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Thermophysiological comfort of different knitted fabrics

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Technical University of Liberec presentation

Technical University of Liberec goes back to 1953, offers a large field of scientific, technical and artistic branches of studies, Besides Tul has reached excellent results in scientific research.

The faculty of Textile Engineering was established in the year of 1960, it is the only textile faculty existing in Czech Republic. it consists six departments: nonwoven department, nanofibrous material department, clothing technologies department, material engineering, department of design and textile evaluation department. It is one of the best faculties of textile research and clothing technology in Europe, providing well occupied laboratories to its students and all the new materials to accomplish their research in best conditions.

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GENERAL INTRODUCTION

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Clothing is an essential human need with several functions. The choice of clothing is based on many factors such as personal desires and the particular application; which are user dependent. However, people's preferences may also be dynamic with seasons, environment, age, and type of activity.

To the wearer, comfort can be qualified as one approach to evaluate performance of clothing. In this sense, fabric engineers and clothing designers ought to consider clothing comfort as a quality aspect contributing to total clothing performance and the user's satisfaction.

The aim of this work is to study the thermal comfort and moisture management properties of different knitted fabrics and find the suitable use for each fabric, as knitted fabrics are usually preferred next-to-skin wear due to their extensibility and soft touch, is divided to 3 main chapters organized as follow:

Chapter 1: literature review which introduces, clothing role, human body thermoregulation, thermal comfort principal keys and testing methods of comfort.

Chapter 2: Devoted to presents methods and materials that describes sampling and different equipment used in laboratory analysis.

Chapter 3: Different results and their discussion are developed.

This report ends with a conclusion summarizing the work done.

Chapter 1 : Literature Review

This first chapter presents basic concepts to better understand the aim of this work and its evolution. It is composed of mainly 3 parts:

First part is an introduction for the fundamentals of human skin interactions with clothing,

the thermoregulation mechanism and the role of clothing in human thermal comfort.

The second part is an elaboration of thermal comfort definition, presenting its principal keys and dependance factors; it discusses also the objective and subjective assessments of thermal comfort and moisture management.

The third part evokes an overall study of some properties of fibers, yarns, fabrics and finishing treatments that contribute to human comfort.

I. Interaction of human body with clothing

1. Anatomy of the skin

Skin is not only the largest, but also, functionally, the most versatile organ of the human body, it can be differentiated into three components; the epidermis, which is the outer protective layer, the dermis that contains important functional structures such as blood, lymph vessels and nerves, and the hypodermis which is composed of a tissue that provides connection between the dermis and the deeper structures of the body [1].

The skin provides a first barrier between the organism and its environment. It keeps the uncontrolled loss or gain of water through the skin at a low constant level. In addition to that, it contains complex vascular systems and sweat glands that allow it to change its conductance in response to thermoregulatory demands of the body. It also contains four types of thermally sensitive nerve endings (to cold, warmth, and hot and cold pain) that sense the skin's temperature and transmit the information to the brain [2]. Figure 1 presents a cross-sectional view of the human skin and it's important 3 parts.

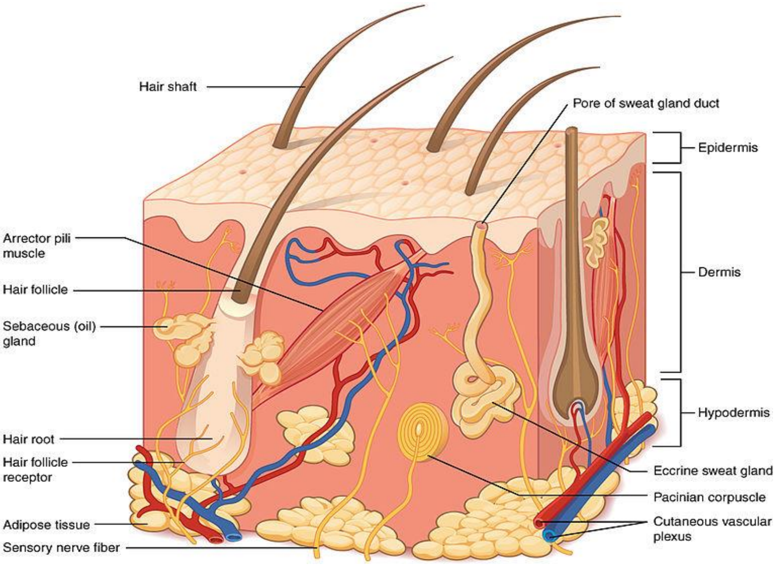


Figure 1 : Cross-sectional view of human skin

2. The human dynamic thermoregulatory system

2.1. The Neurophysiological Basis of Sensory Perceptions

Human body temperature is regulated within a very narrow range. When exposed to hyperthermic conditions, via environmental factors or increased metabolism, heat dissipation becomes vital for survival.

In humans, the primary mechanism of heat dissipation, particularly when ambient temperature is higher than skin temperature, is evaporative heat loss secondary to sweat secretion from eccrine glands.

While the primary controller of sweating is the integration between internal and skin temperatures, a number of non-thermal factors modulate the sweating response. Temperature receptors are located in the skin and they are connected to the hypothalamus, which has the function of providing homothermic and can activate the mechanisms of thermoregulation through nervous pathways [2].

2.2. Thermal regulation

Figure 2 shows some basic features of the human thermoregulatory system, temperature is regulated through control systems that ensure homeostasis through behavioral and physiological mechanisms of thermoregulation.

The first includes all the tools that humans can use to support their thermal comfort, such as the choice of an appropriate clothing or the adjustment of the indoor environmental conditions (opening/closing a window, etc.) [3].

The second consists of several physiological mechanisms which can intervene to maintain homeostasis, which are the vasomotor response (vasoconstriction or vasodilation), sweating, and shivering [3,2];

- **Sweating**: increases body heat loss by increasing sweat evaporation(human temperature is lower than the environment).

- **Shivering:** produces heat by involuntary movement of muscle (human temperature is higher than the environment).
- **Vasodilatation and vasoconstriction**: refer to changes in blood vessel diameter, which affect skin temperature by changing the rate of blood exchange with the interior.

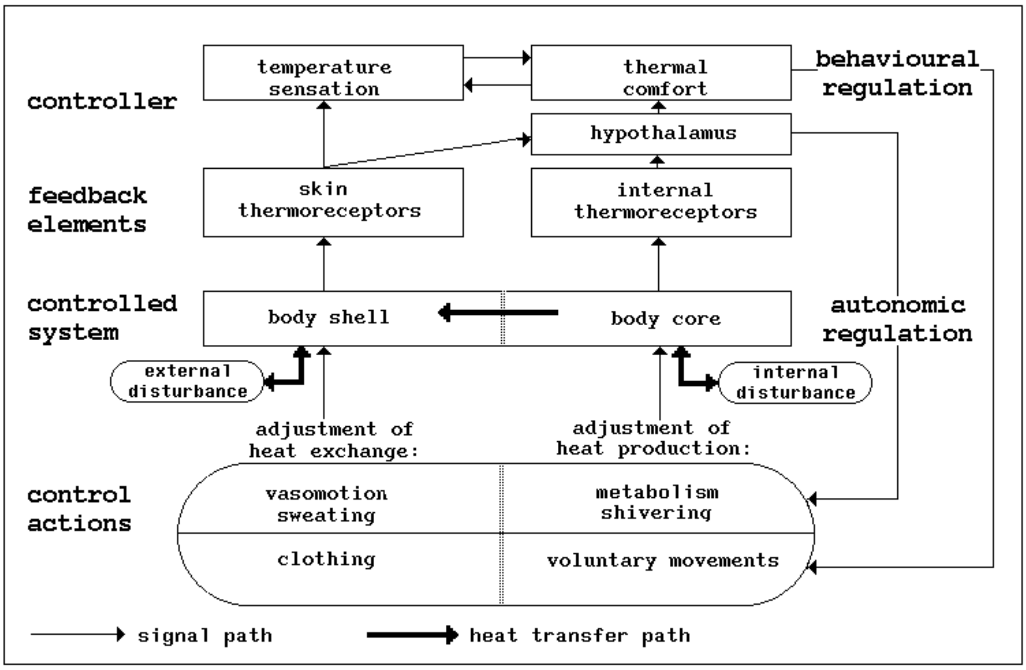


Figure 2 : Diagram of autonomic and behavioral human temperature regulation

3. Heat balance and metabolic rate

3.2. Heat balance

a. Heat production

The heat produced is determined by the amount of energy (metabolic activity) needed to the body functions; in case of rest and in case of activity, muscles will burn nutrients and consume oxygen to produce energy in form of heat [4].

b. Heat transfer mechanism (heat loss)

The body converts the chemical energy of its food, producing through the processes of metabolism a great deal of heat. The amount of heat produced depends on the degree of activity [5].

The heat loss from the body is between skin and environment, it depends on several pathways (the amount of transferred heat, the body surface area involved the resistance, the heat flow, temperature, vapor pressure, clothing insulation ...) [4].

Figure 3 is a presentation for the methods of heat loss mechanism. The human body is represented as a heat engine, which can give or receive heat from the environment through conduction, convection, radiation, and evaporation [3].

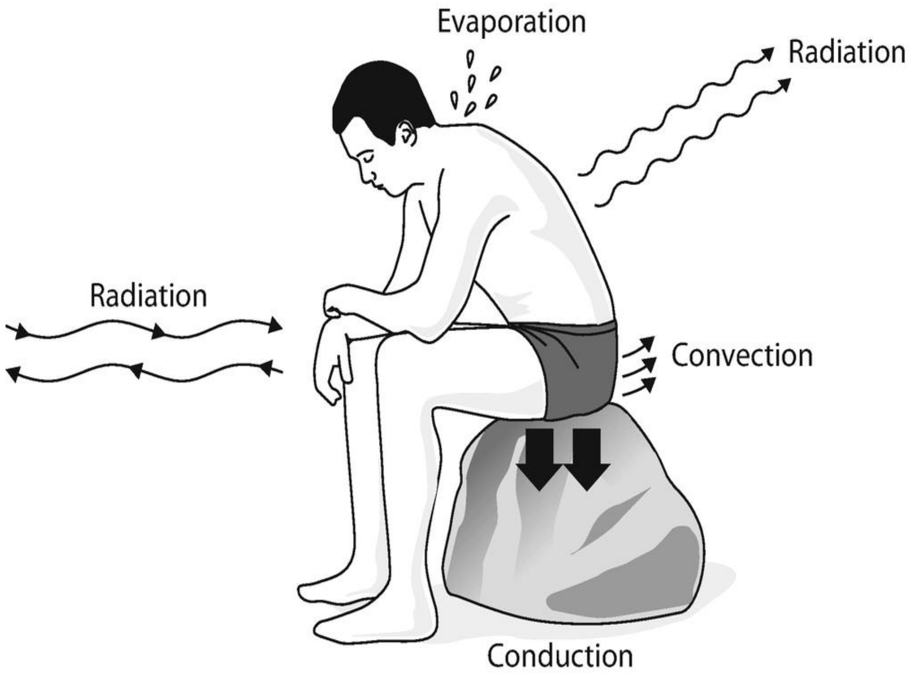


Figure 3 : Schematic representation of human body heat loss pathways

- Heat exchange through convection

Convective heat loss from the body surface is often expressed as a heat transfer coefficient and the difference between the mean temperature of the outer surface of the body and that of the surrounding air [6]:

$$\mathbf{C = hc\ (Tsk - Ta)\ Ac\ fcl} \qquad (1)$$

Where:

- **hc**: the convective heat transfer coefficient ($W/m^2\ K$):
- **Ta**: the air temperature (K);
- **Tsk**: the mean skin temperature (K);
- **Ac**: the body surface involved in the heat exchange through convection (m^2);

- **fcl**: the clothing area factor;

The clothing area factor (fcl) can be calculated as fcl = 1.00 + 0.28 Ic, where Icl (clo) is the thermal insulation of clothing

- Heat exchange through conduction

The conduction takes place when two objects are in direct contact with each other, exchanging the heat occurs when the skin comes in contact with a cold or warm object.

