0.40
G	56.5	2.5	2.5	2.3	20.3	6.2	0.49
H	55.7	3.1	2.4	4.7	14.2	5.2	0.36
I	56.5	0.3	2.7	3.7	18.7	4.8	0.42
J	52.1	2.3	2.9	5.2	18.1	4.4	0.38
K	55.2	7.2	3.7	5.4	17.0	6.3	0.28
L	49.9	0.5	3.3	4.7	18.3	4.6	0.34
M	56.5	4.7	2.8	7.5	20.7	2.3	0.45
N	48.4	7.5	3.7	7.2	18.5	4.9	0.30
O	54.8	5.5	2.8	4.2	14.4	1.8	0.31
P	53.5	5.6	3.0	5.1	17.5	2.6	0.35
Q	54.9	3.3	2.6	6.0	12.0	6.3	0.28
R	48.9	3.9	3.1	4.9	18.3	0.9	0.36
S	48.4	4.1	3.8	3.1	23.5	1.8	0.37
T	47.5	3.4	3.7	3.1	18.7	1.1	0.30
U	49.7	7.5	3.7	5.6	18.0	4.6	0.29
V	49.3	4.1	3.4	4.4	21.4	6.1	0.38
W	52.8	7.1	3.0	7.6	19.0	4.7	0.38
X	47.2	6.5	4.2	2.7	21.8	4.5	0.31
Y	45.1	5.6	4.6	4.6	21.2	2.6	0.28
Z	38.3	1.6	5.2	5.5	30.9	2.3	0.36

(RWVP = Relative water vapour permeability; AWVR = Absolute Water Vapour Resistance; TR = Thermal resistance; MP index = Moisture permeability index; CV% = Coefficient of variation percentage)

4.2 Pearson correlation matrix

Initially, the straightforward correlations (inter-correlations) between the various parameters (dependent and independent variables) were determined and presented in the form of a correlation matrix. A Pearson correlation matrix (Table 10) was drawn up in order to determine the strength and the direction of linear relationships, if any, between the dependent and independent variables.

The dependent variables of the study include the following:

A = Thermal Resistance

B = Absolute Water Vapour Resistance

C = Relative Water Vapour Permeability

D = Moisture Permeability Index

The independent variables include the following:

J = Fabric Thickness

K = Fabric Mass

L = Fabric Air Permeability

M = Fabric Density

It should be noted that L and M are not in the true sense independent variables, since L is itself a function of J and K, while M is simply K divided by J. Table 10 gives the correlation matrix for the group of 26 fabrics, in terms of the correlation coefficient r, which indicates the strength and direction of the linear relationship between the variables, as well as the coefficient of determination R^2. The higher the value of R^2, the greater (more significant) the linear relationship.

Table 10: Correlation matrix

r	K	J	L	M	B	C	A	D
K	1.000							
J	0.807	1.000						
L	-0.469	-0.071	1.000					
M	-0.305	-0.783	-0.310	1.000				
B	0.904	0.722	-0.482	-0.250	1.000			
C	-0.805	-0.635	0.487	0.203	-0.908	1.000		
A	0.695	0.781	-0.079	-0.488	0.771	-0.717	1.000	
D	-0.374	0.034	0.658	-0.342	-0.436	0.412	0.225	1.000
R^2	K	J	L	M	B	C	A	D
K	1.000							
J	0.652	1.000						
L	0.220	0.005	1.000					
M	0.093	0.613	0.096	1.000				
B	0.817	0.522	0.232	0.063	1.000			
C	0.648	0.403	0.238	0.041	0.824	1.000		
A	0.484	0.609	0.006	0.238	0.594	0.514	1.000	
D	0.140	0.001	0.434	0.117	0.190	0.169	0.051	1.000

$r > 0.261$ for significance at 95% confidence level 🟪

$r > 0.340$ for significance at 99% confidence level 🟩

$r > 0.426$ for significance at 99.9% confidence level 🟥

4.2.1 Correlations between independent variables

As could be expected, significant correlations exist between certain independent variables, such as fabric mass (K) and thickness (J), as well as between fabric density (M) and thickness (J). The correlation between fabric mass (K) and thickness (J) is relatively strong (R^2 = 0.652). The positive correlation indicates that an increase in fabric mass is associated with an increase in fabric thickness, as expected. The correlation between fabric density (M) and fabric thickness (J) is also relatively strong (R^2 = 0.613). The relatively strong correlation between fabric density and thickness indicates that, since the sign of r is negative, an increase in fabric density is associated with a decrease in fabric thickness, which could be expected. Air permeability (L) was significantly correlated with fabric mass (K) and density (M), decreasing with an increase in either of the variables, which is as expected.

These correlations must also be taken into consideration in the following analyses. For example, even though thermal resistance is largely determined by fabric thickness, the strong correlation between fabric thickness and mass must be taken into consideration due to the effect of fabric mass on thermal resistance possibly manifesting itself in the effect of fabric thickness.

4.2.2 Correlations between dependent variables

The most significant correlation (R^2 = 0.824) between the dependent variables, is between relative water vapour permeability (C) and water vapour resistance (B), an increase in water vapour permeability being associated with a decrease in water vapour resistance (B), as could be expected.

There is also a moderately strong correlation (R^2 = 0.594) between thermal resistance (A) and water vapour resistance (B), an increase in thermal resistance being associated with an increase in water vapour resistance (B) and with a decrease in relative water vapour permeability (C).

The moisture permeability index (D) was significantly, but not strongly, correlated with water vapour resistance (B) and water vapour permeability (C).

4.3 Regression analysis

Regression analysis is useful in order to determine and quantify the relationship between the dependent and independent variables. Linear regressions are used to determine the linear relationship between each dependent variable and each independent variable in turn, whereas multi-linear and multi-quadratic analyses are used to establish and quantify the relationship between one dependent variable and multiple independent variables simultaneously, also including the effect of interactions. This is particularly important, when the experimental design is such that each independent variable cannot be varied completely independently of the other. Multiple regression analysis also provides a measure of the magnitude of the various effects and the relative importance of the various independent variables, in terms of explaining changes in the dependent variable.

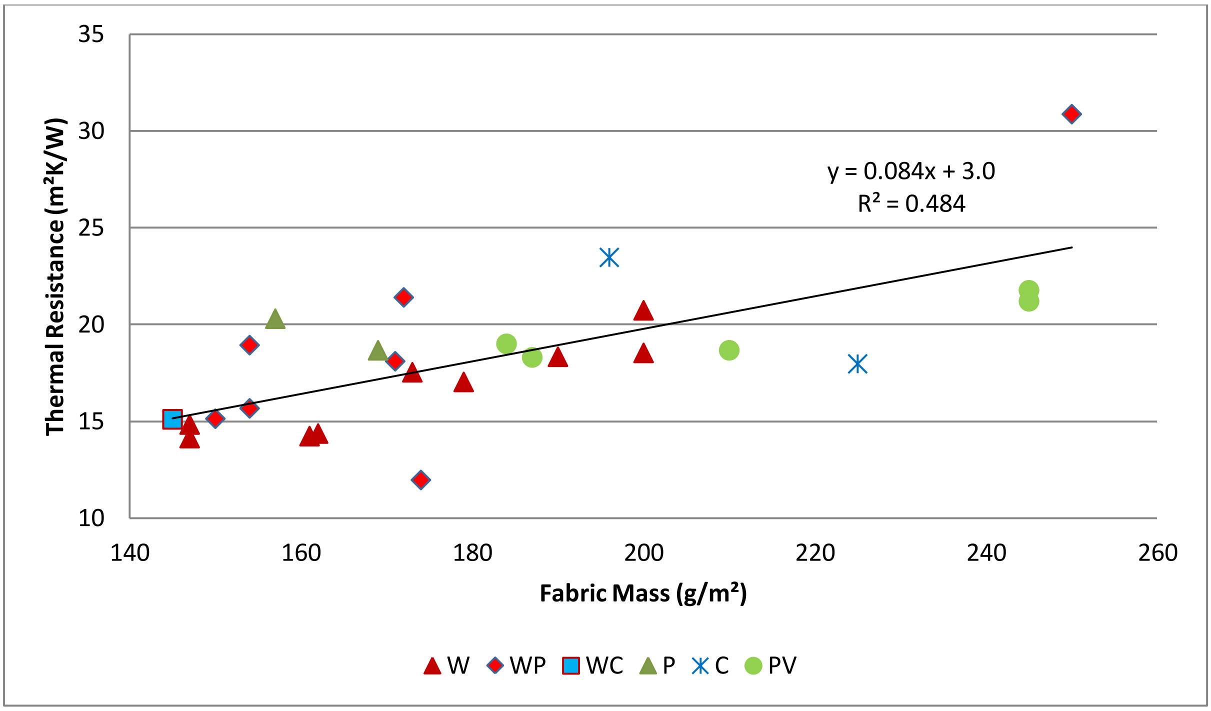
4.3.1 Linear regression analysis

Initially, linear regressions ($y = b_0 + b_1x_1$) were carried out to determine and quantify the individual effects of the two main independent variables, namely fabric mass and thickness, respectively, on the dependent variables, and to establish the empirical relationship (regression equations) in each case. Several graphs are provided in support of the analysis. Where relevant, the results are compared to those obtained in previous studies.

It is important to mention at the outset, that the effects of fibre type and blend, as well as of fabric structure, will not be discussed here, but will be discussed later under the sections dealing with the multi-linear and multi-quadratic analyses.

4.3.1.1 Effect of fabric mass

In Figure 31, thermal resistance has been plotted against fabric mass, with the linear regression line superimposed. Figure 31 illustrates that, as expected, there is a trend for thermal resistance to increase with an increase in fabric mass. This can be partly attributed to the fact that, as the fabric mass increases, the fabric thickness generally also increases, both of which enable the entrapment of more air within the fabric, which in turn improves the insulating capability of the fabric, due to the low thermal conductivity of the entrapped air. Das and Biswas (2011) observed a similar result, where the thermal resistance of multilayered fabrics increased with an increase in the mass per unit area. It is also apparent that the various points lie fairly widely scattered, which will be addressed in the multi-regression analyses later.



W = wool, WP = wool/polyester, WC = wool/cotton, P = polyester, C = cotton, and PV = polyester/viscose

Figure 31: Thermal resistance *versus* fabric mass

In Figure 32, water vapour resistance (B) has been plotted against fabric mass, with the linear regression line once again superimposed. It shows that there is a very strong relationship (R^2 = 0.817) between water vapour resistance and fabric mass, an increase in fabric mass causing in an increase in the resistance of fabrics to water vapour transmission. This is as one would expect, since heavier fabrics present a greater barrier to water vapour transfer, limiting its transport to the outside environment.

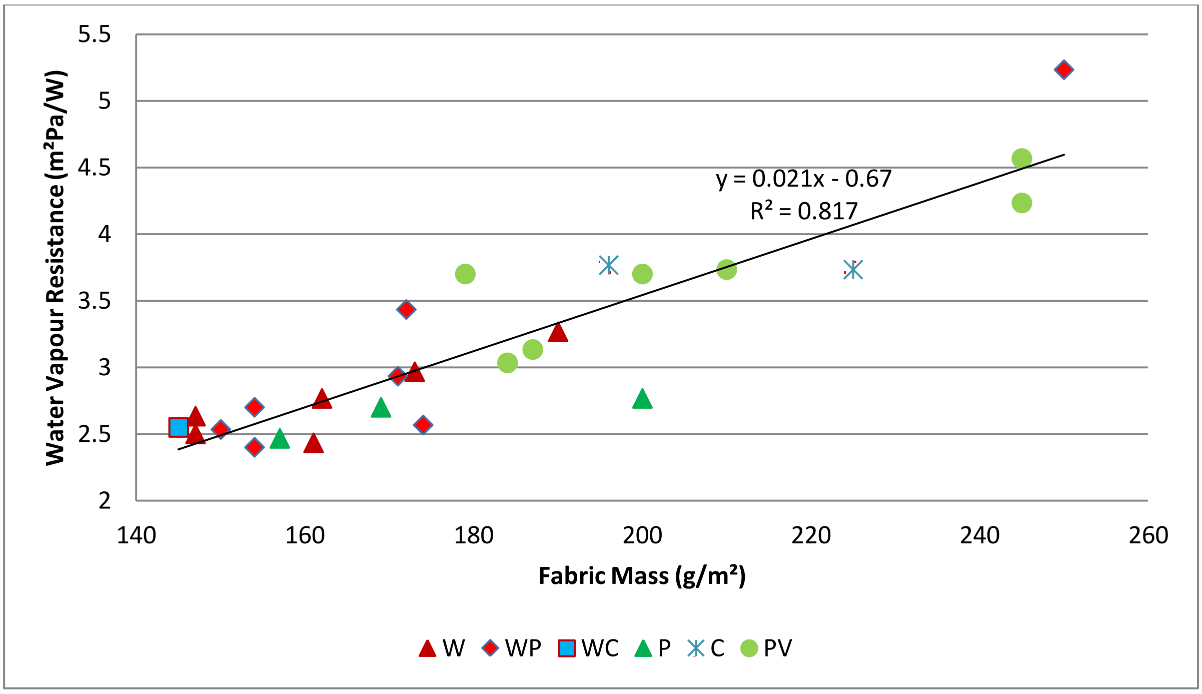


Figure 32: Water vapour resistance *versus* fabric mass

The relative water vapour permeability (C) has been plotted against fabric mass in Figure 33, with the linear regression line superimposed. Figure 33 shows that there is a moderately strong negative relationship between the relative water vapour permeability and fabric mass. The negative relationship is as would be expected, due to the inverse relationship between water vapour resistance and water vapour permeability, and the positive relationship between water vapour resistance and fabric mass. When fabric mass increases, it limits the vapour diffusivity of the fabric, as also discussed previously, and as a result reduces the water vapour permeability of the fabric. The same trend was observed by Boguslawska-Bączek and Hes (2013), as well as Das and Biswas (2011), in terms of the relationship between fabric mass and water vapour permeability and resistance, respectively.