Generally, the heat exchange between the body and the environment through conduction is limited, as it involves small parts of the body.

Therefore, the conductive effects are often neglected. In this case, the heat loss or gain depends on several factors such as the body and surface temperatures, the area of contact and the conductivity of the surface and the body tissues [7].

$$\mathbf{q} = -\lambda \mathbf{A}\frac{\partial T}{\partial x} \qquad (2)$$

where:

- **q**: the heat flow (W/m^2);
- **λ**: the thermal conductivity of the material (W/mK);
- **A**: the area(m^2);
- $\frac{\partial T}{\partial x}$: the temperature gradient in the heat flow direction (K/m);

- Heat exchange through radiation

The heat exchange via infrared waves, it takes place when there is a difference between the body's surface temperature and the temperature of the surfaces in the environment. Thermal radiation is considered to be one of the factors that can influence the most the heat exchange during human activities, if the body temperature is higher than the air temperature, there is loss of the heat, if the environment is warmer than the skin temperature, the body gain heat through radiation [7].

The radiative heat lost from the skin is given by [8]:

$$R = hr\ (Tsk - Tr)\ Ar\ fcl \qquad (3)$$

Where:

- **hr**: the radiative heat transfer coefficient (W/m2K);
- **Tr**: the mean radiant temperature (K);
- **Tsk**: the mean skin temperature (K);
- **Ar**: the effective radiation area of the body (m2);
- **fcl:** the clothing area factor;

➢ Heat exchange through evaporation

Heat loss through evaporation can occur through skin (by passive diffusion or sweating) and respiratory system (by breathing). Sweating is the primary means of cooling the body during exercise [11].

Due to the body's ability to sweat, moisture appearing on the skin can evaporate, with which large amounts of heat can be dissipated from the body. At the level of the skin, regulatory sweating creates evaporative heat loss (E) given by [8];

$$E = he\ (PskH2O - PaH2O)\ Ae\ Fpcl \qquad (4)$$

Where:

- **he:** the evaporative heat transfer coefficient at the surface;
- **PaH2O:** the water vapor pressure in ambient air;
- **$PskH_2O$**: the water vapor pressure in saturated air at Tsk;
- **Ae:** the evaporative surface;
- **Fpcl**: the clothing permeability factor;

3.3. Metabolic rate

The metabolic rate is the amount of energy consumed minus the amount of energy expended by the body. It measures how much energy the body needs for normal, basic, daily activity.

About 70 percent of all daily energy expenditure comes from the basic functions of the organs in the body. Another 20 percent comes from physical activity, and the remaining 10 percent is necessary for body thermoregulation or temperature control.

The heat in the body is produced by the metabolic processes occurring during human life. The heat exchange between the body and the environment can be determined through the heat balance equation [9]:

$$\mathbf{M - W = Ck + C + R + E + S} \tag{5}$$

Where;

- **M**: the metabolic rate of the body (w);
- **W**: the mechanical work (w);
- **Ck**: the heat transfer by conduction(w);
- **C**: the heat transfer by convection (w);
- **R**: the heat transfer by radiation(w);
- **E**: the heat transfer by evaporation(w);
- **S**: the heat storage(w);

The measurement unit of the metabolic rate is the Met; 1 Met corresponds to the metabolic rate at rest [3]. **1 Met = 58 W/m²**

Table 1 presents the metabolic rate for different activities [10].

Table 1 : Typical metabolic rates for different activities

Activity	Metabolic rate (met)
Resting	
Sleeping	0.8
Seating, quiet	1.0
Standing, relaxed	1.2
Sport and activities	
Archery	4.3
Badminton	5.5
Basketball	8.0
Bicycling	7.5
Boxing	12.8
Calisthenics	3.5
Dancing	7.8
Fencing	6.0
Fishing	3.5
Football	8.0
Gymnastics	3.8
Hockey	8.0
Running	7.0
Skiing	7.0
Swimming	4.8-13.8
Tennis	7.3
volleyball	4.0

4. Role of clothing

The main effect of clothing will be its influence on the heat exchange between the skin and the environment, it will affect the heat loss of the body and will also impact the thermal sensation experienced by a person [11].

The clothing insulation helps to maintain the heat transmission from body to environment or vice-versa [4].

In particular, clothing must provide thermophysiological comfort, supporting the wearer’s thermoregulation, keeping the wearer at a comfortable temperature and maintaining the micro-climate between skin and textile as dry as possible [12].

The heat transmission behavior of a fabric plays a very important role in maintaining thermophysiological comfort; means that the human body temperature of approximately 37 °C is maintained depending on the level of physical activity and temperature of the climate, the body temperature increases or decreases which must require dissipation or conservation respectively to balance the heat of the body.

II. Thermophysiological comfort principal keys

1. Definition of Comfort

Thermal comfort, as expressed by British Standard-BS EN ISO 7730, is "the condition of mind which expresses satisfaction with the thermal environment”. Dissatisfaction may be caused by the body as a whole being too warm or cold, or by unwanted heating or cooling of a particular part of the body (local discomfort) [13].

Two conditions must be fulfilled to assure thermal comfort of a person in a given environment:

1) The actual combination of skin temperature and body's core temperature provides a sensation of thermal neutrality.

2) The fulfilment of the body's energy balance: the heat produced by the metabolism should be equal to the amount of heat lost from the body.

The thermal comfort of a garment depends on several factors: heat and vapor transport, sweat absorption and drying ability. Under environmental conditions 15% of the heat loss by evaporation takes place in the form of perspiration accompanied with a film of water on the skin [14]; sweat.

Typically, the sensation of heat or cold and that of humidity or skin wetness are the main determinants of overall comfort. Sensors in the skin register the temperature and the speed with which the temperature changes and these inputs, are relayed to the brain; the brain interprets the drops of sweat trickling down the skin that gives a feeling of wetness and moisture sensation which comes with cold and uncomfortable sensation.

Comfort is a state of mind influenced by a range of factors, some physical, some physiological and some psychological;

1.1. Physical comfort

When the skin touches wholly or partially the clothes we can feel various sensations like [15]:

- **Tactile sensations** like smoothness, roughness, prickliness, pickiness, stickiness, scratchiness, softness and stiffness. Prickliness and itchiness reveal discomfort in form of pain.
- **Thermal sensations** can also be felt in the same way by touch, including; warmth, coolness, breathability, hotness, and chilliness.
- **Moisture sensations** by the same way gives us the feeling of; clamminess, dampness, wetness, stickiness, non-absorbent, and clingy.

1.2. Physiological comfort

Physiological comfort is related to thermoregulation and the coordination between heat production and heat loss, it is also related to body mechanism such as pulmonary system, central nervous system, cardiovascular system [15].

1.3. Psychological comfort

Psychological comfort it is mainly related to individual consciousness and self-satisfaction, it focuses on the comfort in relation with the human values and social being [15].

It can involve different aspects like**:**

- **Personnel aspect;** body image, personality, cultural /religious values …
- **Clothing attributes;** related to details of the fabric including; style, texture, aesthetics, fashion design color …
- **Environmental attributes;** are also part of psychological comfort like; climatic conditions, social cultural settings historical importance ….

2. Dependent factors

In general, thermal comfort depends on the interaction between three sets of factors: environmental factors (air temperature, air velocity, ambient air relative humidity and mean radiant temperature), physiological factors (e.g., human activity level) and clothing factors (insulation, permeability, design elements) [16].

2.1. Environmental factors

➢ Air temperature

The air temperature is defined as the average temperature of air surrounding the body [17].

When the air temperature is higher than the skin temperature the heat loss decrease, the body will actually gain heat from the environment instead of losing heat to it [4].

➢ Radiant temperature

This value, presented as the mean temperature of all walls and objects in the space where one resides, it determines the degree to which radiant heat is exchanged between skin and environment.

In areas with hot objects the radiant temperature can easily exceed skin temperature and results in radiant heat transfer from the environment to the skin [4].

- Relative Humidity

The relative humidity was defined as the ratio of the amount of water vapor that the air could hold at the specific temperature and pressure [18].

Relative humidity between 30% and 70% doesn't influence thermal comfort. When it's over 70%, it will prevent the sweat evaporation and then cause sultry weather sensation and let occupants fell discomfort. When it's lower than 30%, it will cause dry sensation and has a bad effect on mucous membranes [19].

The amount of moisture present in the environment's air (the moisture concentration) determines whether moisture (sweat) in vapor form flows from the skin to the environment or vice versa [4].

- Air velocity

Air velocity is defined as the average speed of the air to which the body is exposed, with respect to the location and time [20]. If the flow rate is too high or irregular, then local thermal discomfort appears. Thus, it's very important to easily control the air velocity and the flow direction [21].

2.2. Physiological factors

- Human activity level

Humans require energy to perform work and produce heat to maintain the internal body temperature around 36.5°C.

The higher activities level, the more heat is produced [17]. If is produced too much heat, then the body will sweat which will cause discomfort. If is produced too little heat then, the skin temperature will fall, and the person will feel cold and uncomfortable [21].

2.3. Clothing factors

- Clothing insulation

A key function of clothing is insulation, thickness of the material and therefore the volume of air enclosed in the fabric appears to be the major determinant for preventing the heat exchange with the environment.

The thermal comfort is related to fabrics ability to maintain skin temperature and allow transfer of perspiration produced from the body [22].

The insulating properties of clothing it is measured in clo, it is equal to 0.155 m^2. °C/W.

Table 2 presents an estimation of some types of clothing insulation:

Table 2 : Clothing types and their corresponding Clo values

Clothing Type	Clo Value
T-shirt	0.09
Briefs	0.06
Long underwear	0.10
Bra and panties	0.06
Light-shirt (men) short sleeve	0.14
Light-shirt (men) Long sleeve	0.22
Heat and over coat	2
Heavy shirt (men) short sleeve	0.25
Heavy shirt (men) long sleeve	0.29
Light Trousers (men)	0.26
Heavy Trousers (men)	0.32
Light dress (women)	0.22
Heavy dress (women)	0.7
Long sleeve Blouse (women) Light	0.20
Long sleeve Blouse (women) Heavy	0.29
Boots	0.08
Light Slacks (women)	0.10
Heavy Slacks (women)	0.44

III. Testing methods of comfort

1. Subjective evaluation of sensorial comfort

Subjective analysis associates the handle assessment to a psychological result due to the sense of touch.

When fingers are run across the fabric surface, the person acquires series of sensory reactions, giving emotion and cognition within the mind [23]. The perceived impression of the feeling is assigned to a particular hand parameter.

Particularly, it is related to somatic sensory receptors, which are in charge of the body sensory analysis.

These receptors relay information felt about texture, pressure, thermal reaction, elongation, tightness, softness, and pain among others, depending on the style or technique of touch [24].

Specific types of touch are presented in figure 4 can be used to assess particular details of the perception:

- **The touch-stroke method:** This involves all fingers stroking the fabric surface, is used to evaluate texture and thermal feel related to temperature.
- **The rotating cupped method**: Used for comfort relative to stiffness, weight, resilience, temperature, and texture.
- **The multiple pinch action** involves fabric being rotated between the thumb and one or two other fingers of the same hand to feel the stiffness, texture, structure, friction property, stretch, and temperature.
- **The two-hand rotation** seeks to evaluate the sheerness and stretch [23]

Figure 4: Handle evaluation techniques

1- Touch stroke; 2-Rotating cupped, 3-Multiple finger 4-Two handed rotation [23]

2. Objective evaluation

Objective based methods by use of equipment's offer the chance of consistency and reproducibility of results, hardly attainable with subjective methods.

2.1. Thermal comfort assessment

2.1.1. Guarded hot plate

Figure 5 presents schematic presentation of guarded hot plate, it is used to measure thermal transmittance, which is the reciprocal of the thermal resistance. The apparatus consists of a heated test plate surrounded by a guard ring with a plate in the bottom these three heating plates are sandwiched between aluminum sheets [25].

All the plates maintained at the same constant temperature in the range of human skin temperature (33-36°C). The amount of heat passing through the sample is measured in w/m^2 from the power consumption of the test plate heater.

Tests are taken without any fabric sample present so the apparatus can reach equilibrium before any readings. The measured thermal transmittance consists of the thermal transmittance of the fabric plus the thermal transmittance of the air layer above the fabric which is not negligible.

The test method determines the thermal transmission equivalent to the coefficient of heat exchange by conduction, convection and radiation.

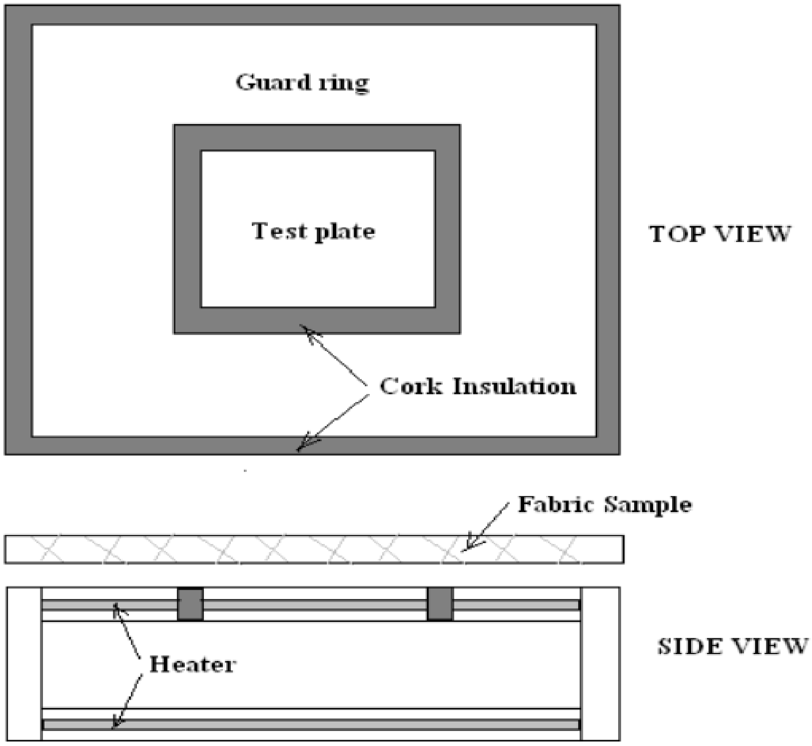


Figure 5: Guarded hot plate

2.1.2. Togmeter

The Togmeter Test System is designed to produce accurate, repeatable measurements of the thermal resistance of textiles and similar materials under steady-state conditions. The device as shown in figure 6, includes a temperature-controlled test plate, cabinet housing with airflow and temperature sensors related to a computer occupied with thermDAC control software.

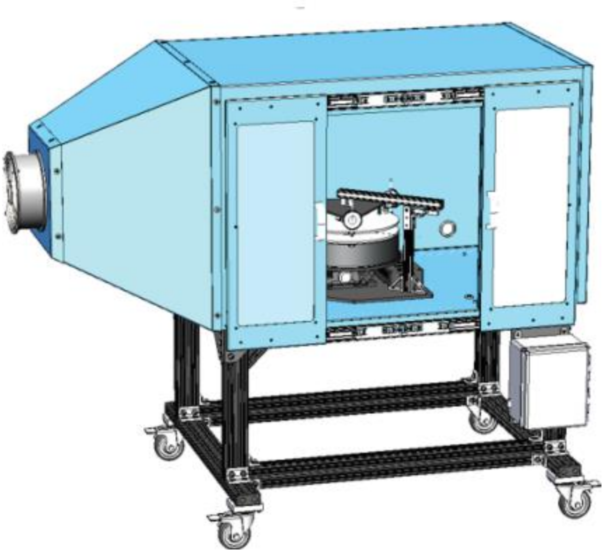


Figure 6 : Togmeter

The togmeter consists of a thermostatically controlled heating plate which covered with a layer of insulating board of known thermal resistance.

According to ISO 5085-1 the temperature is measured at both faces of the standard. The heater is adjusted so that the temperature of the upper face of the standard is at skin temperature (31-35°C). A small airflow is maintained over the apparatus.

There are two methods of test that can be used with the togmeter: two plate method and single plate method.

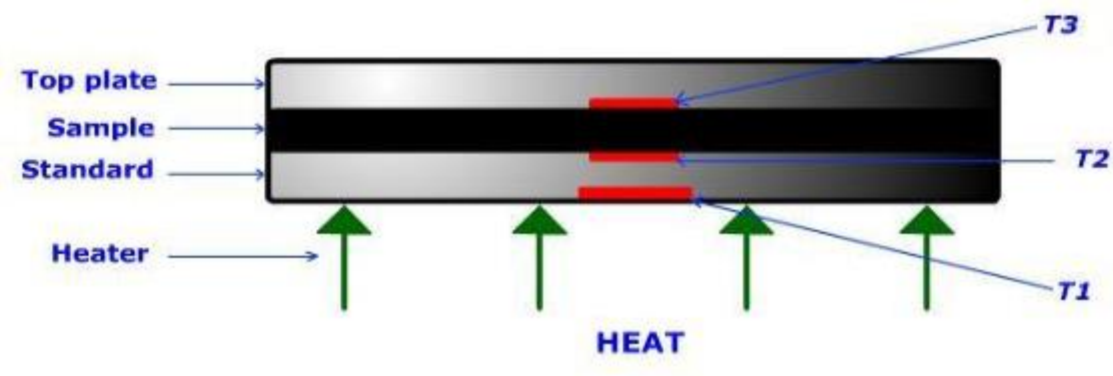


Figure 7: Two plates method

In two plate method (figure 7): The sample under test is placed between the heated lower plate and an insulated top plate. The top plate has low mass so that it does not compress the fabric. The temperature is measured at the heater (T1), between the standard and test fabric (T2) and between the fabric and the top plate (T3).

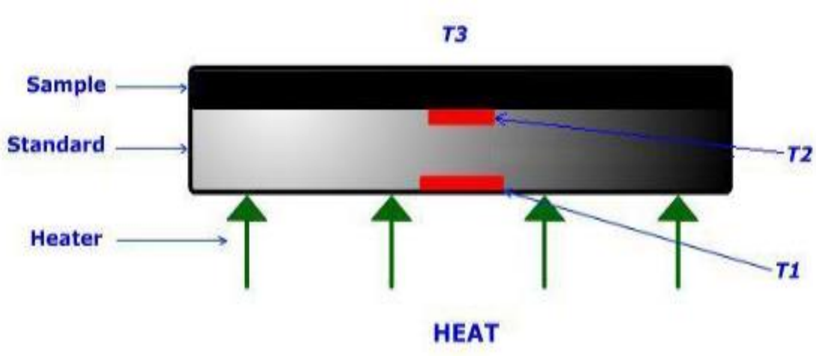


Figure 8: Single plate method

In single plate method (figure 8): The sample under test is placed on the heated lower plate as above but it is left uncovered, the top plate being used to measure the air temperature (T3) [25].

In single plate method the air above the test specimen has a considerable thermal resistance itself, so that the method is in fact measuring the sum of the thermal resistance and the air thermal resistance while the two plates method measures the thermal resistance only of the fabric.

2.1.3. Clo test

According to ASTM D-1518, Clo test determines the thermal resistance of a batting fabric system, it has considerable importance in determining its suitability for use in cold weather protective clothing, sleeping bags, and bedding systems [26]. This test method measures the heat transfer from a warm, dry, constant-temperature, horizontal flat plate up through a layer of the test material to a cool atmosphere and calculates the resistance of the material.

The measurements are made under still air conditions or with a horizontal air flow over the specimen with the thermal resistance tester as shown in figure 9.

Figure 9 : Thermal resistance tester

For practical purposes, this test method is limited to specimens of batting and layered batting fabric assembly having an intrinsic thermal resistance from 0.1 to 1.5 m²K/W and thicknesses not in excess of 50mm. The test method also provides a method for determining the bulk density of the material, the insulation per unit thickness, and the insulation per unit weight.

2.1.4. Alambeta instrument

Alambeta measuring device is the fast measuring of transient and steady state thermo-physical properties (thermal insulation and thermal contact properties) [25].

Developed in the next chapter.

2.1.5. Permetest

The instrument measures the dynamic heat flow caused by the evaporation of water passing through the specimen tested by a similar procedure to that given by BS EN 31092. Developed in the next chapter.

2.1.6. Thermal manikin

In order to evaluate thermal comfort by numerical approach using the equivalent temperature, it is necessary to integrate thermal manikins in the model [21].

Manikin have been developed in sitting and standing positions as shown in figure 8 [6] in order to stimulate the heat exchange process between human body and environment also to assess clothing insulation [27].

A man-sized and shaped sensor with the surface covered with numerous individually controlled zones makes it a useful instrument for measuring the whole-body heat fluxes.

It is possible to regulate pulsed power for each zone at a rate that allows the maintenance of a chosen constant or variable surface temperature.

The power consumption under steady-state conditions is then a measure of the convective, radiative and conductive heat losses (dry heat loss), Q (in W/m²), and the surface temperature, tsk (in °C). Measurements and regulation are taken care by a computer system.

(A) (B)

Figure 10: Thermal manikin

A- Standing position, B- Sitting position

2.1.7. The Kawabata thermal tester (Thermolabo)

Used to measure the warm/cool feeling offered by the fabrics. which is generated when fabric initially contacts the skin, it is related to the heat flow between the skin and the contacted object [28].

Kawabata has reported that transient heat flux significantly affects clothing comfort in next-to-skin fabrics.

Figure 9 shows the principle used by Kawabata’s Thermolabo device to measure the warm/cool sensation of fabrics.

When a preheated hot plate (as a simulator of human skin) is placed on a fabric sample, a heat flux versus time curve is generated.

Maximum heat flow is measured for a fraction of a second after the hot plate contacts the fabric, a time that approximates the warm/cool feeling experienced when fabric is placed on skin.

The qmax value depends on the heat capacity and conductivity of the fabric and on the area of contact established between the skin and fabric surface.

The surface of contact is the most important part that can determines how the fabric feels to an individual; the surface character of the fabric has great influence on this sensation: a rough fabric surface reduces the area of contact appreciably, and a smoother surface increases the area of contact and the heat flow thereby creating a cooler feeling.

Because qmax is influenced by a combination of fabric surface and thermal properties, it can be expected to be an important predictor of next to skin fabric contact comfort.

NCSU studies have confirmed the correlation between Thermolabo measurement of qmax and subjectively perceived coolness of touch. Hes has also demonstrated the importance of thermal contact properties on clothing comfort.