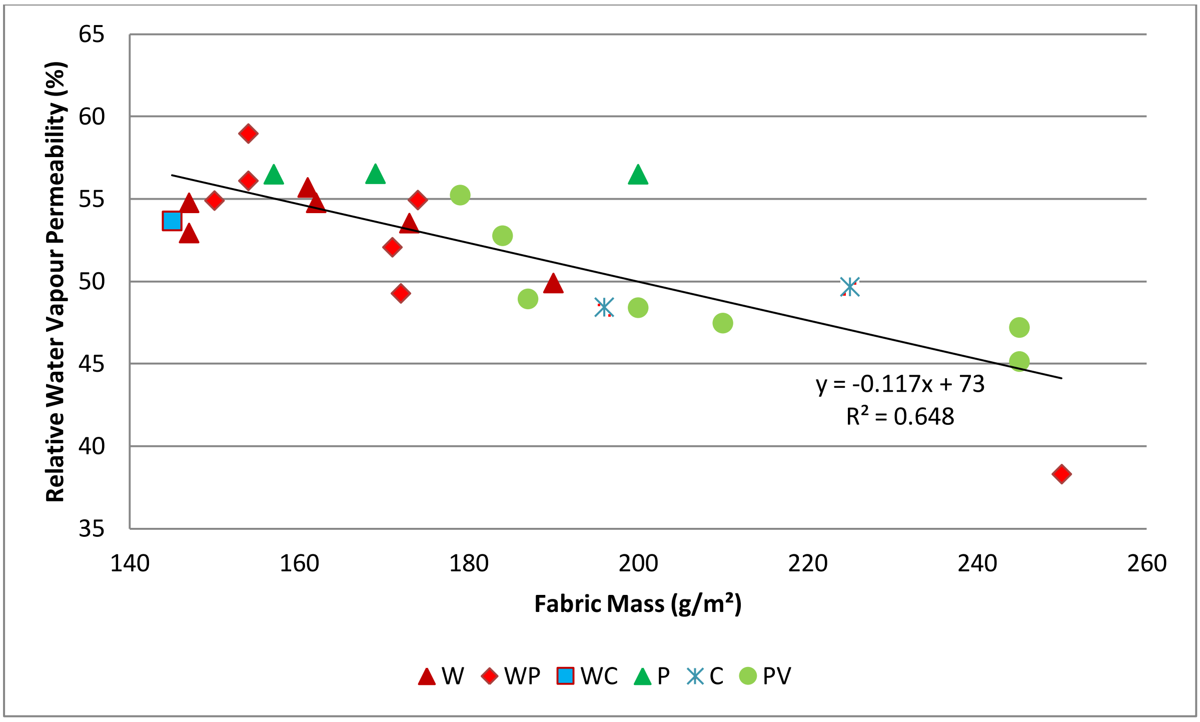


Figure 33: Relative water vapour permeability *versus* fabric mass

4.3.1.2 Effect of fabric thickness

Figure 34 shows thermal resistance plotted against fabric thickness, with the linear regression line superimposed. It is apparent that there is a linear relationship, with a moderately strong correlation (R^2 = 0.609) between thermal resistance and fabric thickness. It is widely accepted that entrapped air plays a dominant role in fabric thermal resistance, the ability of the fabric to trap air increasing with an increase in fabric thickness, all other factors being constant. A thicker fabric provides more volume and air spaces for the entrapment of air, which produces higher thermal insulation. This result is in line with that of previous studies, where a similar relationship was found between fabric thickness and thermal resistance (Chidambaram *et al.*, 2011, and Senthilkumar *et al.*, 2010).

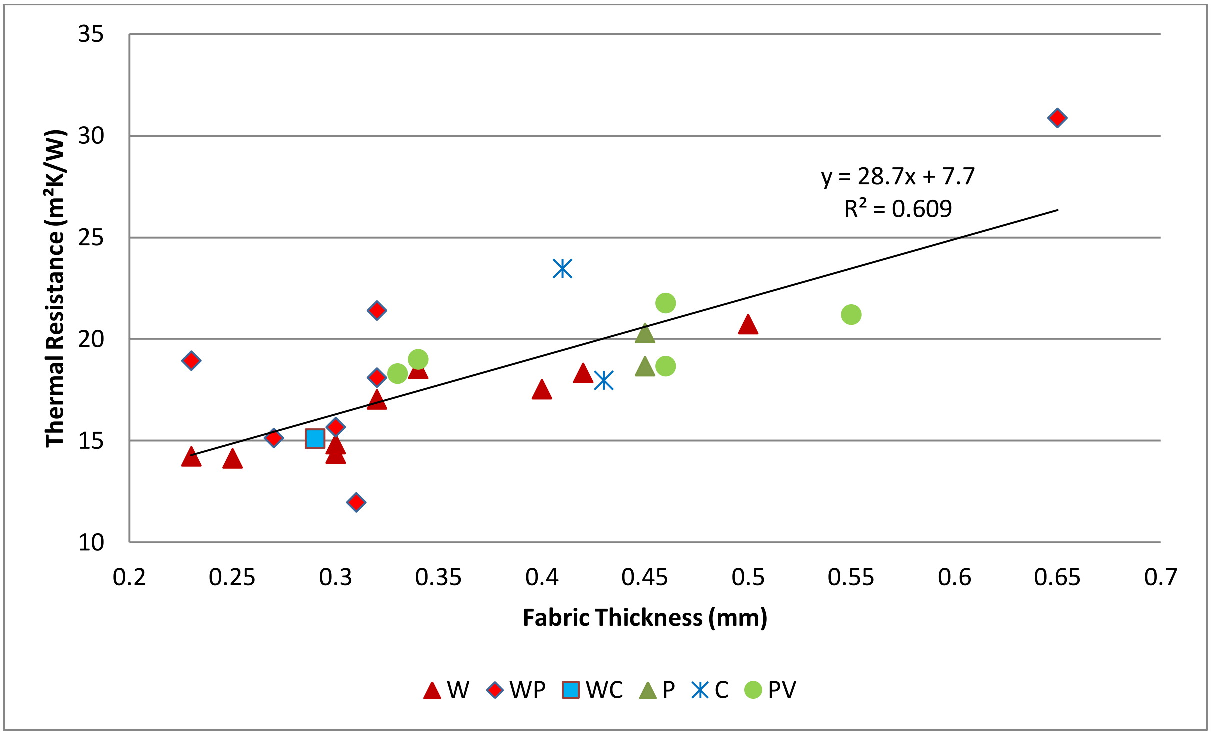


Figure 34: Thermal resistance *versus* fabric thickness

Water vapour resistance has been plotted against fabric thickness in Figure 35, from which it can be seen that, although there is a relationship between water vapour resistance and fabric thickness, the points lie fairly widely scattered, as could also be deduced from the correlation coefficient (R^2 = 0.522). It is evident that water vapour resistance tends to increase with an increase in fabric thickness, thicker fabrics limiting diffusivity, as also reported by Mehta (1984). It is important to note, however, that fabric thickness is correlated with fabric mass, which could play a role here, an aspect which will be addressed by the multi-regression analyses.

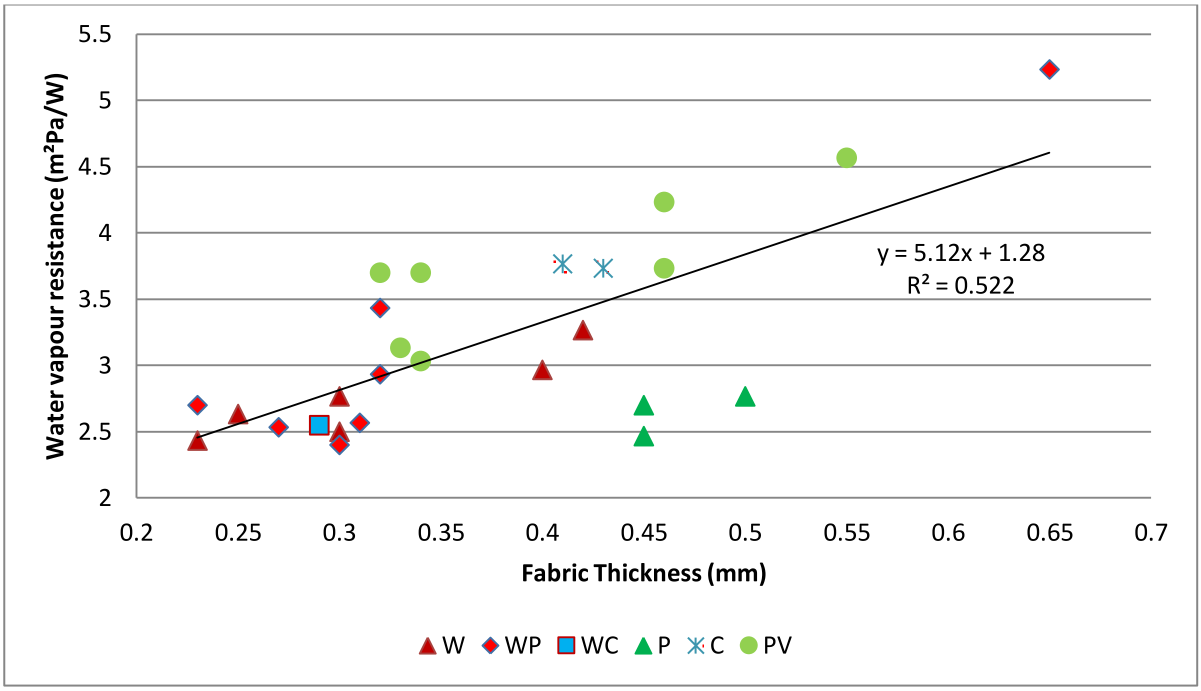


Figure 35: Water vapour resistance *versus* fabric thickness

Relative water vapour permeability has been plotted against fabric thickness in Figure 36, with the linear regression line superimposed. As can be seen from Figure 36 and Table 10, that there is a significant, though relatively poor, negative relationship (R^2 = 0.403) between relative water vapour permeability and fabric thickness. As already illustrated in Figure 34, thicker fabrics tend to limit water vapour transmission, causing them to have a poor water vapour permeability compared to thinner fabrics. The same trend was observed by Das and Kothari (2012), where thicker 100% cotton fabrics had a poor water vapour permeability compared to the thinner 100% cotton fabrics.

Figure 35 and Figure 36 illustrate the expected trend, that the lower the relative water vapour permeability, the higher the water vapour resistance tends to be, and *vice versa.*

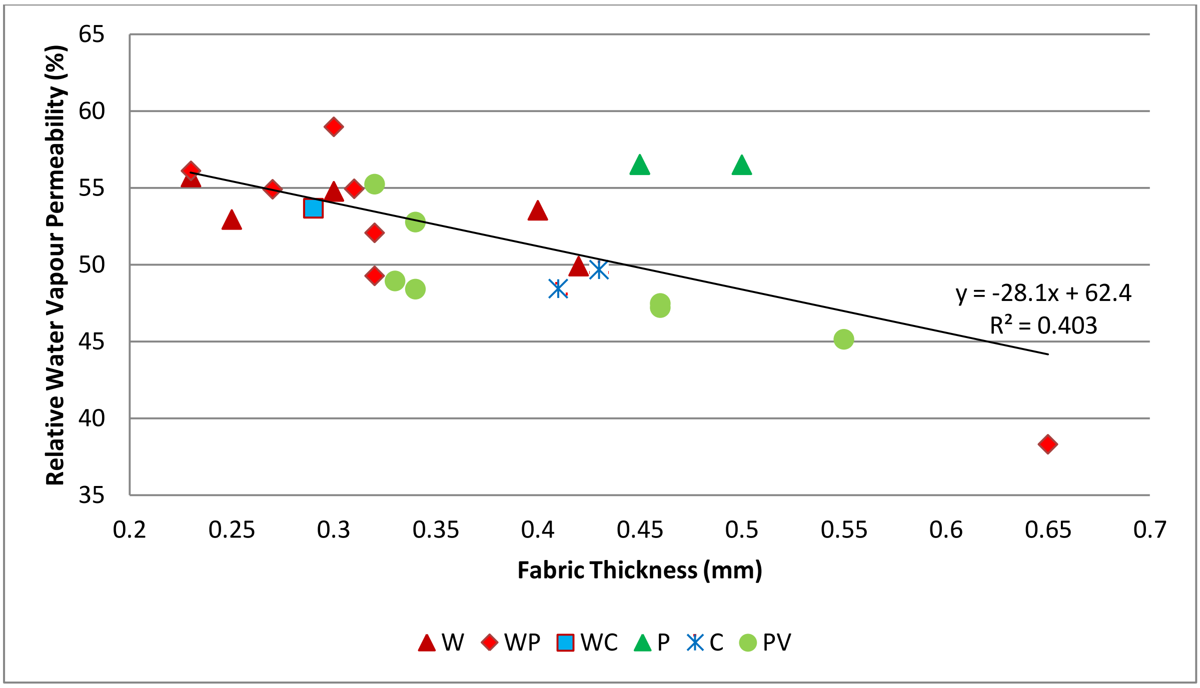


Figure 36: Relative water vapour permeability *versus* fabric thickness

4.3.1.3 Effect of air permeability

Air permeability correlated the best (R^2 = 0.434) with the moisture permeability index, although the correlation was not very high. Air permeability has been plotted against the moisture permeability index in Figure 37, with the linear regression line superimposed. Figure 37 illustrates that there is a trend for the moisture permeability index of the fabrics to increase with an increase in air permeability, as could be expected.

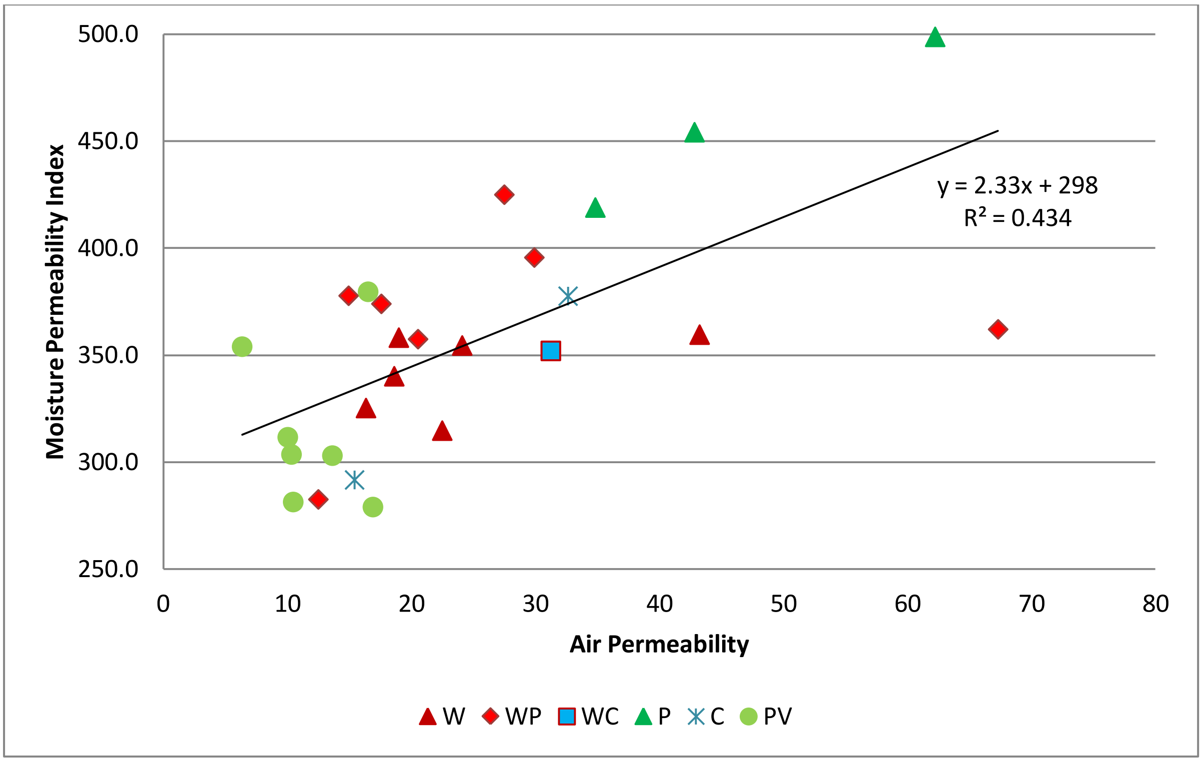


Figure 37: Moisture permeability index *versus* air permeability

4.3.1.4 Summary

According to the correlation matrix, linear regression analysis results and corresponding graphs discussed in this section (4.3.1), the two variables that correlated best with the comfort related properties, namely water vapour resistance, relative water vapour permeability and thermal resistance, were fabric mass and thickness. Fabric mass correlated best with water vapour resistance and permeability, whereas fabric thickness correlated best with thermal resistance. Both thermal resistance (insulation) and water vapour impermeability (resistance) tended to increase linearly with an increase in either fabric thickness or mass, or both. These findings are in line with those expected from theoretical considerations and previous empirical studies.

The analysis also highlighted the correlations between the various independent variables, as well as between the various dependent variables. The most significant correlations between the independent variables were between fabric mass and thickness, as well as between fabric density and fabric thickness. In terms of the correlations between the dependent variables, the highest correlations were water vapour permeability and resistance, there being a moderate correlation between water vapour transmission and thermal resistance. The indirect influence of these correlations, between the dependent variables themselves, and between the ibdependent variables themselves, must be considered when interpreting the results and trends observed in this section, but will be further explored in the following section.

The correlation matrix also highlighted the fact that air permeability and the comfort related properties were not highly correlated, the former correlating best with the moisture permeability index. Fabric density did not correlate well with any of the comfort related properties.

4.4 Multi-linear and multi-quadratic regression analysis

Multi-linear and multi-quadratic regression analyses were used to isolate and quantify the effects of the various independent variables on the comfort related properties by simultaneously incorporating the various independent variables in the analysis. The analysis was carried out using the step-wise forward procedure, statistical significance being tested at the 95% confidence level. In all cases, each of the dependent variables (A, B, C and D) was analysed against fabric mass, thickness, density and air permeability.

The following model (4-1) was used in the multi-linear regression analysis:

$$y = b_0 + b_1x_1 + b_2x_2 + \ldots b_px_p \text{ \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ } (4\text{-}1)$$

Where: y = dependent variable

b_0 = intercept

$x_{1,}x_2 \ldots x_p$ = values of independent variables (namely fabric mass, thickness, density and air permeability)

$b_1, b_2 \ldots b_p$ = regression slopes/coefficients

For the multi-quadratic regression analysis, the following model (4-2) was used:

$$y = b_0 + b_1x_1^2 + b_2x_2^2 + b_3x_1x_2 + b_4x_1 + b_5x_2 \ldots. b_px_p^2 + b_px_px_q + b_px_p \text{ \_\_\_\_\_ } (4\text{-}2)$$

4.4.1 Thermal resistance

4.4.1.1 Effect of fabric parameters

The following best fit multi-linear regression equation was obtained for thermal resistance (A):

$$A\ (m^2K/W) = -12.4+67.3*J+0.035*M-0.066*K \quad (4\text{-}3)$$

Contribution to R^2 x 100(%) = 60.9 3.9 2.1 =66.9%

Where: fabric thickness J (in mm), is the most significant independent variable, with fabric density, M (in kg/m^3), and mass K (in g/m^2) the only other variables making a significant, though small, contribution to the regression equation. It is evident from equation 4-3 that J is the independent variable that makes the largest contribution, by far, towards R^2, and has the most significant effect on fabric thermal resistance, thermal resistance increasing with an increased fabric thickness.

In Figure 38, the predicted thermal resistance values, based upon equation 4-3, have been plotted against the actual values, with the corresponding regression line superimposed, as well as the 1:1 line. Approximately 67% of the variation in thermal resistance can be explained by a variation in fabric thickness, density and mass, with fabric thickness being the most significant by far, contributing 61% to the 67%. This is largely in line with the results of previous research, namely that the main factor determining thermal insulation is fabric thickness, thermal resistance (insulation) increasing with fabric thickness due to the associated increase in the entrapment of air between the yarns and fibres in the fabric. Comparing the R^2 obtained here (0.669) with that obtained earlier (0.609) between thermal resistance and fabric thickness on its own, shows that the inclusion of fabric density and mass, only increased the overall correlation (and fit) marginally, though statistically significant at the 95% level. The small, but significant increase in thermal resistance, with an increase in fabric density is not easy to explain, but may be due to denser fabrics, at a constant fabric thickness, trapping the air more effectively, i.e. limiting the movement of the air, and therefore loss of heat by convection. The negative effect of an increase in fabric mass (K) on thermal resistance is equally difficult to explain, but may be an artefact of the fabric sample population used in the study.

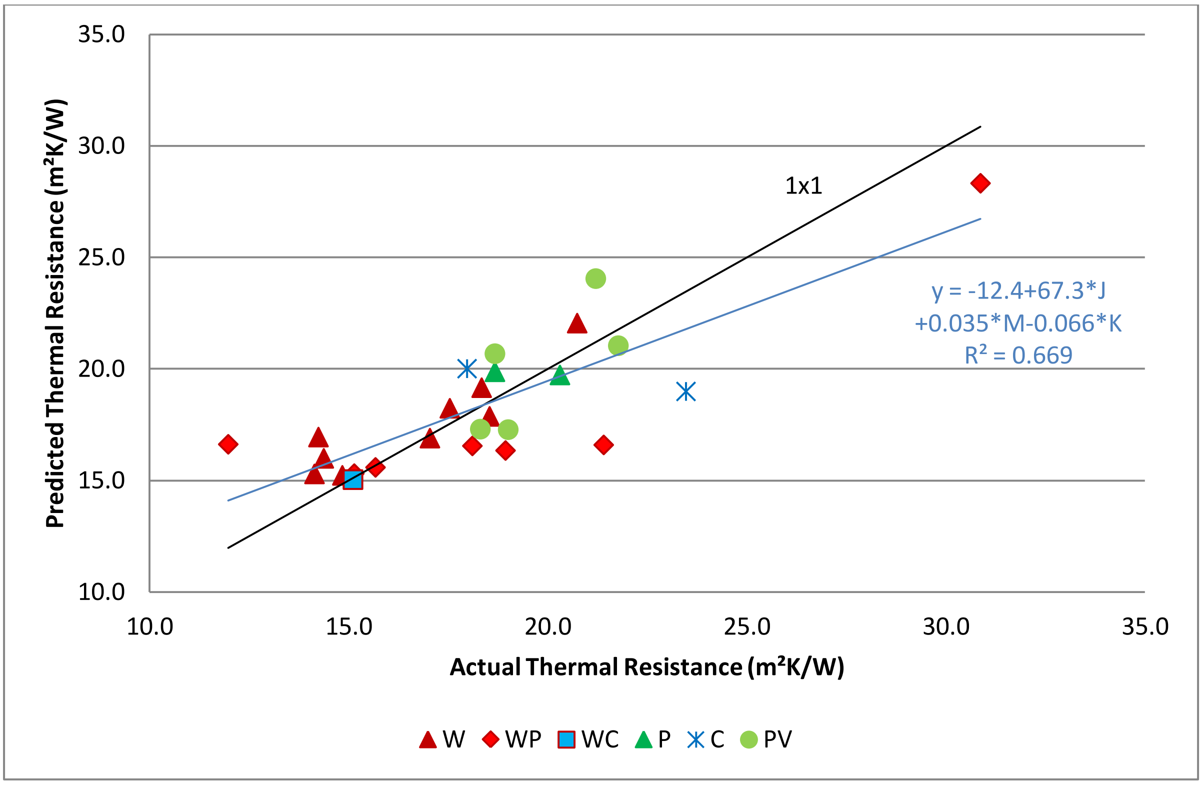


Figure 38: Predicted *versus* actual thermal resistance (multi-linear equation)

Multi-quadratic regression analysis yielded the following best fit regression equation for thermal resistance (A):

$$A\ (m^2K/W) = 9.49+42.5J^2+9.6X10^{-6}M^2 \quad (4\text{-}4)$$

Contribution to R^2 x 100(%) = 65 2.4 =67.4%

It is apparent that the multi-quadratic regression yielded only a very slight, and non-significant, improvement in the multiple correlation coefficient (R^2 = 0.674 vs 0.669) and percentage fit (67.4 vs 66.9%), compared to the multi-linear regression. Once again, the fabric thickness (J) contributed the most by far, to the correlation and fit. Fabric density (M) once again makes a small contribution, as was the case in the multi-linear regression. In Figure 39, the predicted thermal resistance values, based upon equation 4-4, have been plotted against the actual values, with the corresponding regression and 1:1 lines superimposed. The squared terms in the multi-quadratic regression equation indicate a possible slight curvilinear, as opposed to linear, relationship between thermal resistance and fabric thickness (J) and density (M), but further work, on a larger data set, is required to verify this.