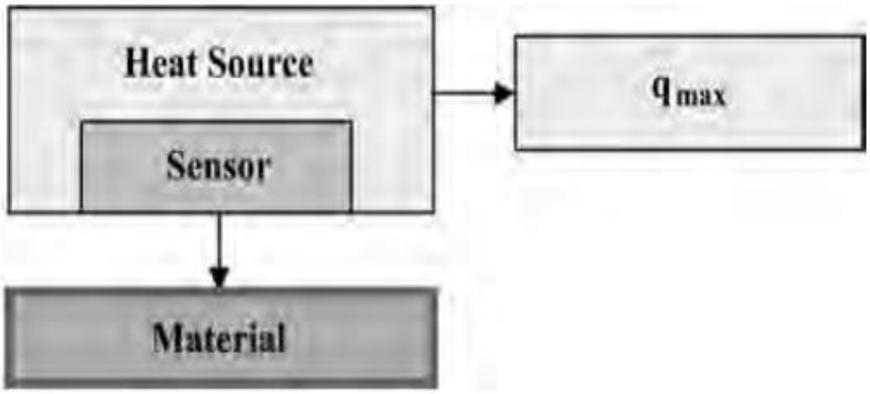


Figure 11: Warm/ cool feeling measuring device

2.2. Sensorial comfort

2.2.1. Kawabata evaluation system of textiles

The Kawabata Evaluation System (KES) is a series of instruments used to measure textile material properties that enable prediction of the aesthetic qualities perceived by human touch [29].

The Hand Evaluation and Standardization Committee (HESC) of Japan recognized and developed the Kawabata's Hand Evaluation System for Fabrics (KES-F), in 1972. The method is based on scientific and empirical reasoning to measure mechanical and surface behavior of fabrics under low stress conditions.

Measurable factors include [30]: surface friction, bending, shear, and compression properties, which are decisive to handle comfort.

- Shear Property Measurement - (KES-FB1)
  In shear testing, the KES-FB1 Tensile-Shear Tester applies opposing, parallel forces to the fabric, until a maximum offset angle of is reached. A pretension load is applied to the specimen.
- Bending Property Measurements - (KES-FB2)
  The Kawabata bending instrument is based on the pure bending of fabric over an arc of a circle. The bending hysteresis and the rigidity values are obtained from the bending tester.
- Compression Property Measurement (KES-FB3**)**

The compression tester compresses a fabric to a maximum pressure of 50gf/cm2 at a constant velocity of 20pm/s. Three different compression parameters such as the compression energy (WC), compressional resilience (RC) and linearity of compression are provided.

- Surface Property Measurements (KES-FB4)

  The surface properties of friction (resistance / drag) and surface roughness are determined using the KES-FB4 Surface Tester. The surface properties of fabrics are characterized using three parameters. They are MIU, mean frictional coefficient, mean deviation of the frictional coefficient, Mean deviation of surface contour.

2.2.2. The Cantilever stiffness tester

The method involves uniformly feeding a flat horizontal strip of fabric between two parallel flat plates in the lengthwise direction and used to measure fabric stiffness according to the ASTM D 1388 standard [31].

The fabric is allowed to deform under its own weight as it emerges at the tip of the plates.

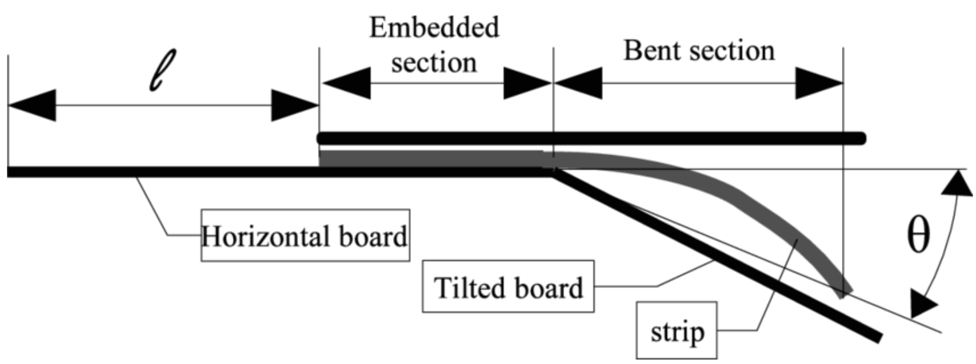


Figure 12: cantilever stiffness tester and bending length

2.2.3. The FAST system (Fabric assurance by simple testing)

The FAST system has been developed by CSIRO Commonwealth Scientific and Industrial Research Organization, primarily for quality control and assurance of fabrics.

It measures properties that are closely related to the ease of apparel manufacturing, handle characteristics and the durability of surface finishing.

Unlike the KES system, FAST measures only the resistance of fabric to deformation and not its recovery from deformation [31].

- FAST-1 (compression meter)

It measures the fabric thickness over a range of loads, the variability and the durability of the thickness of the fabric surface layer. It can measure fabric thickness to micrometer resolution at two predetermined loads, and thereby enables the accurate measurement of surface layer thickness. The fabric thickness is measured at a pressure of 2 gf/cm^2.

- FAST-2 (bending meter)

FAST-2 measures the bending length (BL) and bending rigidity (B) of fabric.

The fabric BL simulates the draping behavior of fabric and B is related to the quality of stiffness when a fabric is handled.

- FAST-3 (extension meter)

It measures extensibility and formability of fabric at various loads as well as its shear rigidity. It is capable of measuring the fabric extensibility in warp, weft and bias directions over a range of loads, with direct reading of extension as a percentage of the initial gauge length, it is measurement of the ability of a fabric to absorb compression in its own plane without buckling.

- FAST-4 (dimensional stability test method)

This is a test method for measurement of relaxation shrinkage and hygral expansion. A template and a ruler are the only equipment required to do the test. The results from this method simulate the change in fabric dimensions that may occur during the actual wear as the fabric is subjected to washing and changing humidity conditions. Relaxation shrinkage is mainly due to the recovery of fabric structure that became strained during manufacturing, while hygral expansion (and hygral contraction) is caused by the swelling or de-swelling of hygroscopic fibers [32].

2.2.4. The Hohenstein Institute development

Hohenstein provides neutral and independent testing of quality and performance for both claim verification and innovative product development.

Areas of expertise include textile sustainability (GMO testing of cotton, microfiber analysis, biodegradation, wastewater analysis, chemical management), quality (material identification, textile and leather tests, chemical tests, audits, color, technical performance descriptions), functionality (comfort, compression, odor management, biocides) health (harmful substances, face masks, textile medical devices, medical compression, applied hygiene), fit (body size and shape measurement and scanning, change during motion, pattern development, 3D fitting, avatars and visualization, material parameters, fit testing) and care (industrial and domestic laundering).

2.3. Liquid moisture management testing

2.3.1. Gravimetric absorbency testing system (GATS)

The GATS procedure measures demand wettability. The test indicates the lateral wicking ability of the fabric or the ability of the material to take up liquid in a direction perpendicular to the fabric surface.

This test is used to measure the ability of fabric wettedness and retainability of liquid; Liquid is delivered to the tested material placed on a porous plate from a fluid reservoir by the capillary action of the fabric, the delivered amount and the percentage of moisture evaporated by the fabric are recorded as a function of time [28].

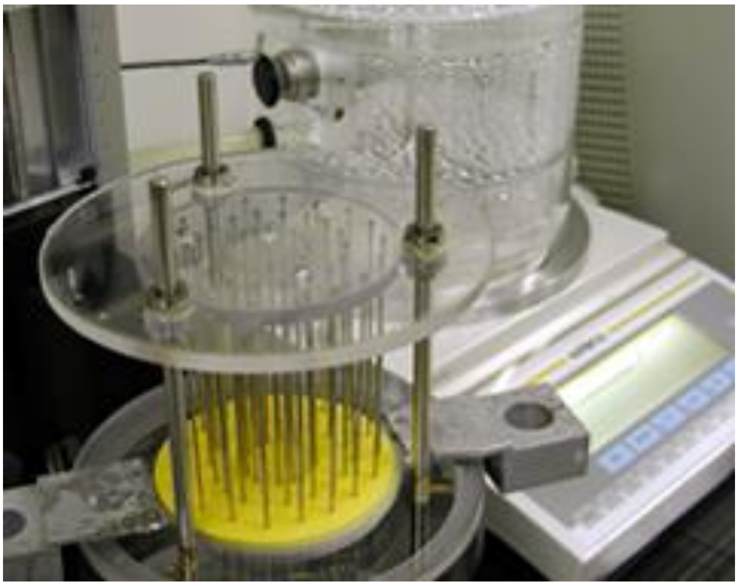


Figure 13 : Gravimetric absorbency system

2.3.2. Sweating guarded hot plate

Used to assess fabric and microclimate response to pulsed heat and moisture loads. With this apparatus, illustrated in figure 14, a momentary vapor pressure gradient is created using a diffusion column with a shuttering device housed in an environmental chamber.

Strategically placed high sensitivity/rapid response probes track the moisture and temperature pulse history in the microclimate [28].

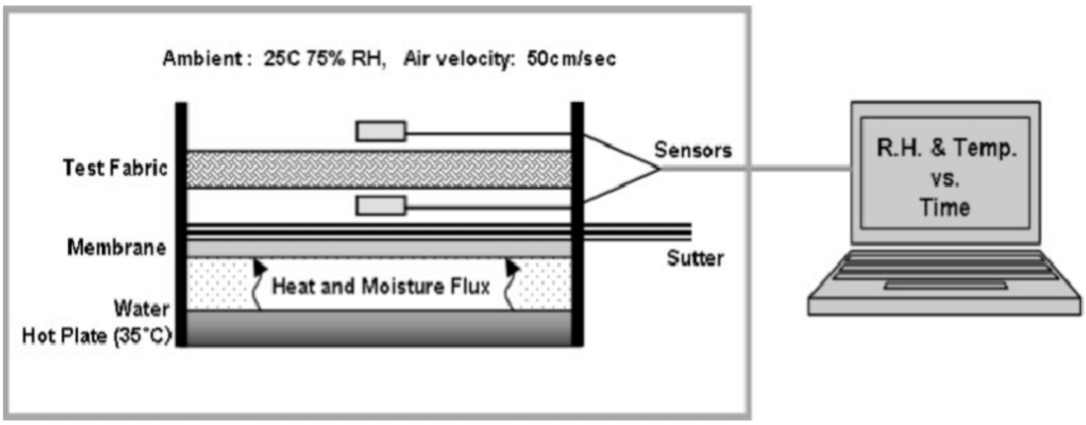


Figure 14: Dynamic sweating hot plate

2.3.3. Sweating manikin

The manikin is capable of internally generating a controlled supply of moisture through 187 individually controlled sweat glands simulating human physiological heat loss mechanism.

Moisture and heat loss can be continuously monitored for full clothing ensembles in a variety of climatic conditions and simulated activity levels.

The manikin is housed in a climatic chamber. Water is supplied from a reservoir, placed on a balance near the ceiling in the chamber.

A microvalve system in the manikin distributes the water to the 187 sweat glands, and the computer system allows individual control of each sweat gland.

The operator controls the water supplied to each of the simulated sweat glands, by setting the desired “sweating” rate.

Individual “sweat glands” are calibrated with software-controlled routing.

To estimate the amount of moisture condensation in the individual clothing layers, the garments are weighted before and immediately after the test [28].

Thermal manikins and sweating thermal manikins as presented in figure 15 are becoming increasingly popular for thermal testing purposes. In addition, special design could allow different motions like walking while testing.

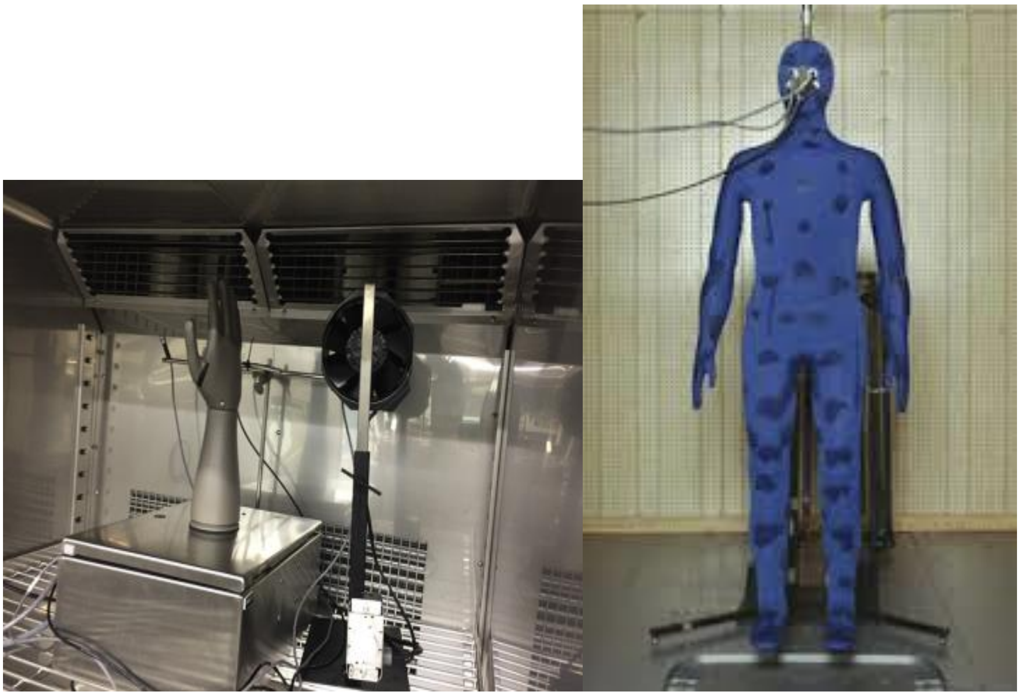


Figure 15: Advanced sweating manikin and sweating hand used for comfort studies

2.3.4. Moisture management tester

Instrument used for measuring moisture transport properties of textiles, it has great influence on the thermo-physiological comfort of the human body, which is maintained by perspiring both in vapor and liquid form (developed in next chapter).

IV. Fibers, yarns and fabrics properties

1. Fibers and yarns

Thermally insulating fibers and yarns are of high importance in the design of cold or hot protection clothing, boots, gloves, etc. Hollow fibers and microfibers are also gaining importance [33]:

- Microfibers

Microfibers provide luxurious appearance, improved physical and hand properties and, high level of wearing comfort for fabrics.

Microfibers are commonly used in fashionable cloths, sportswear, home textiles, and industrial products.

The microfiber produced by man like polyester, nylon and acrylic have similar properties to pure cellulose manufactured fibers as cotton and viscose is specially preferred in knitted garments worn next to the skin such as underwear, sportswear etc [34].

➢ Profiled Fibers

Synthetic fibers are used to provide a high level of thermal insulation not only by texturing the yarn but also by introducing a modified fiber cross section [35].

Some synthetic fibers have been produced with a hollow core or channel.

Hollow fibers have many unique properties and have found numerous applications as well; it can provide a great texture with less weight and are often used to make insulated clothing materials with better moisture and heat transport properties than conventional fibers.

Circular fibers when brought close to each other by transverse forces have the potential to establish large area of contact with the surrounding fibers in contrary to non-circular fibers, which are suitable for voluminous structures and texturation.

The yarn structure, the fiber cross-sectional shape and the incorporation of non-circular fiber have a big influence on thermal comfort and wicking behavior of fabric [36].

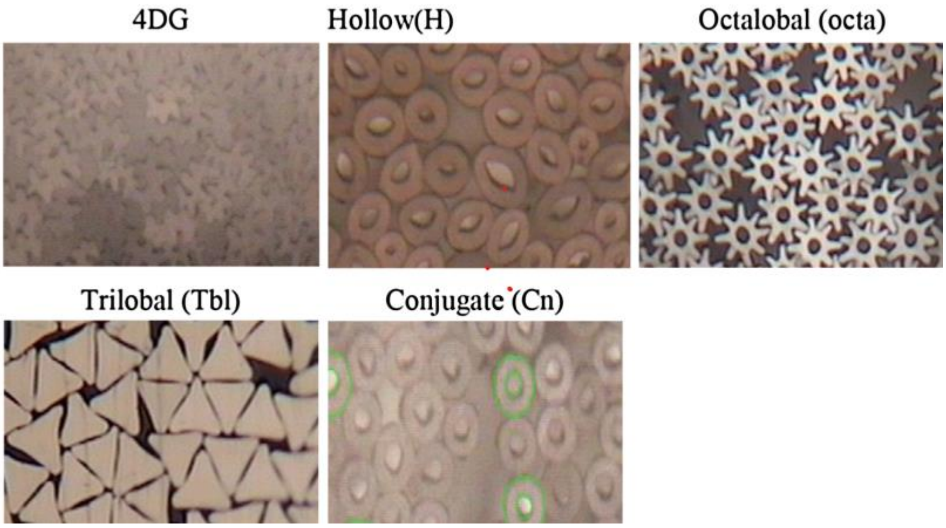


Figure 16: Single yarn cross-section

2. Fabric properties

➢ Multilayer fabrics

There are many different possibilities related to multilayer fabrics and fabric assemblies, first textile layer and second textile layer may be woven, nonwoven or knitted and may be made of one or more suitable textile materials like nylon, polyester, polyamide, polyolefin, acrylic, expanded polytetrafluorethylene (ePTFE), cotton, silk, any combination, blend, or recycled version of the same, the first layer can be in a direct contact with the skin [37] as presented in figure 17.

Preferably, the textile material of first and second textile layers is water vapor permeable. First textile layer and second textile layer protect microporous water vapor permeable layer from damage (e.g., Water, abrasion, puncturing, etc.).

Microporous water vapor permeable layer may include a metallic material. Such as aluminum, titanium, silver, copper, gold, Zinc, cobalt, nickel, platinum, or any combination or a microporous membrane coated with a metallic material.

The microporous membrane may be composed also of polymeric materials, metallic materials, or ceramic materials.

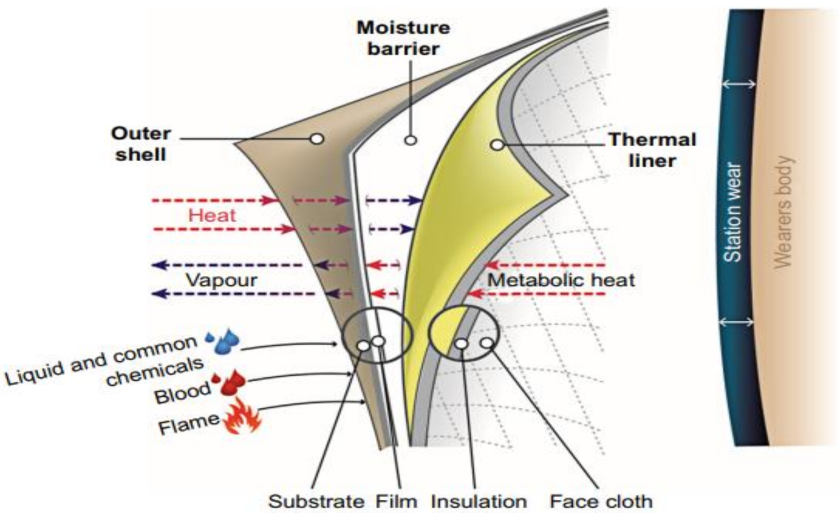


Figure 17: Schematic representation of multilayer fabric

- spacer fabric

The basic construction of spacer fabrics is formed of two textile layers having different properties held by spacer threads in a defined spacing, to form a unique structure.

This structure provides tortuous spaces which let heat and moisture to be transferred through the fabric with air easily.

Spacer fabrics can be produced by using weaving, nonwoven, warp and weft knitting techniques.

These fabrics are characterized by excellent compression elasticity, high breathability and air permeability, high thermal insulation and temperature regulation, surface resistance.

It can be used in various applications, from protective clothing to mattresses and composites, there characteristics make them suitable to use for medical purpose such as beds, supporting pillows, bandages, shoes, operation tables and so on the ability to knit [38].

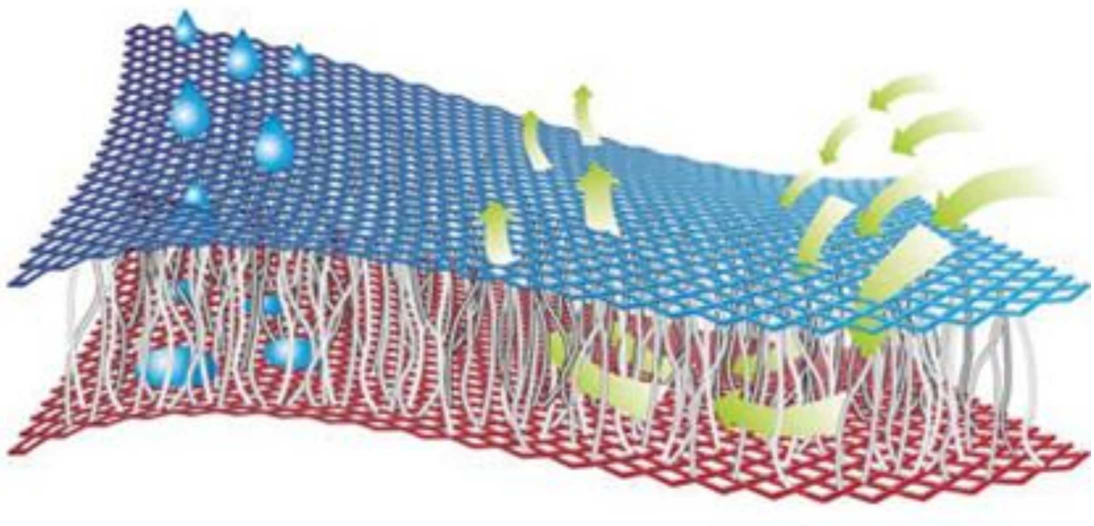


Figure 18: Schematic representation of spacer fabric

3. Recent advances

3.1. Phase change materials

A phase change material (PCM) is a thermoregulation material that can be used for its cooling, refreshing effect. The effect involves heat absorption during a reversible thermal transition from a solid to a liquid state.

Phase change materials are microencapsulated, enclosed into microcapsules. These microcapsules can be incorporated into fibers, in a melt extrusion process or applied as a coating using a liquid finishing process for instance [37].

In the latter case, the liquid finishing formulation requires a polymeric binder in order to secure the microcapsules at the surface of the fibers and ensure durability to repeated washings.

When the outer environment temperature risethe PCM contained in the fabric begin the phase change process, change from solid to liquid, absorb the heat stored in fabric.

When the outer environment temperature lower, the PCM contained in the fabric change from liquid to solid, release the stored heat, maintain the body temperature and let the human body in a comfortable temperature state as shown in figure 19.

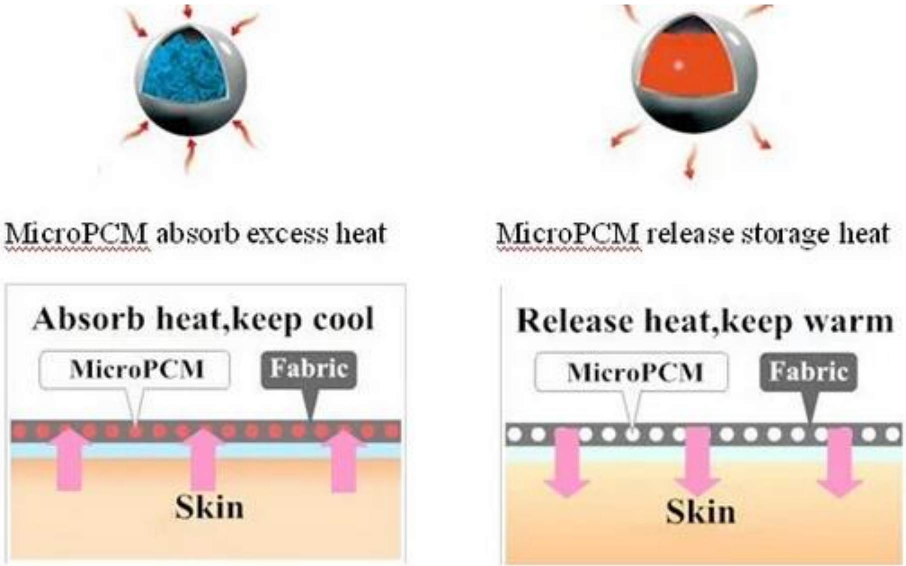


Figure 19: MicroPCM application technology in textile fabric

3.2. Cooling vest

A thermophysiological study with human subjects wearing cooling vest was made;

cooling vest was worn next to the skin as a novel concept of uniform, showed a significant reduction of the thermophysiological stress; They observed that the cooling vest allowed maintaining the microclimate temperature below 35°C, about five degrees lower than the control condition (without cooling vest), while performing the test.