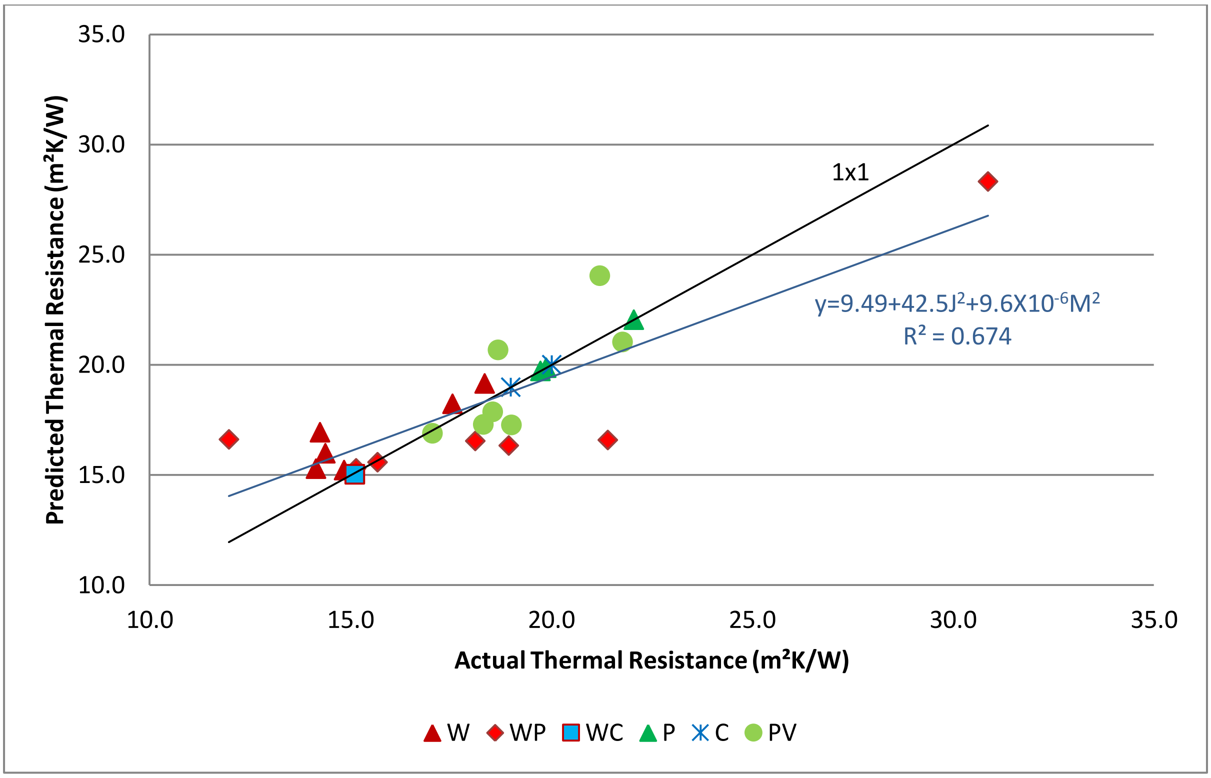


Figure 39: Predicted *versus* actual thermal resistance (multi-quadratic regression)

4.4.1.2 Impact of fibre type and blend on thermal resistance

Up to this point, the possible effects of fibre type and blend, as well as of fabric structure, have been ignored, since it was essential that the effects of the fabric structural parameters, mainly fabric thickness and mass, first be established and quantified, so that they can be allowed for when trying to establish what effect, if any, fibre type and blend and fabric structure have on the various comfort related properties. By deriving the best fit multi-linear and multi-quadratic regression equations, involving the statistically significant fabric parameters, it becomes possible to eliminate (or allow for) the effects of the latter, and to plot the predicted versus the actual values, distinguishing between the different fibre types and blends. If fibre type or blend behaves consistently or generally different to what is predicted, by lying consistently, or mostly, above or below the regression line, for a particular fabric comfort related property, one can conclude that fibre type or blend has an effect up and above the effect of any change in a fabric parameter perhaps associated with that particular fibre or blend.

The discussion which follows hereafter, for all the comfort related properties, involving fibre type or blend, and later also fabric structure, therefore focuses purely on whether the points representing a particular fibre type or blend, or fabric structure, mostly or consistently lie below or above the best fit multi-linear or multi-quadratic regression line in each case. Considering, therefore, Figures 31, 34, 38 and 39, it is clear that no particular fibre type or blend lies consistently above or below the regression lines. From this one can conclude that, in terms of fabric thermal resistance, none of the fibre types of blends behave consistently different to the others, once one allows for differences in the fabric structural parameters, such as mass and/or thickness, the respective points lying scattered around the regression line. These findings are largely in line with those of Gericke and Van der Pol (2010). Other studies, such as by Das and Biswas (2011), Nayak *et al.* (2009) and Tyagi *et al.* (2004) in which an effect of fibre type or blend on thermal resistance was observed, may not have taken into consideration possible associated changes in fabric thickness, mass, etc.

Although it can be argued, that a particular fibre, such as wool, may produce a thicker or bulkier fabric due, for example, to its crimpiness, and therefore to better thermal resistance, the counter argument based upon this study, is that by increasing the crimp of another fibre, for example a man-made fibre, a similar result can be obtained. Hence, the difference cannot be attributed to any intrinsic characteristic of the fibre structure *per sé.*

4.4.1.3 Impact of fabric structure on thermal resistance

The results of the multi-quadratic regression analysis were used for investigating the impact of fabric structure on the comfort related properties, due to it yielding a slightly higher correlation coefficient (R^2 = 0.674) compared to the multi-linear regression. Applying the same reasoning, as for fibre type and blend, to fabric structure, as identified and plotted in Figure 40, for fabric thermal resistance, leads one to the conclusion that if fabric mass and thickness are constant (the same), then the three fabric structures will have a similar fabric thermal resistance. This is based upon the fact that not one of the three fabric structures lie consistently above or below the regression line.

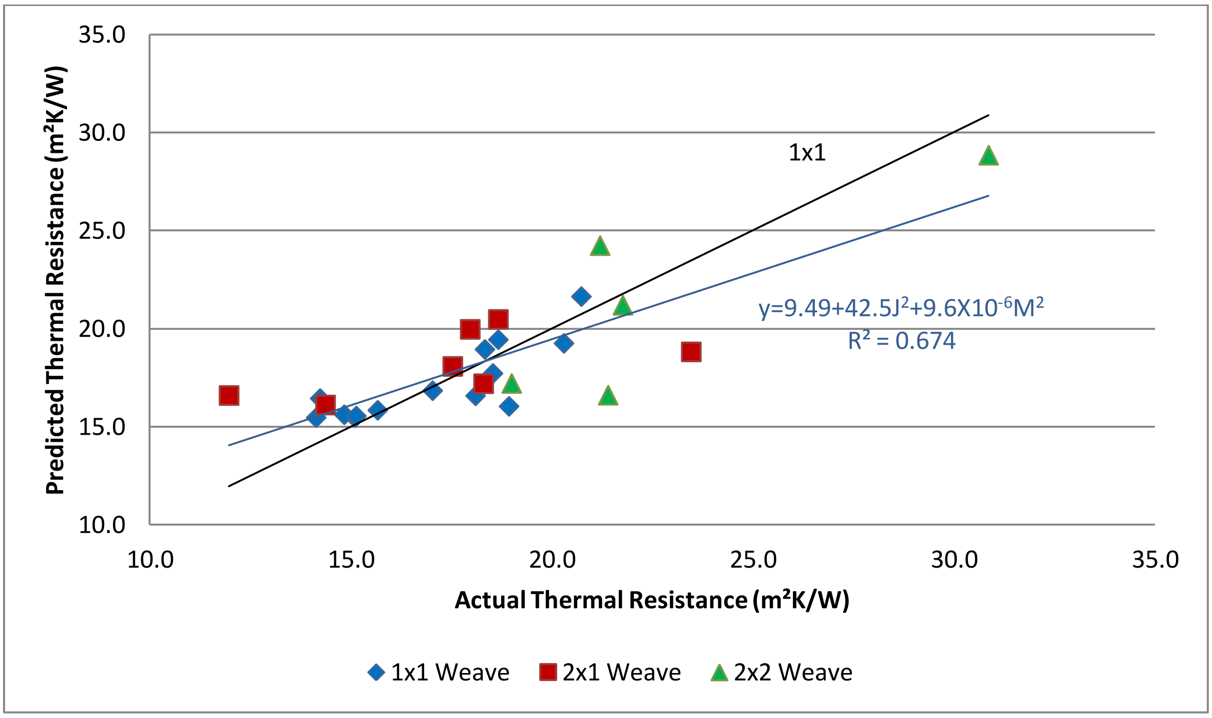


Figure 40: Predicted *versus* actual thermal resistance (multi-quadratic regression)

4.4.2 Water vapour resistance

4.4.2.1 Effect of fabric parameters

The best fit multi-linear equation for absolute water vapour resistance (B) is shown in equation 4-5:

$$B\ (m^2Pa/W) = -0.672+0.021*K \qquad (4\text{-}5)$$

Contribution to R^2 x 100(%) = 81.74 =81.7%

The above equation shows that only fabric mass (K) has a statistically significant effect on water vapour resistance, giving an R^2 x 100 of 81.7%, none of the other independent variables having a statistically significant effect. Therefore, approximately 82% of the observed variation in water vapour resistance can be explained by the variation in fabric mass (K), water vapour resistance increasing with an increase in fabric mass, which is as expected. Predicted versus actual water vapour resistance has been plotted in Figure 41, with the multi-linear regression and 1x1 lines superimposed.

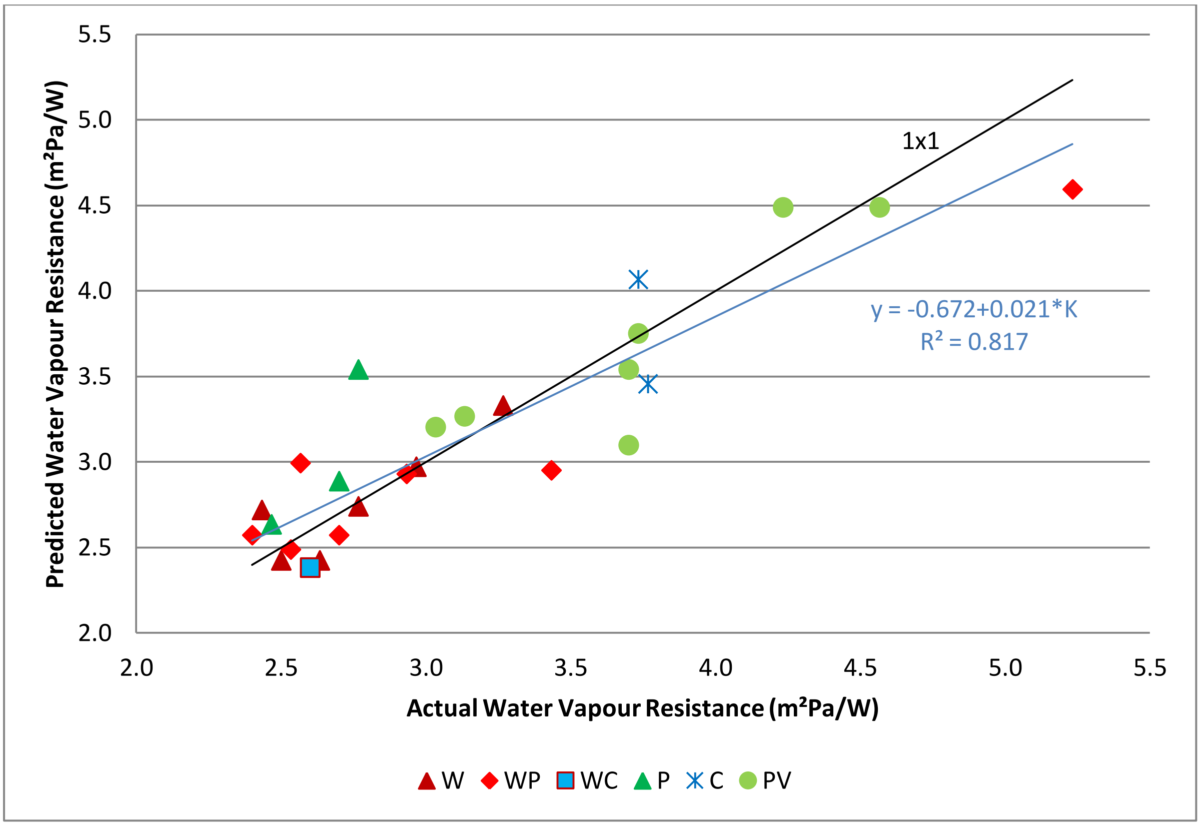


Figure 41: Predicted *versus* actual water vapour resistance (multi-linear equation)