In addition, the relative humidity inside the garment (in the microclimate) was also reduced by 17%, thereby improving comfort [37].

Figure 20: PCM-cooling vest

Conclusion

The early study related to the thermal comfort principal keys, set up the theoretical background for the concept of thermal behavior of clothing and its relationship with the human body. Clothing comfort is composed of three main features: thermophysiological, sensorial, and physiological comfort. This chapter has introduced the important thermal and moisture related properties of textiles that deals with the thermophysiological comfort needed for next chapter, that presents the materials and method used.

Chapter 2: Materials and Methods

This chapter is a general presentation for the important needs to ensure the progress of this work; it is divided to two main parts :

The first part presents the sample used, their composition, structures and the characteristics of their fibers.

The second part presents the equipment used to determine the structural and physical properties of all samples, their thermal and moisture management properties; this chapter ends with a conclusion.

I. Used materials

In this study, 12 knitted fabrics were used, 7 sample single jersey (polyester, coolmax, polyviscose, cotton-polyester-elastane, polyester-elastane, Modal, rhovyl) and 5 sample rib 1*1 structure (polypropylene, wool, viscose, cotton, modal)

1. Cellulosic fibers

Cellulose is primarily defined as the non-branched macromolecule containing chain of variable length of 1-4 linked β-d-anhydro glucopyranose units, figure 21 present the chemical structure of cellulose [40]. The length of different types of chains depends upon the source of cellulose.

The prime interest in natural cellulosic fibers arises due to their eco-friendly advantages, economical production and higher specific strength compared to their traditional synthetic counterparts.

Cotton was used as naturel cellulose, viscose and modal as regenerated cellulose.

The regenerated cellulosic fibers, such as viscose and modal combine the advantages of natural and synthetic fibers and offer unique properties in textile. Their production is environment friendly and pollution-free [39].

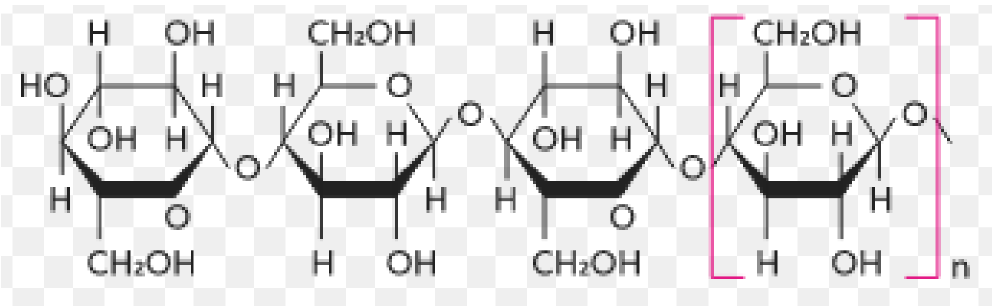


Figure 21: chemical structure of cellulose

- Cotton

Cotton fibers are natural hollow fibers; they are soft, cool, known as breathable fibers and absorbent. They are strong, dye absorbent and can stand up against abrasion wear and high temperature [41].

- Modal

Modal fibers are defined in International Standard ISO 206: 999 (E) as high wet modulus, high breaking strength regenerated cellulose fibers produced by using particular viscose rayon, and regeneration bath compositions which allows greater molecular orientation during stretch and coagulation of the fibers.

- Viscose

Viscose is a semi-synthetic material used in clothes, upholstery and other bedding materials. It’s derived from wood pulp, which is treated and spun into yarns to make fabric.

Viscose rayon is derived from cellulose, the main constituent of plant cell walls. Cellulose is treated with chemicals to make similar fiber qualities of natural fibers, such as silk and cotton.

2. Wool

Wool is animal fiber that is made from the skin of sheep. It is also known as protein fiber. Wool has a range of diameters that make it multifunctional, hygroscopic and versatile fiber. Wool is composed of carbon, hydrogen, nitrogen, and this is the only animal fiber, which contains sulfur in addition [42].

3. Synthetic fibers

- Polyester

Polyester fiber is synthetic fiber having great strength, luster and abrasion resistant. It has 35% crystalline region and 65% amorphous region. The longitudinal appearance of the fiber is very regular and featureless because of the near circular cross section. Polyester can be blended with natural fiber to achieve comprehensive properties of the product.

- CoolMax

CoolMax is a high-tech material specifically and uniquely engineered to keep users dry and comfortable. CoolMax material is made from specially engineered hollow polyester fibers that is not hygroscopic; material that does not have the tendency to absorb moisture and has 20% higher surface area than traditional round fiber [43].

- Polypropylene (PP)

One of the widest used thermoplastic polymers for application in textile (especially in carpets and nonwovens). This is attributed to its low density, low cost, easy processing, high-tensile strength and excellent chemical stability.

- Rhovyl; Chlorofiber, polyvinylchloride (PVC)

Rhovyl is an antibacterial material that has antibacterial agents integrated into the fiber itself. This prevents the formation of bacteria and does not wash out. It is used in bedding, children's clothes, sportswear and underwear, and has many properties: thermal insulation and natural fire retardancy [44].

4. Sample used

The knitted fabric composition, structure and fabric code are presented in table 3:

Table 3 : presentation of samples

Fabric code	Fabric composition	Fabric structure
PES	100% polyester	Single jersey
CM	Coolmax	Single jersey
CPE	60% cotton 30% polyester 10% elastane	Single jersey
P/E	90% polyester 10% elastane	Single jersey
P/V	65% polyester 35% viscose	Single jersey
RH	100% rhovyl	Single jersey
Msj	100% Modal	Single jersey
PP	100% polypropylene	Rib 1*1
W	100% wool	Rib 1*1
COT	100% cotton	Rib 1*1
VIS	100% viscose	Rib 1*1
Mrib	100% modal	Rib 1*1

II. Instrument and methods used for measurements

All of the experimental studies in this section were conducted in the textile laboratories at the technical university of Liberec, Czech Republic, Faculty of textile engineering, Department of textile evaluation.

Table 4 : equipment used

Process	Equipments
Structural and physical testing	
Mass per unit area	Sartorius Measuring Balance
thickness	Sodemat Thickness tester AS 2001.2.15.198
porosity	The optical microscope
Thermophysiological comfort testing	
Warm/cool feeling	ALAMBETA instrument ISO 11092
Thermal resistance	ALAMBETA instrument ISO 11092
Thermal conductivity	ALAMBETA instrument ISO 11092
Moisture absorptivity	ALAMBETA instrument ISO 11092
Liquid moisture transport	Moisture Management Tester ISO 9073-8
Air permeability	TEXTEST 3300 TESTER-ISO 9237: 1995(F)
Water vapor permeability	PERMETEST apparatus-ISO 11092
Water vapor resistance	PERMETEST apparatus-ISO 11092

1.Structural and physical properties of knitted fabrics

1.1. Mass /unit area

Specimens of 10cm x 10cm from the knitted fabric sample were conditioned and tested in a standard atmosphere. Each of specimens is weighed by a measuring balance.

The mass per unit area was calculated as the mean mass per unit area of the specimen using the following formula:

$$M=m/a \qquad (6)$$

Where;

- **M**: Mass per unit area (g/m²);
- **m**: The mass of the specimen (g);
- **a**: The area of the specimen (m²);

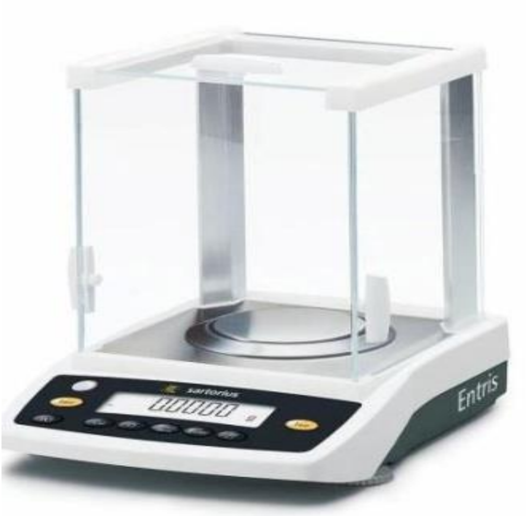


Figure 22 : the measuring balance

1.2. Air permeability

One of the comfort measures that greatly affects the wearer is air permeability.

Defined as the volume of the air flow passing through the fabric at certain pressure gradient.

Air permeability values were determined by using Textest FX 3300 instrument, according to TS 391 EN ISO 9237.

The measurements were done in controlled laboratory conditions, and the results were established after five readings for each sample in different places of the knitted fabric.

The surface area tested is 20 cm² and the air pressure differential applied between the two surfaces of the textile material was 100 Pa**.** The airflow is gradually adjusted until the flow meter indicator is stabilized**.**

The main components of the air permeability tester are: Test head for positioning the test sample, clamping system for securing the test specimen to the test head without any distortion, air pump to draw a steady flow of air perpendicularly through the test fabric and pressure gauge or manometer connected to the test head below the test sample to measure pressure drop across test sample in Pascals [45].

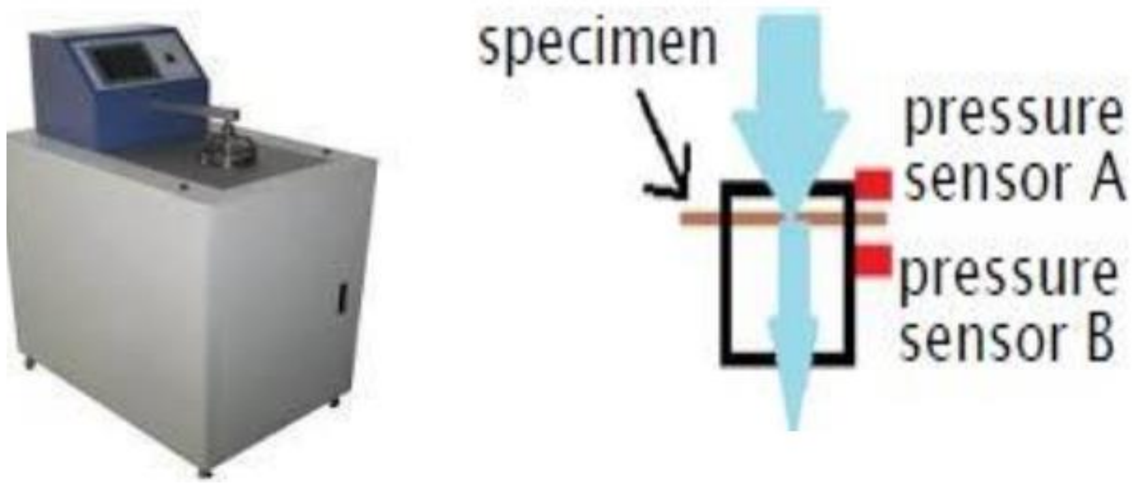


Figure 23 : air permeability tester

1.3. Thickness

The thickness of fabric samples is measured as the distance between the reference plate and parallel presser foot (AS 2001.2.15-198).