The following best fit multi-quadratic regression equation was obtained:

$$B\ (m^2Pa/W) = 1.60+3.4X10^{-5}K^2-0.0757*L*J+4.31J^2+0.0179*L \_\_\_ (4\text{-}6)$$

Contribution to R^2 x 100(%) = 82.8 0.9 1.4 1.0 = 86.1%

The multi-quadratic equation (4-6) provided a slightly better fit than the multi-linear equation (4-5), but contained three more terms, and is therefore much more difficult to interpret, particularly considering the interaction term and also the very small contributions of the additional terms to the fit. In the multi-linear regression analyses, only the fabric mass emerged as statistically significant, whereas in the multi-quadratic analyses, the independent variables L (air permeability) and J (fabric thickness) also emerged as statistically significant, although their contributions to the overall fit were very small, 3.3% versus the 82.8% of fabric mass. The high R^2 of equation 4-6 indicates it can provide a fairly accurate prediction. In Figure 42, the predicted values, based upon equation 4-6, have been plotted against the actual values, with the corresponding regression and 1:1 lines superimposed.

The quadratic term for fabric mass (K), in equation 4-6, indicates the possibility of a slight curvature in the relationship between water vapour resistance and fabric mass, but further work, on a larger sample set, is required to verify this.

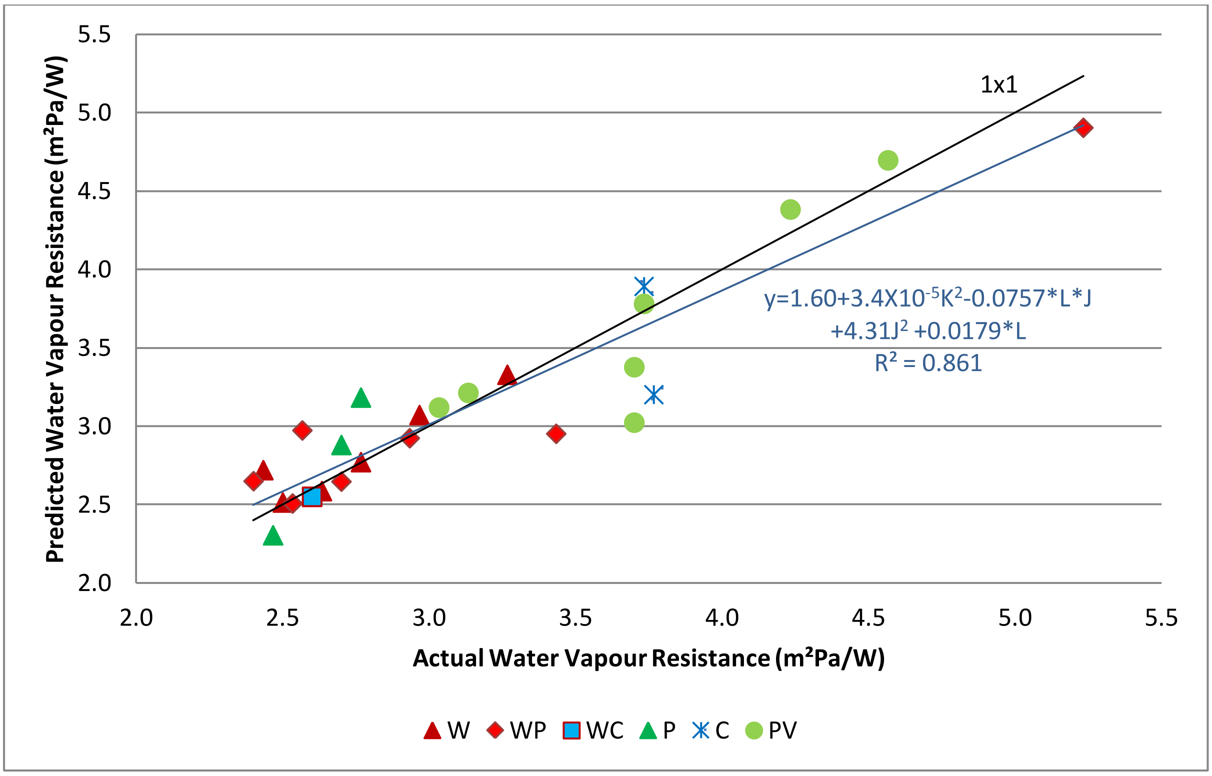


Figure 42: Predicted *versus* actual water vapour resistance (multi-quadratic regression)

4.4.2.2 Impact of fibre type and blend on water vapour resistance

Applying the same reasoning as that for thermal resistance, namely whether or not points representing a particular fibre type or blend lie mostly or consistently below or above the regression line, allows one to determine whether in fact a fibre type or blend behaves differently to the others i.e. whether fibre type or blend has an effect which cannot be explained in terms of the associated fabric parameters.

From Figures 41 and 42, it is evident that there is no consistency in the positions of the different fibre types and blends relative to the regression line, they generally lying randomly above and below the regression line, indicating that fibre type or blend *per sé* did not have a consistent effect on water vapour resistance.

4.4.2.3 Impact of fabric structure on water vapour resistance

Again applying the same reasoning to fabric structure, as to fibre type and blend, one can determine whether fabric structure *per sé,* as opposed to fabric mass and thickness, plays a role in determining fabric water vapour resistance. As can be seen from Figure 43, the points representing each of the three fabric structures, largely lie randomly spread around the regression line. From this it may be concluded that structure *per sé,* did not have an influence on the water vapour resistance of the fabrics. It appears that, only insofar as fabric structure affects fabric parameters, such as thickness and mass, will it affect water vapour resistance. This once again shows that water vapour resistance is mainly, if not solely, determined by the measureable fabric properties, such as mass and thickness, and to a lesser extent by air permeability, with fabric structure playing a role only insofar as it affects these fabric properties.

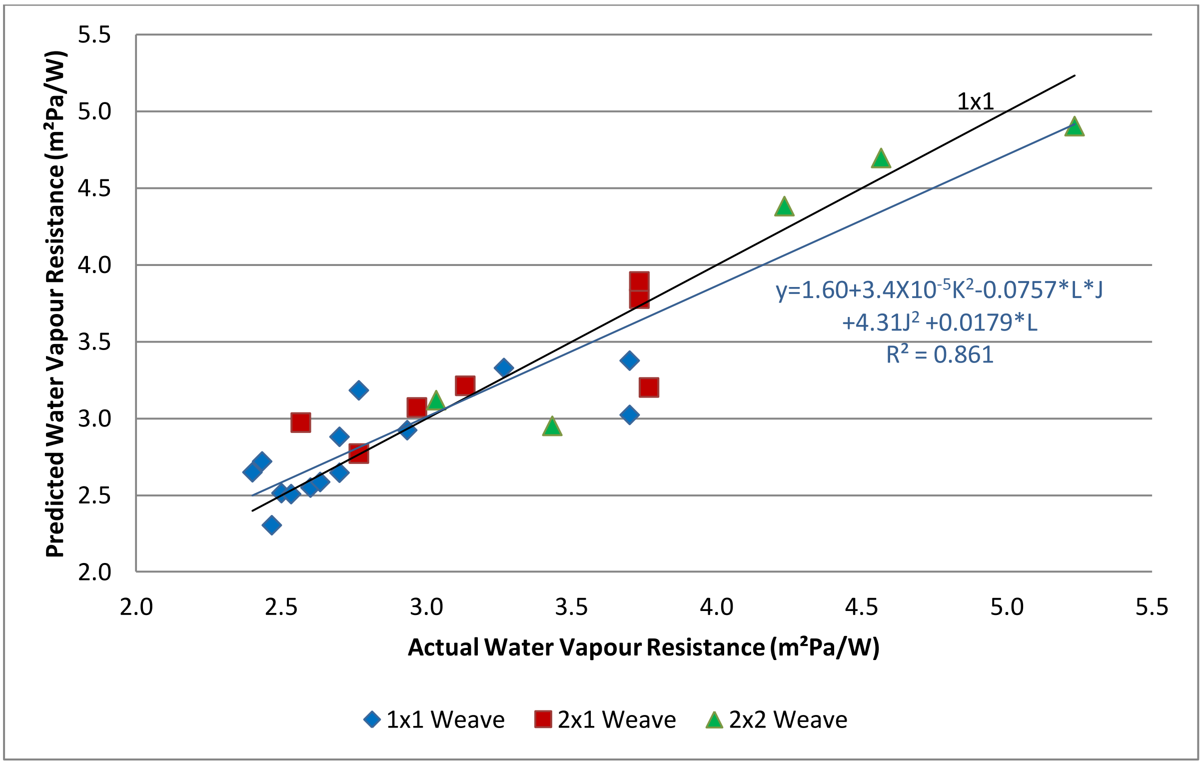


Figure 43: Predicted *versus* actual water vapour resistance (multi-quadratic regression)

4.4.3 Relative water vapour permeability

4.4.3.1 Effect of fabric parameters

The following best fit multi-linear equation was obtained for relative water vapour permeability (C):

$$C\ (\%) = 70.6-0.108*K+0.042*L \qquad (4\text{-}7)$$

Contribution to R^2 x 100(%) = 64.8 1.5 = 66.3%

It is evident from equation 4-7, that fabric mass (K) plays the dominant role in determining relative water vapour permeability (C), with fabric air permeability (L) playing only a very small role. Just over 66% of the observed variation in the relative water vapour permeability can be explained by fabric mass (K) and air permeability (L), the latter only contributing 1.5% to the fit. The predicted *versus* actual values have been plotted in Figure 44, with the best fit multi-linear regression line, as well as the 1:1 line superimposed. It is evident from the scatter of the points in Figure 44 and the percentage fit (R^2 x 100=66.3%), that the multi-linear regression equation is only moderately reliable in predicting the relative water vapour permeability.