Test specimens was conditioned and tested in the standard atmosphere.

After that the thickness tester was prepared, the presser foot was lifted, and the fabric sample was positioned on the thickness tester reference plate, then the presser foot was gently lowered to apply pressure to the fabric sample. Ten measures on different areas of the sample were recorded.

Figure 24 : thickness tester

1.4. Optical microscope

This microscope uses visible light and a system of lenses to magnify the images of textile materials. Those images can be captured by normal, photosensitive cameras to generate a micrograph.

It works on 2X to 20X magnification, but we have used 10X magnification. Images of fabrics were captured by a digital camera integrated to a microscope with a 10-magnifying lens.

Figure 25 : Optical microscope

1.5. Stitch density

Stitch density and loop length have an important influence on tightness factors, together with twist multipliers have an effect on air permeability property of different knitted structures.

Stitch density expressed in terms of:

$$\text{Stitch density} = \text{courses/cm} \times \text{wales/cm} \qquad (7)$$

where:

- **Stitch Density -** The number of loops or stitches per unit area: stitches/cm²
- **Wale vertical column of loops**: Number of horizontal rows of loops per unit length expressed as: courses/cm or
- **Number of vertical columns of loops** per unit width expressed as: wales/cm

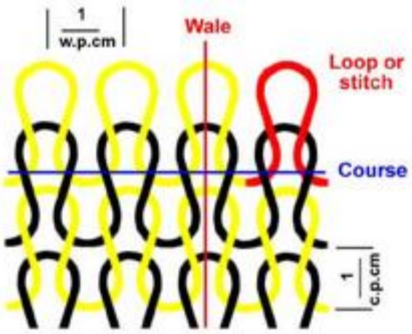


Figure 26 : Stitch density

2. Determination of thermophysiological comfort properties

2.1. ALAMBETA

The Alambeta device is a computer-controlled instrument constructed by professor Lubos HES for measuring the basic static and dynamic thermal characteristics of textiles.

This method belongs to the so-called ‘plate methods’, the acting principle of which relies on the convection of heat emitted by a hot upper plate in one direction through the sample being examined to the cold bottom plate; The sample is kept between the hot and cold plate according to ISO11092.

The hot plate comes in contact with the fabric at a pressure of 200 Pa.

The principle of this instrument depends on the application of an ultra-thin heat flow sensor (4) which is attached to a metal block (2) with constant temperature which differs from the sample temperature. When the specimen is inserted, the measuring head (1) containing the mentioned heat flow sensor drops down and touches the measured sample (5), which is located on the instrument base (6) under the measuring head.

At this moment, the surface temperature of the sample suddenly changes, and the instrument computer registers the heat flow course.

Simultaneously, a photoelectric sensor measures the sample thickness. All the data are then processed in the computer according to an original program, which involves the mathematical model characterizing the transient temperature field in a thin slab subjected to different boundary conditions.

To simulate the dry human skin and the real conditions of warm-cool feeling evaluation, the instrument measuring head is heated to 32ºC (the heater (3) and the thermometer (8)), which correspond to the average human skin temperature, while the fabric is kept at the room temperature 22ºC. The measurement lasts for several minutes only, the evaluation of humid samples is reliable too since they don’t turn dry during the measurement [45].

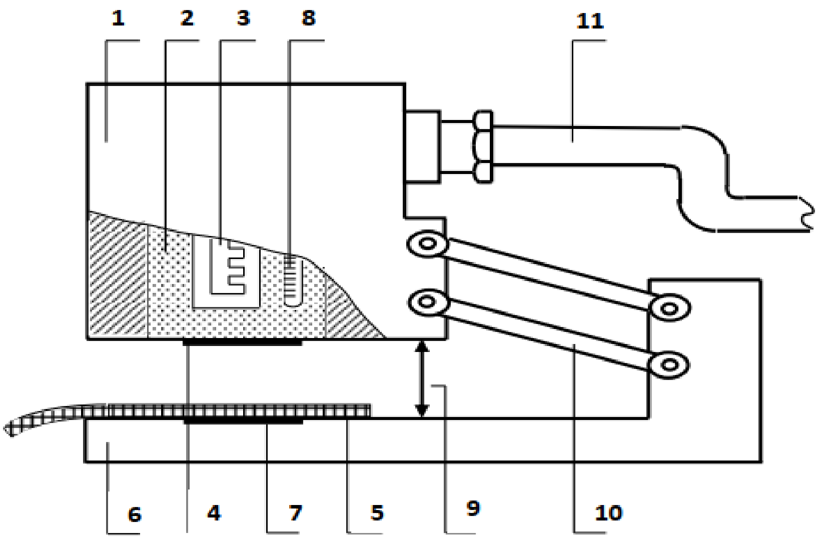


Figure 27 : Alambeta non-destructive commercial tester of thermal properties of textile

An Alambeta instrument was used to measure thermal conductivity, thermal resistance, thermal absorptivity, sample thickness and to calculate all the statistical parameters of the measurement:

Thermal conductivity is an intensive property of a material that indicates

its ability to conduct heat. This parameter is affected by fabric thickness and density.

$$\lambda = Q * \frac{h}{\Delta t}(W/mk) \qquad (8)$$

Where:

- **Q**: The heat quantity (W/m²k);
- **h**: The fabric thickness (m);

Thermal conductivity of textile structures extends in general from 0.033 to 0.01 w/m k While thermal conductivity of the steady air is 0.026 w/m k and thermal conductivity of water is 0.6 w/m k; that proves why the existence of water is textile is not desirable [46].

Thermal resistance is a measure of the body's ability to prevent heat from flowing through it. Under a certain condition of climate, if the thermal resistance of clothing is small, the heat energy will gradually reduce with a sense of coolness [47].

$$R=h/\lambda \qquad (9)$$

Where:

- **R** : Thermal resistance (K m²W)
- **h** : The fabric thickness(m)
- **λ** : The thermal conductivity (W/mK).

Thermal absorptivity is the objective measurement of the warm-cool feeling of fabrics. A warm-cool feeling is the first sensation when a human touch a garment that has a different temperature than the skin, heat exchange occurs between the hand and the fabric.

If the thermal absorptivity of clothing is low, it gives a warmer feeling at first contact. The better feeling depends on customer: for instance, in cold regions warmer feeling is demanded, whereas in hot summer days cooler clothing is preferred [47].

$$b = \sqrt{(\lambda \rho c)} \qquad (10)$$

Where:

- **b**: Thermal absorptivity (w $s^{1/2}$ /m^2 k);
- **λ**: The fabric thermal conductivity (w/mk);
- **ρ** : The fabric density (kg/m^3);
- **c:** The specific heat of fabric (J/kg k) ;

Table 5 : Thermal absorptivity intervals of textile fabrics

ALAM-BETA	Effect of fabric structure, composition and treatment of the level of thermal absorptivity b [$Ws^{1/2}/m^2K$], contact pressure 200 kPa
20-40	Microfibre or fine PES fibre non-woven insulation webs
30-50	Low density raised PES knits, needled and thermally bonded PES light webs
40 - 90	Light knits from synthetic fibers (PAN) or textured filaments, raised tufted carpets
70 - 120	Light or rib cotton RS knits, raised light wool/PES fabrics, brushed micro-fiber weaves
100 - 150	Light cotton or VS knits, rib cotton woven fabrics
130 - 180	Light finished cotton knits, raised light wool woven fabrics
150 - 200	Plain wool or PES/wool fabrics with rough surface
180 - 250	Permanent press treated cotton/VS fabrics with rough surface, dense micro-fiber knits
250 - 350	Dry cotton shirt fabrics with resin treatment, heavy smooth wool woven fabrics
300 - 400	Dry VS or Lyocell or silk weaves, smooth dry resin-free heavy cotton weaves (denims)
330 - 500	Close to skin surface of wetted (0,5 ml of water) cotton/PP or cotton/spec. PES knits
450 - 650	Heavy cotton weaves (denims) or wetted knits from special PES Fibers (COOLMAX)
600 - 750	Rib knits from cotton or PES/cotton or knits from micro-fibers, if superficially wetted
> 750	Other woven and knitted fabrics in wet state
1600	Liquid water (evaporation effect not considered)

2.2. PERMETEST

The Permetest is a measuring instrument (skin model) for the non-destructive determination of water-vapor and thermal resistance of textile fabrics (figure 28).

The porous sweating surface of the device simulates the skin and records the cooling heat flow caused by perspiration.

The fabric sample to be measured is placed on a measuring head over a semi-permeable foil and exposed to parallel air flow at a velocity of 1m/s as shown in (figure 29) [48].

As with all the skin model systems, the measurements are carried out under isothermal conditions (23°C±0.5).

This isothermal principle involves the temperature of the skin model surface, the air temperature and fabric temperature, when the fabric is kept in direct thermal contact with the skin model surface.

The computer connected to the apparatus determines the evaporative resistance (Ret) and the thermal resistance (Rct) of textile fabrics in a similar way to that described in standard ISO 11092, as well as the RWVP (or relative negative heat flow responsible for the cooling of the body). These values serve to reflect the thermophysiological properties of textile fabrics and garments.

The higher the RWVP, the lower the Ret, and the better the thermal comfort of the human. Due to the very short measuring time which normally does not exceed 3 minutes, the fabric mass remains mostly unchanged during the measurements [45].

Relative water vapor permeability of the textile sample RWVP (%) is the percentage of water vapor transmitted through the fabric sample compared with the percentage of water vapor transmitted through an equivalent thickness of air can be determined from the relation:

$$RWVP\% = (qv/q0) * 100 \qquad (11)$$

Where:

- **qv**: it presents the heat loses of the wet measuring head (skin model) with a sample (W/m^2).
- **q0**: it means the instrument reading without a sample (heat loses of the free wet surface in W/m^2);

Water vapor resistance Ret when expressed in terms of the according to the ISO 11092 standard (Textiles-physiological effects-Measurement of the thermal and water vapor resistance) is as the following relationship:

$$\mathbf{Ret}\ [m^2Pa/W] = (Pwsat - Pwo)\ (1/Us - 1/U_o) \qquad (12)$$

Where:

- **Pwsat:** partial pressure of saturate vapor water (Pa)
- **Pwo:** partial pressure of water vapor (Pa)