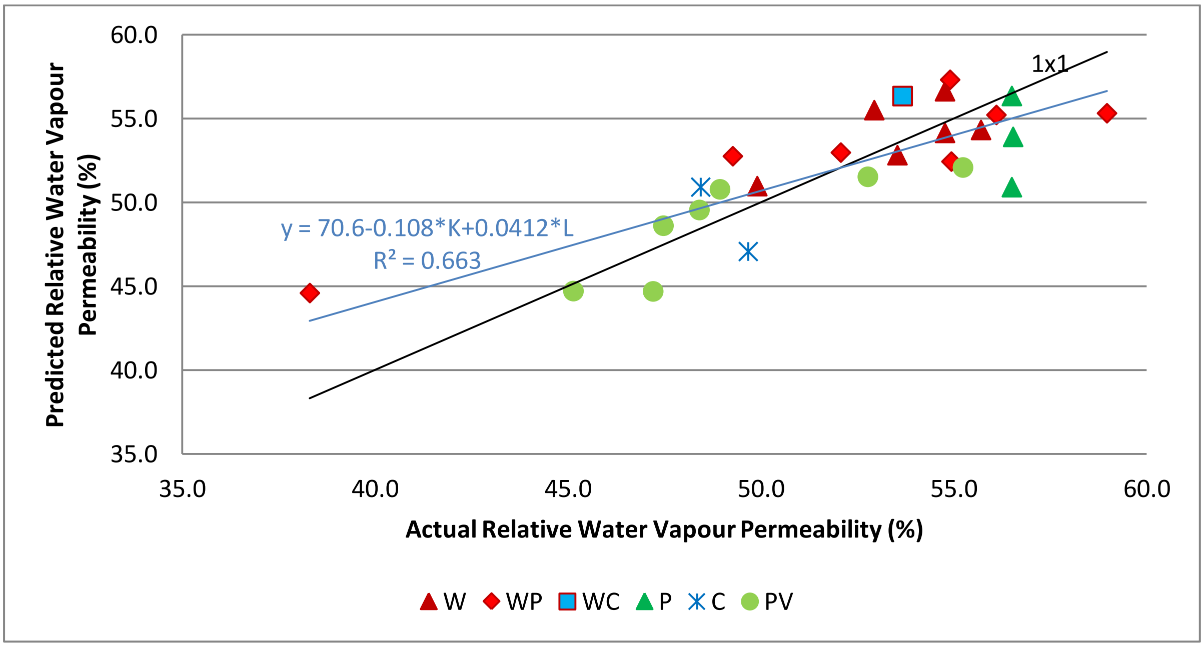


Figure 44: Predicted *versus* actual relative water vapour permeability (multi-linear equation)

The following best fit multi-quadratic linear regression equation was obtained for relative water vapour permeability (C):

$$C\ (\%) \quad = \quad 56.0-4.8X10^{-5}K^{2}+0.781*L*J-50.1J^{2}-0.0024\ L^{2}\_\_\_(4\text{-}8)$$

Contribution to R^2 x 100(%) = 66.2 2.3 3.6 4.5 = 76.6%

Comparing equation 4-7 and 4-8, it can be seen that the multi-quadratic analysis increased the percentage fit, by introducing the squared and interaction terms, as well as by including an additional parameter (J). Therefore, equation 4-8 is more reliable for prediction purposes than equation 4-7. It is, however, a more complex equation and not easy to interpret. Furthermore, the contributions of each of the additional terms are small, and their significance could, in some cases, be an artefact of this particular fabric and data set. Further work, on a much larger number and range of fabrics, is necessary to confirm the validity of equation 4-8. In Figure 45, the predicted values, based upon equation 4-8, have been plotted against the actual values, with the corresponding regression line as well as the 1:1 line superimposed.

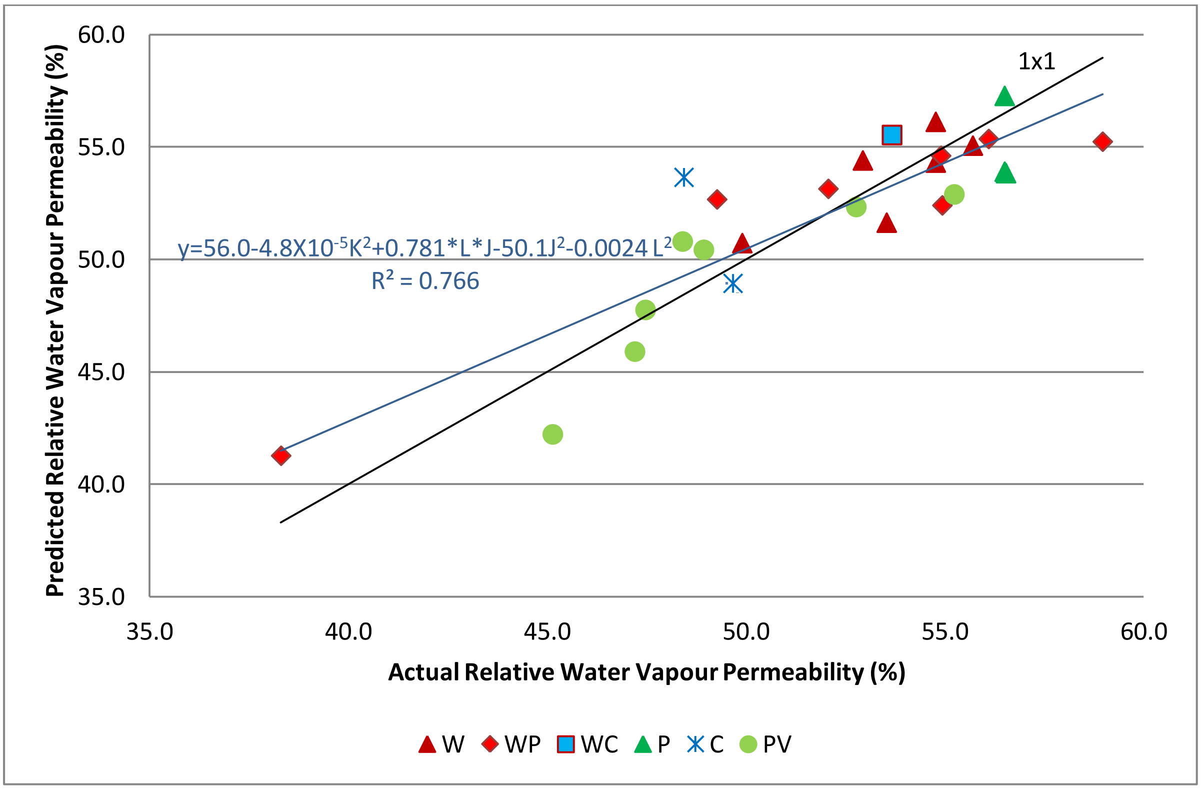


Figure 45: Predicted *versus* actual relative water vapour permeability (multi-quadratic regression)

4.4.3.2 Impact of fibre type and blend on water vapour permeability

Using the same reasoning as before, concerning the distribution of the points representing each of the different fibre types and blends, relative to the regression line, it can be concluded that no fibre type or blend behaved consistently different to the others, all lying approximately randomly around the regression line. It once again indicates that fibre type and blend *per sé,* do not have a significant effect on water vapour permeability, once one has taken into consideration the effects of fabrics mass, thickness, etc. These findings suggest that the trends observed by Boguslawska-Bączek and Hes (2013), namely that an increase in the percentage of wool in fabrics results in an increase in water vapour permeability, could have been due to associated changes in fabric mass and thickness.

4.4.3.3 Impact of fabric structure on water vapour permeability

Figure 46, in which the relative water vapour permeability predicted from equation 4-8 has been plotted against the actual values, shows that none of the fabric structures lie consistently below or above the regression line, which therefore indicates that fabric structure does not have an effect on relative water vapour permeability, except insofar as it affects the fabric properties (independent variables), such as mass, thickness, and air permeability.

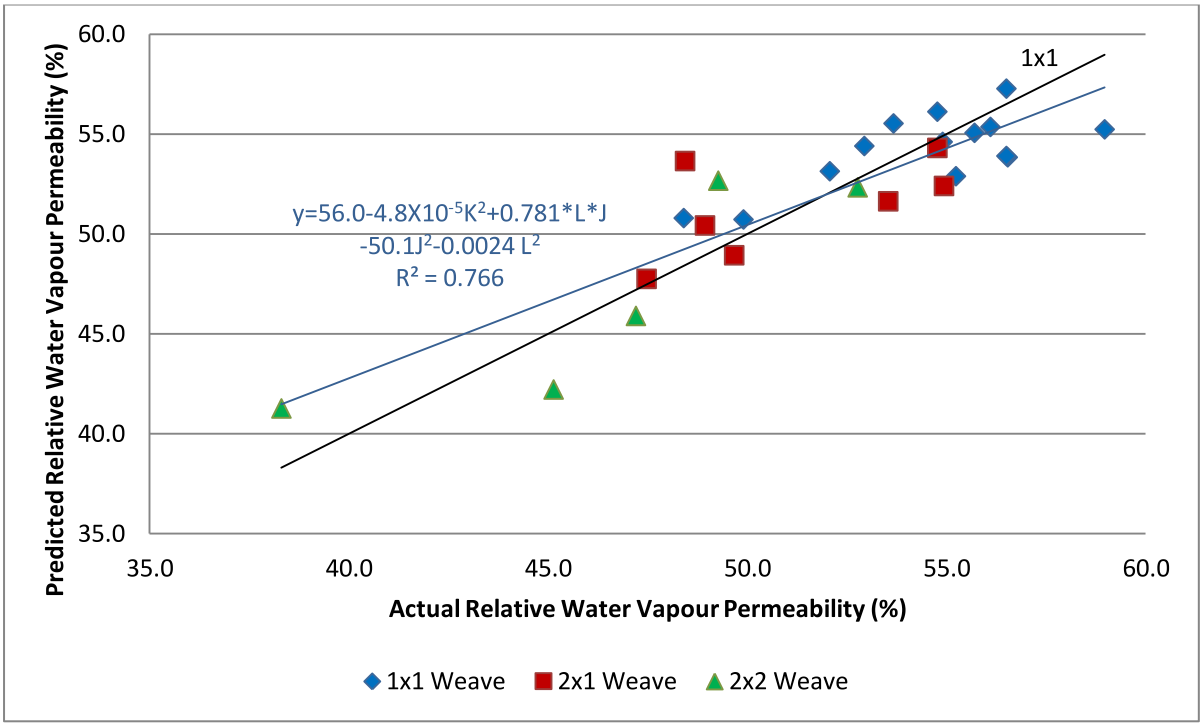


Figure 46: Predicted versus actual relative water vapour permeability (multi-quadratic regression)

4.4.4 Moisture permeability index

4.4.4.1 Effect of fabric parameters

The following best fit multi-linear equation was obtained for the moisture permeability index (D):

D = 0.298+0.00232*L____________________________(4-9)

Contribution to R^2 x 100(%) = 43.4 = 43.4%

As can be seen from equation 4-9, only one independent variable emerged as statistically significantly affecting the moisture permeability index, with the percentage fit (43.4%) being rather low. This indicates that properties, other than those included here as independent variables, may play an important role in determining the moisture permeability index, or that quadratic and/or interaction terms are involved. The predicted *versus* actual values have been plotted in Figure 47, with the regression line derived from equation 4-9, as well as the 1x1 line, superimposed. It is evident from Figure 47, that the equation is not very reliable for prediction purposes, since the scatter of the points is rather large, and only 43% of the variation in the moisture permeability index being explained by air permeability.

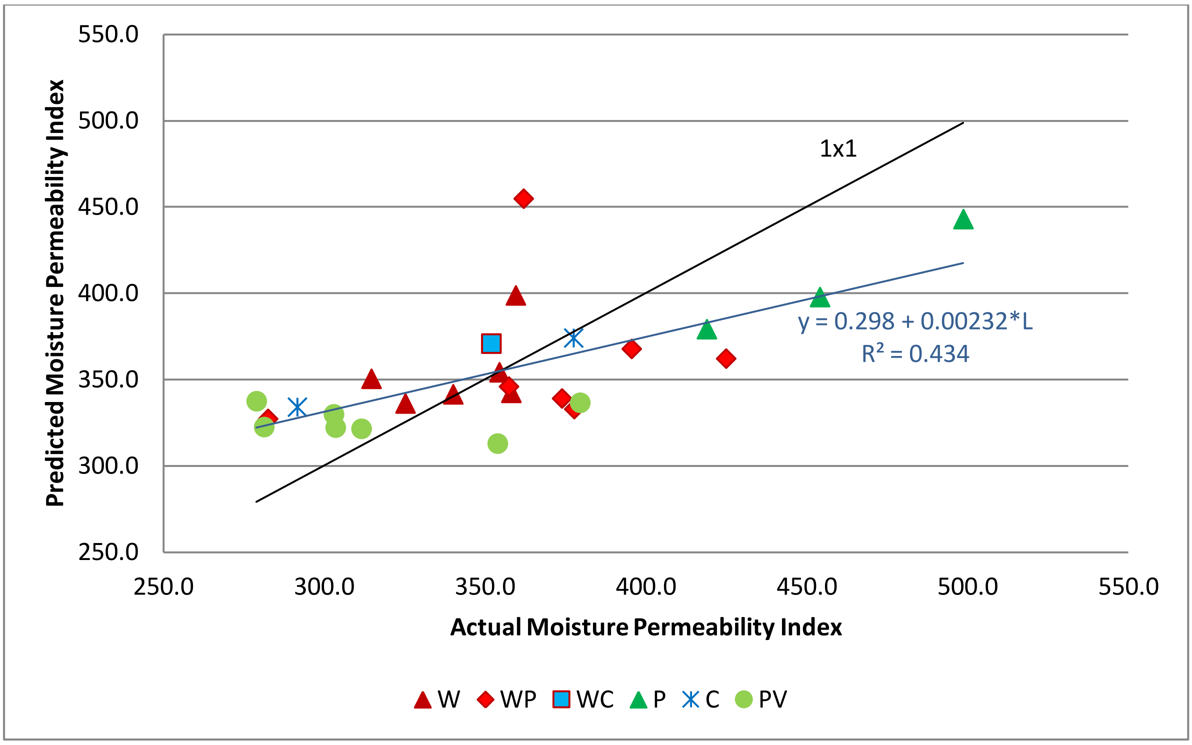


Figure 47: Predicted *versus* actual moisture permeability index (multi-linear equation)

If the independent variable L (air permeability) is omitted from the regression analysis, and the backward step wise regression procedure is used, the following best fit multi-linear regression equation for moisture permeability index is obtained:

D = 0.531-0.002*K+0,509*J__________________(4-10)

Contribution to R^2 x 100(%) = 14 32.3 = 46.3%

When equation 4-9 and 4-10 are compared, it is evident that, by omitting the independent variable L, and using the backward regression procedure, R^2 increases from 43.4% to 46.3%, i.e. there is a small improvement in the goodness of fit. It is evident from equation 4-10, that fabric thickness (J) plays the dominant role in determining the moisture permeability index, with fabric mass (K) playing a smaller role. It can be reasoned, therefore, that the significant effect of air permeability (L) is due to the fact that air permeability itself is largely a function of, i.e. correlated with, fabric mass and thickness (K and J). The predicted values, based upon equation 4-10, have been plotted against the actual values in Figure 48, with the regression line derived from equation 4-10, as well as the 1x1 line, superimposed.

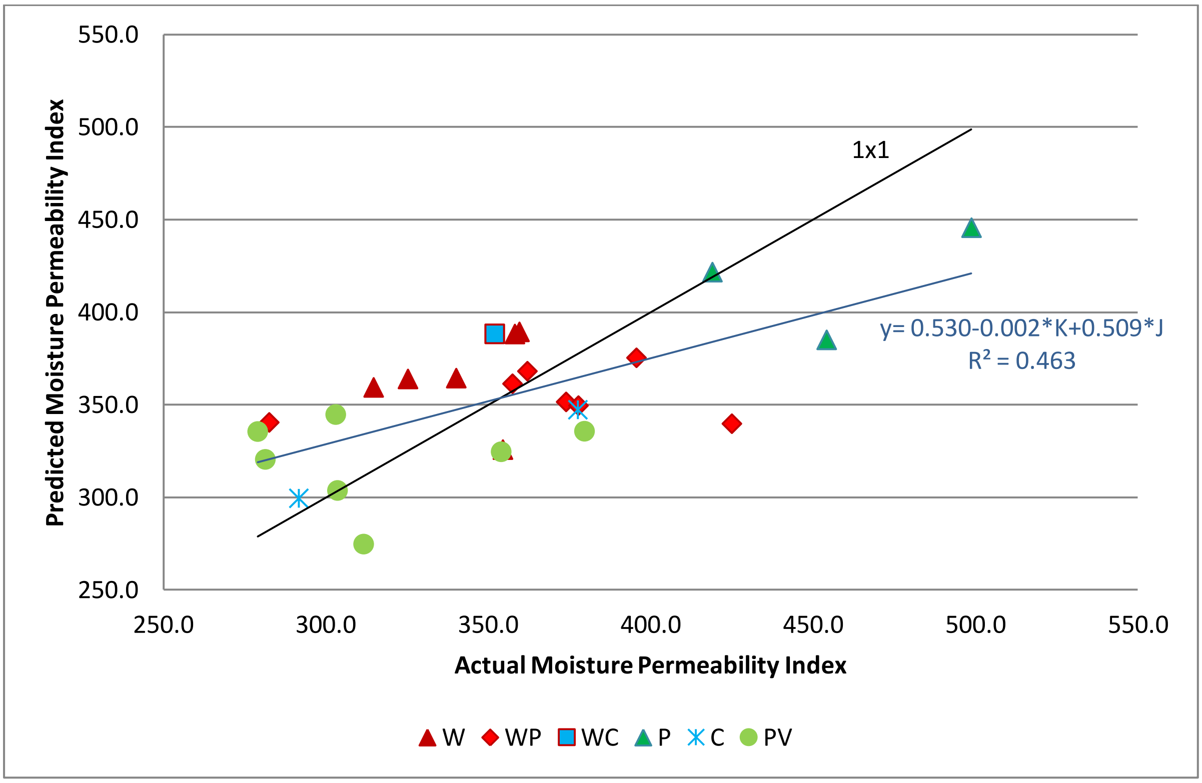


Figure 48: Predicted *versus* actual moisture permeability index (multi-linear equation, omitting L)

The following best fit multi-quadratic regression equation was obtained for the moisture permeability index (D):

$$D = 0.270+0.0131*L*J-1.57X10^{-6}K^{2}-3.61X10^{-5}L^{2}+1.91X10^{-7}M^{2} \_\_\_ (4\text{-}11)$$

Contribution to R^2 x 100(%) = 52.4 7.7 5.7 3.6 = 69.4%

The multi-quadratic regression equation gives a much better fit than the multi-linear one, R^2 increasing from 0.463 to 0.694. Therefore, equation 4-11 is much more reliable for prediction purposes. According to equation 4-11, the most significant term is that involving the interaction between L (air permeability) and J (fabric thickness). According to equation 4-11, the moisture permeability index will increase as either fabric thickness (J) or air permeability (L), or both, increases, and as fabric mass (K) decreases or fabric density (M) increases, provided the other parameters remain constant. The negative quadratic term for L indicates that, at a certain point, the moisture permeability index will reach a turning point and start to decrease with further increases in air permeability (L). In Figure 49, the predicted values, based upon equation 4-11, have been plotted against the actual values, with the corresponding regression line, as well as the 1:1 line, superimposed.

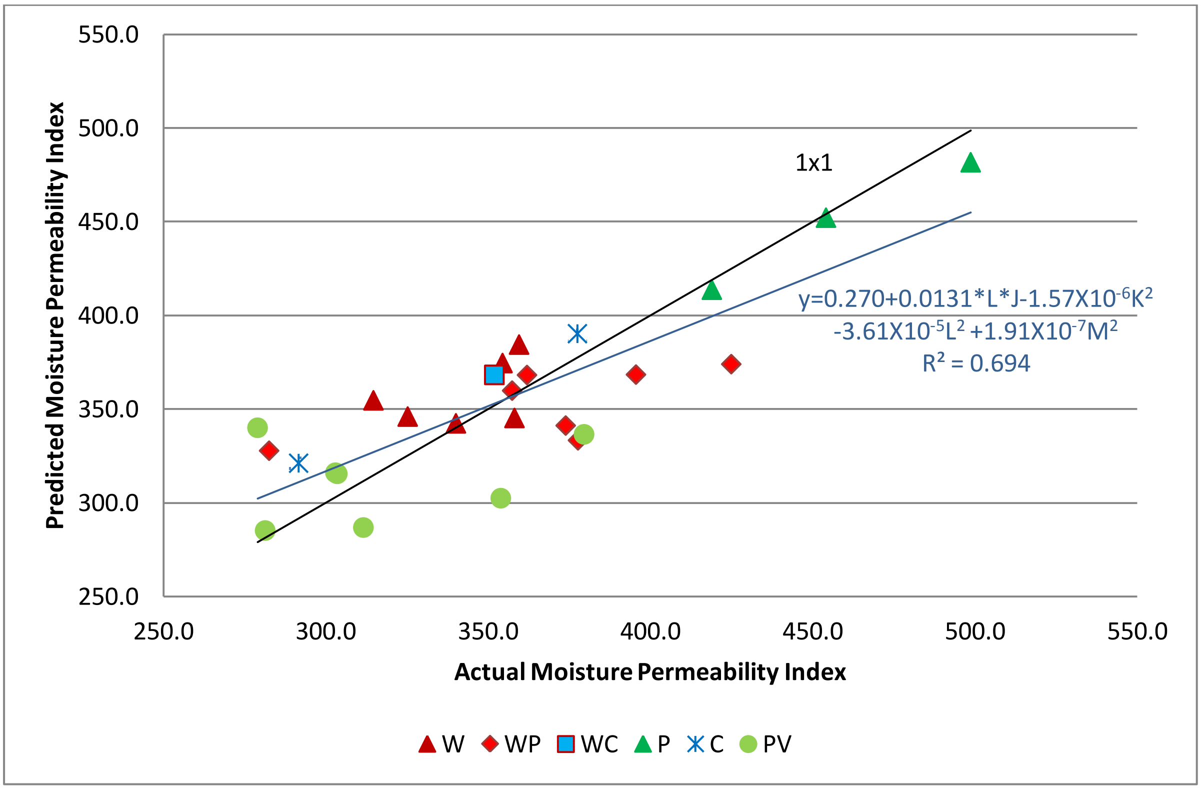


Figure 49: Predicted *versus* actual moisture permeability index (multi-quadratic regression)

4.4.4.2 Impact of fibre type and blend on moisture permeability index

Again applying the same reasoning as before, to Figure 49, it appears that the points representing the different fibre types and blends, mostly lie scattered around the regression line, except for the polyester and cotton points, which now lie consistently above the line, and the polyester/viscose points which lie mostly below the line. This indicates that the polyester and cotton fabrics have a worse moisture permeability index, and the polyester/viscose fabrics a better moisture permeability index, than predicted from the fabric properties.

If, however, one takes the 1:1 line as the reference line, i.e. force the line to go through zero, then the results change somewhat, in that the polyester points lie on, or marginally below the line, and the polyester/viscose points lie scattered around the line, i.e. both fibre type and blend behave as predicted. The cotton points still lie above the line, indicating a worse moisture permeability index relative to that predicted from the fabric properties.

4.4.4.3 Impact of fabric structure on moisture permeability index

In Figure 50, the moisture permeability index values, predicted according to equation 4-11, have been plotted against the actual values. From this figure it appears that the 2x2 twill weave fabrics tend to have a higher moisture permeability index than that predicted from the fabric properties, and the plain weave (1x1) mostly a slightly lower moisture permeability index than expected from the regression equation, although in neither case are the results always consistent.

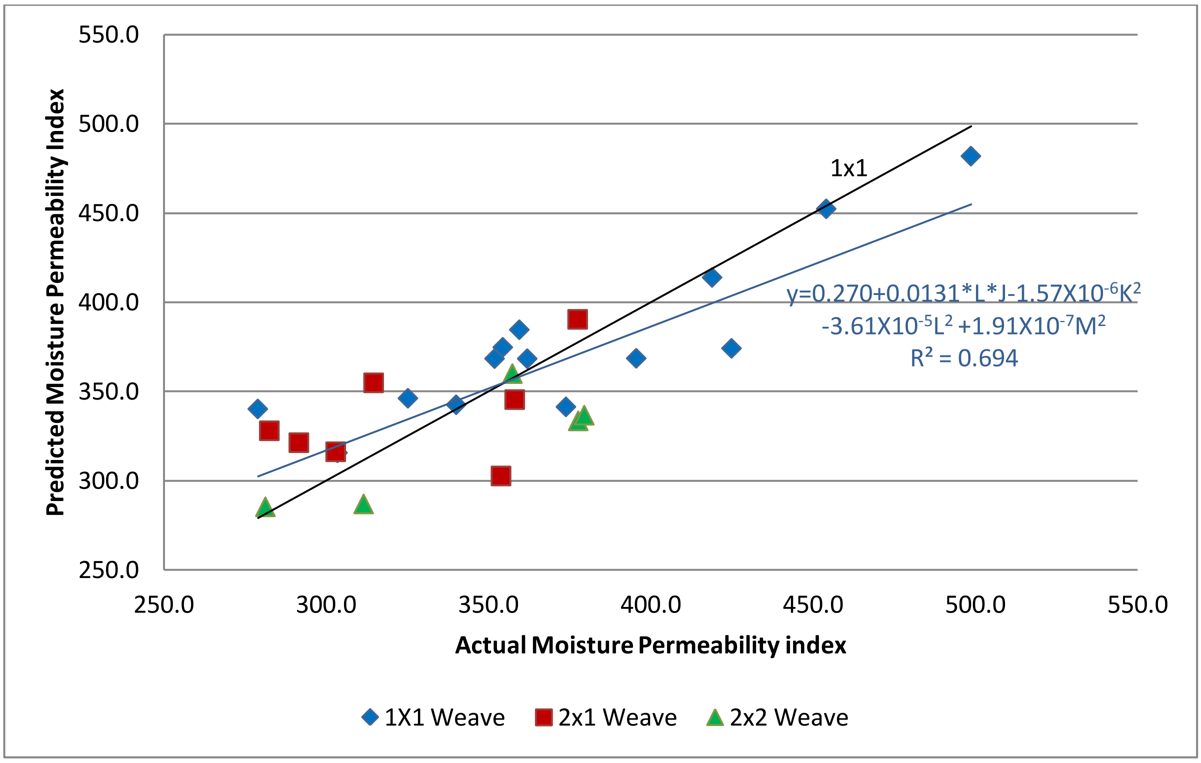


Figure 50: Predicted *versus* actual moisture permeability index (multi-quadratic regression)

CHAPTER 5 SUMMARY AND CONCLUSIONS

The objective of this study was to determine the relationships between fabric properties, namely mass, thickness, density and air permeability, and the fabric comfort related properties, namely thermal resistance, water vapour resistance, relative water vapour permeability, and moisture permeability index for commercial woven suiting fabrics, differing in mass, fabric composition and weave structure. The comfort related properties, measured on a Permetest, were empirically related to the fabric mass, thickness, density, and air permeability, using multiple regression analysis. In addition, the role and importance of fibre type and blend, as well as weave structure, were examined, to determine if changes in comfort related properties could possibly be explained in terms of fibre type or fabric structure *per sé,* as opposed to the previously mentioned fabric properties. This research study was conducted on commercial fabrics, as opposed to specially manufactured non-commercial fabrics, mostly used in previous fabric comfort studies, since many claims are made in practice concerning the superiority in terms of comfort, of a particular commercial fibre type or blend.

Commercial fabrics (26 in total) were sourced which covered a considerable range in fabric mass, from 145 to 250 g/m², and thickness, from 0.23 to 0.65 mm. Three different weave structures were chosen for the study, namely plain weave, 2x1 twill weave, and 2x2 twill weave, these being the most popular for men's suiting. Linear, multi-linear and multi-quadratic regression analyses were used to analyse the relationships between the various dependent and independent variables, the 95% confidence level being used to test for significance. The following is a summary of the main results and findings of this study:

1. The first aspect investigated was the correlations between each dependent and independent variable in turn, since this could affect certain of the trends and conclusions. Significant correlations existed between fabric mass and thickness, as well as between fabric density and thickness, an increase in fabric mass generally being associated with an increase in fabric thickness, and an increase in fabric density with a decrease in fabric thickness, both of which are as expected. The most significant correlations, between the

dependent variables, were between water vapour resistance and relative water vapour permeability, there also being a moderately strong correlation between thermal resistance and water vapour resistance. As could be expected, an increase in water vapour permeability was associated with a decrease in water vapour resistance, and an increase in thermal resistance with an increase in water vapour resistance.

2. In terms of the straight correlations between the comfort related properties (dependent variables) and fabric properties (independent variables), the highest correlations were between fabric mass and water vapour resistance, and fabric mass and water vapour permeability, a heavier fabric presenting a greater barrier to the transfer of water vapour, as expected. Another high correlation existed between fabric thickness and thermal resistance, a thicker fabric providing more volume for the entrapment of air, and consequently increased thermal resistance, once again as expected from a theoretical consideration and previous studies. Air permeability correlated best with the moisture permeability index, although, the correlation was not very high.

3. Multi-linear and multi-quadratic regression analyses and the resulting regression equations, were used to quantify the relationships between the comfort related properties and the statistically significant fabric parameters. It was established that fabric thickness was the main contributor towards explaining changes in thermal resistance. For water vapour resistance and water vapour permeability, fabric mass was the most significant and contributed most to explaining changes in these two comfort related properties. In the multi-linear equation for moisture permeability index, air permeability emerged as the most significant. When air permeability was omitted from the regression analysis, fabric thickness and mass emerged as the main contributors towards explaining changes in the moisture permeability index, there also being a small improvement in the goodness of fit. The multi-quadratic regression equation for moisture permeability index

produced the best fit, but included all the independent variables, and certain interactions, making it difficult to interpret.

4. From the multi-linear and multi-quadratic regression equations, together with the corresponding regression and 1:1 lines, and identifying the different fibre types and blends, by means of different symbols, enabled the positions of the various fibre types and blends, relative to the regression lines, to be assessed. On this basis, the role and importance of fibre type and blend could be evaluated, independent of their associations, if any, with the other measured fabric properties, notably mass and thickness. It was found that for thermal resistance, water vapour resistance, and water vapour permeability the different fibre types and blends did not consistently lie above or below the corresponding regression lines. From this it could therefore be concluded that the fibre type or blend *per sé,* did not appear to have a consistent effect on these comfort related properties, since the points of each of the different fibre types and blends generally lie randomly around the relevant regression lines. For the moisture permeability index, most of the points representing fibre types and blends were scattered around the regression line, except for polyester, polyester/viscose and cotton, indicating that these fibres may have performed differently than predicted from the fabric properties.

5. The final aspect investigated, was the impact, if any, of fabric structure, *per sé* (i.e. independently of fabric mass, thickness, etc.), on the comfort related properties. It was found that, when the values, predicted from the multi-linear and multi-quadratic regression equations, were plotted against the actual values, and distinguishing between the different structures by the use of different symbols, the symbols for each fabric structure were generally scattered randomly around the regression lines, for thermal resistance, water vapour resistance, and water vapour permeability. Therefore, it was concluded that fabric structure did not have an effect on these comfort related properties, except insofar as it affected the other fabric properties measured, such as mass, thickness, and air permeability. In terms of the

moisture permeability index, both the plain weave and 2x2 twill weaves performed differently than expected from the fabric properties, however, the results were not consistent.

Concluding remarks

From the various analyses and results, it is concluded that the role of fabric parameters, mass and thickness in particular, in determining the various comfort related properties measured, was much greater than that of fibre type or blend, and fabric structure. The most significant empirical relationships found were between thermal resistance and fabric thickness, water vapour resistance and fabric mass, water vapour permeability and fabric mass, and moisture permeability index and air permeability. Fibre type or blend, and fabric construction, did not appear to have a consistent influence on any of these comfort related properties. Therefore, it appears that it is the fabric parameters (mass, thickness, etc.), rather than the intrinsic characteristics of a particular fibre, whether natural or man-made, which mainly determine the fabric comfort related properties measured in this study. It is, however, possible to argue that differences in the shape, crimp, cross section and fineness of a particular fibre (e.g. wool) can affect the fabric thickness and bulk and thereby the comfort related properties, but the counter argument would be that man-made fibres can be engineered to match these fibre properties and therefore, also the corresponding comfort related properties, as measured here. In addition to these conclusions, this study has provided evidence that similar relationships between fabric parameters and comfort related properties exist, whether commercial or non-commercial fabrics are used.

Further work

Further research opportunities exist to verify and possibly expand the relationships and equations established here in the multi-linear, and particularly the multi-quadratic regression analyses. Research on a much larger data set is required to verify the empirical relationships obtained in this study and the extent to which the various parameters determine comfort related properties as measured here. The research should also be extended to other comfort testing equipment, with particular reference to sweating manikins, since it can be argued that the instrument used here, Permetest, does not perhaps give a complete, or the most complete, picture or overall measure of comfort, as would be experienced by a human being. Even though the values obtained for the comfort related properties will be different for different testing equipment, it would be interesting to determine whether the trends and relationships are similar. Another area of research could be to determine whether testing fabrics and identical garments produced from the fabrics, show similar trends, since once a fabric is made into a garment, additional factors must be considered, such as design, fit, movement (e.g. walking) and the influence of combinations of various ensembles, which can, for example, be tested on a walking sweating manikin, such as Walter.

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Appendix A: Relative water vapour permeability results on Permetest

Code	Relative water vapour permeability (%)					
	Test 1	Test 2	Test 3	Average	SD	CV%
A	53.0	53.5	54.5	53.7	0.76	1.42
B	52.3	54.1	52.4	52.9	1.01	1.91
C	56.8	52.6	54.9	54.8	2.10	3.84
D	53.4	56.2	55.1	54.9	1.41	2.57
E	58.4	52.0	57.9	56.1	3.56	6.34
F	57.6	61.3	58	59.0	2.03	3.44
G	55.1	56.5	57.9	56.5	1.40	2.48
H	54.6	57.7	54.8	55.7	1.73	3.11
I	56.5	56.4	56.7	56.5	0.15	0.27
J	52.5	53.0	50.7	52.1	1.21	2.32
K	59.8	52.8	53.1	55.2	3.96	7.17
L	49.8	50.2	49.7	49.9	0.26	0.53
M	57.6	53.5	58.4	56.5	2.63	4.65
N	52.5	45.6	47.1	48.4	3.63	7.50
O	55.6	51.4	57.3	54.8	3.04	5.55
P	52.0	57.0	51.6	53.5	3.01	5.62
Q	52.9	55.5	56.4	54.9	1.82	3.31
R	47.0	49.0	50.8	48.9	1.90	3.88
S	47.7	46.9	50.7	48.4	2.00	4.14
T	48.9	45.7	47.8	47.5	1.63	3.43
U	53.8	46.6	48.6	49.7	3.72	7.48
V	49.2	47.3	51.3	49.3	2.00	4.06
W	56.8	52.1	49.4	52.8	3.74	7.10
X	50.3	44.2	47.1	47.2	3.05	6.46
Y	48.0	43.3	44.1	45.1	2.51	5.57
Z	37.6	38.5	38.8	38.3	0.62	1.63

Appendix B: Absolute water vapour permeability results on Permetest

Code	**Absolute water vapour permeability (m^{2}Pa/W)**					
	Test 1	**Test 2**	**Test 3**	**Average**	**SD**	**CV%**
A	2.7	2.5	2.6	2.6	0.10	3.85
B	2.7	2.5	2.7	2.6	0.12	4.38
C	2.3	2.7	2.5	2.5	0.2	8.00
D	2.6	2.5	2.5	2.5	0.06	2.28
E	2.8	2.7	2.6	2.7	0.10	3.70
F	2.4	2.3	2.5	2.4	0.10	4.17
G	2.5	2.5	2.4	2.5	0.06	2.34
H	2.5	2.3	2.5	2.4	0.12	4.75
I	2.6	2.7	2.8	2.7	0.10	3.70
J	2.9	2.8	3.1	2.9	0.15	5.21
K	3.7	3.9	3.5	3.7	0.20	5.41
L	3.1	3.3	3.4	3.3	0.15	4.68
M	2.6	3.0	2.7	2.8	0.21	7.52
N	3.6	3.5	4.0	3.7	0.26	7.15
O	2.7	2.7	2.9	2.8	0.12	4.17
P	3.1	2.8	3.0	3.0	0.15	5.15
Q	2.6	2.4	2.7	2.6	0.15	5.95
R	3.3	3.1	3.0	3.1	0.15	4.88
S	3.7	3.9	3.7	3.8	0.12	3.07
T	3.8	3.8	3.6	3.7	0.12	3.09
U	3.9	3.8	3.5	3.7	0.21	5.58
V	3.4	3.3	3.6	3.4	0.15	4.45
W	2.9	2.9	3.3	3.0	0.23	7.61
X	4.3	4.3	4.1	4.2	0.12	2.73
Y	4.8	4.5	4.4	4.6	0.21	4.56
Z	4.9	5.4	5.4	5.2	0.29	5.52

Appendix C: Thermal resistance results on Permetest

Code	**Thermal resistance (m²K/W)**					
	Test 1	**Test 2**	**Test 3**	**Average**	**SD**	**CV%**
A	14.8	15.5	15.0	15.1	0.36	2.39
B	15.0	13.4	14.0	14.1	0.81	5.72
C	13.9	15.7	14.9	14.8	0.90	6.08
D	14.4	14.8	16.2	15.1	0.95	6.25
E	18.0	19.8	19.0	18.9	0.90	4.76
F	15.5	15.3	16.2	15.7	0.47	3.02
G	19.0	21.5	20.4	20.3	1.25	6.17
H	13.4	14.8	14.5	14.2	0.74	5.18
I	18.2	19.7	18.1	18.7	0.90	4.80
J	17.3	18.9	18.1	18.1	0.80	4.42
K	15.8	17.5	17.8	17.0	1.08	6.33
L	17.5	18.3	19.2	18.3	0.85	4.64
M	20.2	20.9	21.1	20.7	0.47	2.28
N	19.2	17.5	18.9	18.5	0.91	4.90
O	14.1	14.6	14.4	14.4	0.25	1.75
P	17.0	17.8	17.8	17.5	0.46	2.63
Q	11.1	12.4	12.4	12.0	0.75	6.27
R	18.2	18.2	18.5	18.3	0.17	0.95
S	23.8	23.6	23.0	23.5	0.42	1.77
T	18.5	18.9	18.6	18.7	0.21	1.12
U	18.9	17.3	17.7	18.0	0.83	4.63
V	20.1	22.7	21.4	21.4	1.30	6.07
W	19.0	19.9	18.1	19.0	0.90	4.74
X	22.9	21.2	21.2	21.8	0.98	4.51
Y	21.1	21.8	20.7	21.2	0.56	2.63
Z	30.5	30.4	31.7	30.9	0.72	2.34