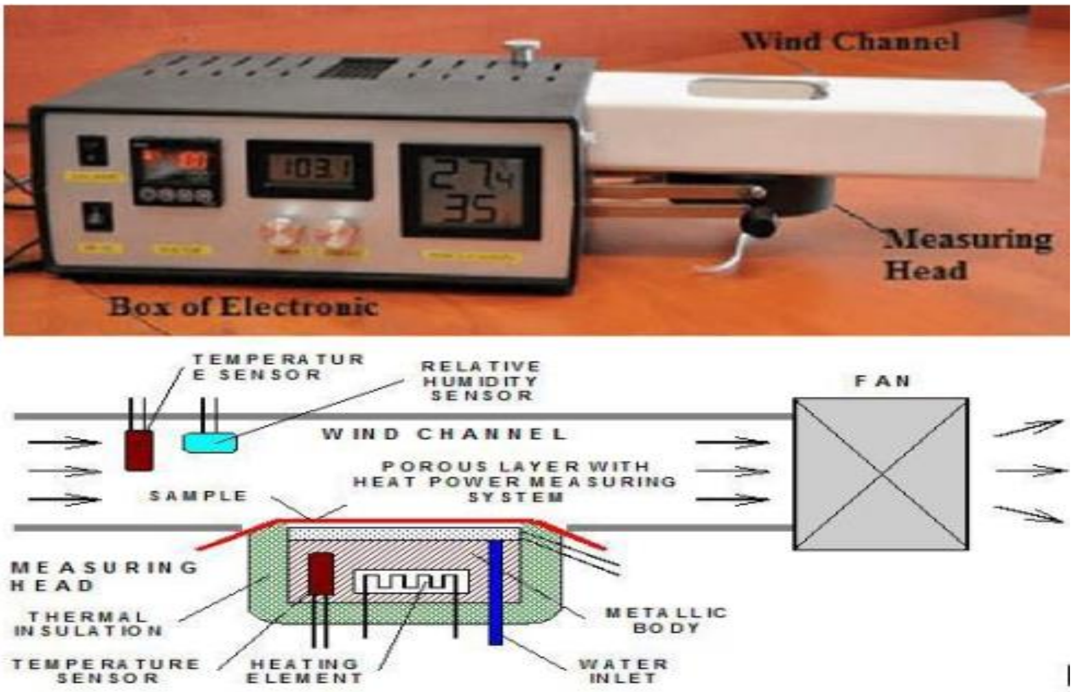


Figure 28 : Permetest device

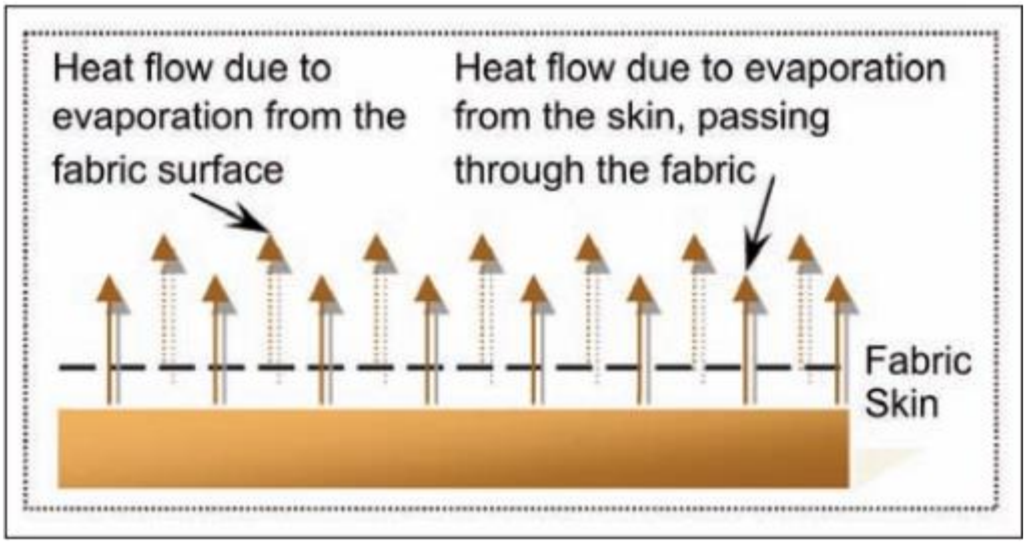


Figure 29 : Heat flow generation due to sweat evaporation from the skin surface and moisture evaporation from the fabric surface

3. Determination of liquid moisture properties

3.1. Moisture Management Tester (MMT)

Fabric liquid moisture transport properties in multi-dimensions, called moisture management properties influence the human perception of moisture sensations significantly [49].

Some standards and test methods can be employed to evaluate the fabric’s simple absorbency and wicking properties, according to ISO 9073-8. However, the existing standards are unable to measure the behavior of liquid transfer of the clothing materials dynamically [50].

The MMT is designed to sense, measure, and record the liquid moisture transport behaviors in multiple directions.

When moisture is transported in a fabric, the contact electrical resistance of the fabric changes and the change in resistance value depends on two factors: the components of liquid and the water content in the fabric.

The liquid components are fixed, so that the measured electrical resistance is related to the water content in the fabric.

In order to simulate sweating (synthetic sweat), a special solution was prepared, by using one liter of distilled water and approximately 9 g of sodium chloride to achieve 0.2 mS of solution conductivity and dropped onto the fabric’s top surface; The specimen was held flat by top and bottom sensors with a certain pressure. During the test, the same quantity of solution (0.15 g) was applied into each specimen’s top surface automatically by the instrument.

The test liquid is dropped from the top part of the instrument to the top surface of the fabric, which is designed as an inner surface that will be in touch with the human skin.

The results found are compared according to the grading scale presented in table 6 [51].

Table 6 : Grading table

Index	Grade	1	2	3	4	5
Wetting time (sec)	**Top**	≥120	20-119	5-19	3-5	<3
		No wetting	Slow	Medium	Fast	Very Fast
	Bottom	≥120	20-119	5-19	3-5	<3
		No wetting	Slow	Medium	Fast	Very Fast
Absorption Rate(%/sec)	**Top**	0-10	10-30	30-50	50-100	>100
		Very Slow	Slow	Medium	Fast	Very Fast
	Bottom	0-10	10-30	30-50	50-100	>100
		Very Slow	Slow	Medium	Fast	Very Fast
Max wetted radius (mm)	**Top**	0-7	7-12	12-17	17-22	>22
		No wetting	Small	Medium	Large	Very large
	Bottom	0-7	7-12	12-17	17-22	>22
		No wetting	Small	Medium	Large	Very large
Spreading speed (mm/sec)	**Top**	0-1	1-2	2-3	3-4	>4
		Very slow	Slow	Medium	Fast	Very Fast
	Bottom	0-1	1-2	2-3	3-4	>4
		Very slow	Slow	Medium	Fast	Very Fast
One-way transport capacity		<-50	-50-100	100-200	200-400	>400
		Poor	Fair	Good	Very good	Excellent
OMMC		0-0,2	0,2-0,4	0,4-0,6	0,6-0,8	>0,8
		Poor	Fair	Medium	Fast	Very Fast

3.2. Ultrasonic cleanser

The classic definition of cleaning is the removal of foreign contaminants from the surface of a substrate without creating a physical change, mechanical or chemical, in the substrate itself.

An ultrasonic cleaning system is made up of two components: an ultrasonic transducer and a high-frequency power supply, commonly called a generator. The ultrasonic transducer elements are attached to a diaphragm, which is arranged to come into contact with the liquid to be ultrasonically activated.

When vibrations are introduced into a liquid, sound waves consisting of areas of alternating high and low pressure are created and radiate from the source of vibration. In an ultrasonic cleaning system, the source of vibration is the ultrasonic transducer [52].

All samples were washed after each measurement on moisture management tester.

Figure 30 : Ultrasonic cleanser

3.3. Moisture absorptivity

In order to explain the thermal comfort of garments after sweating, a new parameter called ‘moisture absorptivity’ was introduced by Hes, it is a new method based on the objective evaluation of cool feeling effect within an experimental procedure which simulates the real fabric wearing conditions. This method is based on the instrument used for the objective warm-cool feeling determination.

Warm-cool feeling means the feeling that we get when the human skin touches shortly any object. This parameter characterizes the transient thermal feeling well which we get in the moment when we put on the undergarment, shirts, gloves or other textiles, especially in wet state.

The determination of warm-cool feeling between the measuring surface and the surface of the fabric simulating wet skin with the tested fabric is with ALAMBETA instrument;

0.2 ml of water (containing detergent) was injected on the center of the interface fabric surface that simulates human wet skin (coolmax)

Coolmax is used as a skin simulator fabric because of its high moisture wicking and fast evaporation.

Within one minute, the liquid distributed uniformly within a circle of 45-50 mm, when this occurred the human skin simulator is placed on the top of the sample (next to skin fabric simulation) and then inserted into the space between the measured sample and the center of the measuring head of the instrument.

At the same time, the interface of coolmax fabric and the measuring head of the instrument dropped down towards to the measured fabric within a few seconds, after contact of both fabrics under pressure 200 Pa, the liquid from coolmax was more or less taken away by absorption in the lower fabric.

In the case of low absorption into the fabric, thermal absorptivity value increase what gives a cooler and wetter feeling, in the case of high absorption, the moisture is rapidly distributed within the whole thickness of the fabric, so the interface gets nearly dry and the instrument shows a lower thermal absorptivity [53].

Fabrics with higher sorption and higher capillary conduction of moisture then make the skin simulating fabric drier and indicate drier (warmer) warm-cool feeling and vice versa.

Figure 31 : moisture absorptivity measuring method

3.4. Moisture regain calculation

The samples are weighed after getting in contact with the human skin simulator (coolmax) while measuring moisture absorptivity.

The moisture content or the mass increase *Mn* (%) due to absorbed moisture was calculated as follow;

$$Mn\ (\%) = \frac{Wwet - Wdry}{Wdry} . 100 \qquad (13)$$

Where:

- **Mn (%)**: the fabric relative moisture content.
- **Wwet**: the fabric weight in wet state.
- **Wdry**: the fabric weight in dry state

Conclusion

This chapter represents the used materials and methods for characterizing the thermal comfort properties and moisture as well.

Alambeta is used as an assessment for the determination of thermal properties of all knitted fabrics, it gives an overall about the comfort and warm-cool feeling, permetest and air permeability tester were used to determine the breathability and permeability of all specimens and MMT is used to characterize the moisture properties and the ability of fabric to manage moisture.

The next chapter represents the experimental results with discussion.

Chapter 3 : Results and discussions

Based on the experimental findings; in this chapter we aim to study the thermophysiological comfort properties for different knitted fabrics, having different raw material, structural and physical properties and then to find the suitable use for each knitted fabric, according the results and the literature background.

So, this chapter divided to three parts organized as follow:

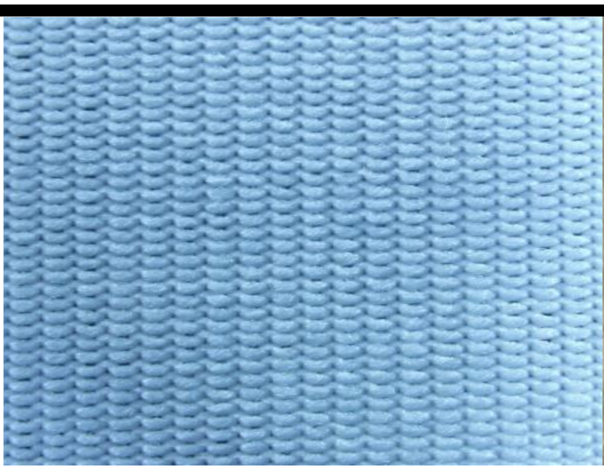
First part presents the structural and physical properties, second part shows the thermal properties and third part determine the moisture management properties of each sample. This chapter ends by an overall conclusion.

I. Structural and physical properties of knitted fabrics

The fabric structural and physical properties like aerial density (g/m^2), thickness(mm), stitch density ($loops/cm^2$) and air permeability ($l/m^2/s$) were evaluated in the table 7 .
The microscopic view is presented in figure 32.

Table 7 : Fabric structural and physical properties

Knitted structures	Fabric code	Course (count / cm)	Wales /cm	Stitch density [$loops/cm^2$]	Weight per unit area, [g/m^2]	Thickness [mm]	Air permeability [$l/m^2/s$]
Single jersey	PES	12	22	385	179.9	0.571	1442
	MSJ	16	22	352	165.32	0.4519	1760
	P/V	14	27	378	179.44	0.569	1510
	C/P/E	15	30	450	202.71	0.709	183.2
	P/E	19	23	437	198.9	0.591	367
	RH	21	19	399	198.74	0.622	629
	CM	14	30	420	180.58	0.4	693.4
Rib 1*1	M RIB	16	23	368	162.74	0.612	1744
	VIS	21	18	378	174.14	0.766	1168
	COT	23	17	391	174.14	0.766	1168
	PP	20	19	380	139.77	0.752	1540.6
	W	31	27	837	258.29	1.037	180.3



COOLMAX(100µm)

60%COTTON 30%POLYESTER 10% ELASTANE(150µm)

90%POLYESTER 10% ELASTANE(200µm)

MODAL RIB (100µm)

WOOL(100µm)

POLYPROPELYNE(250µm)

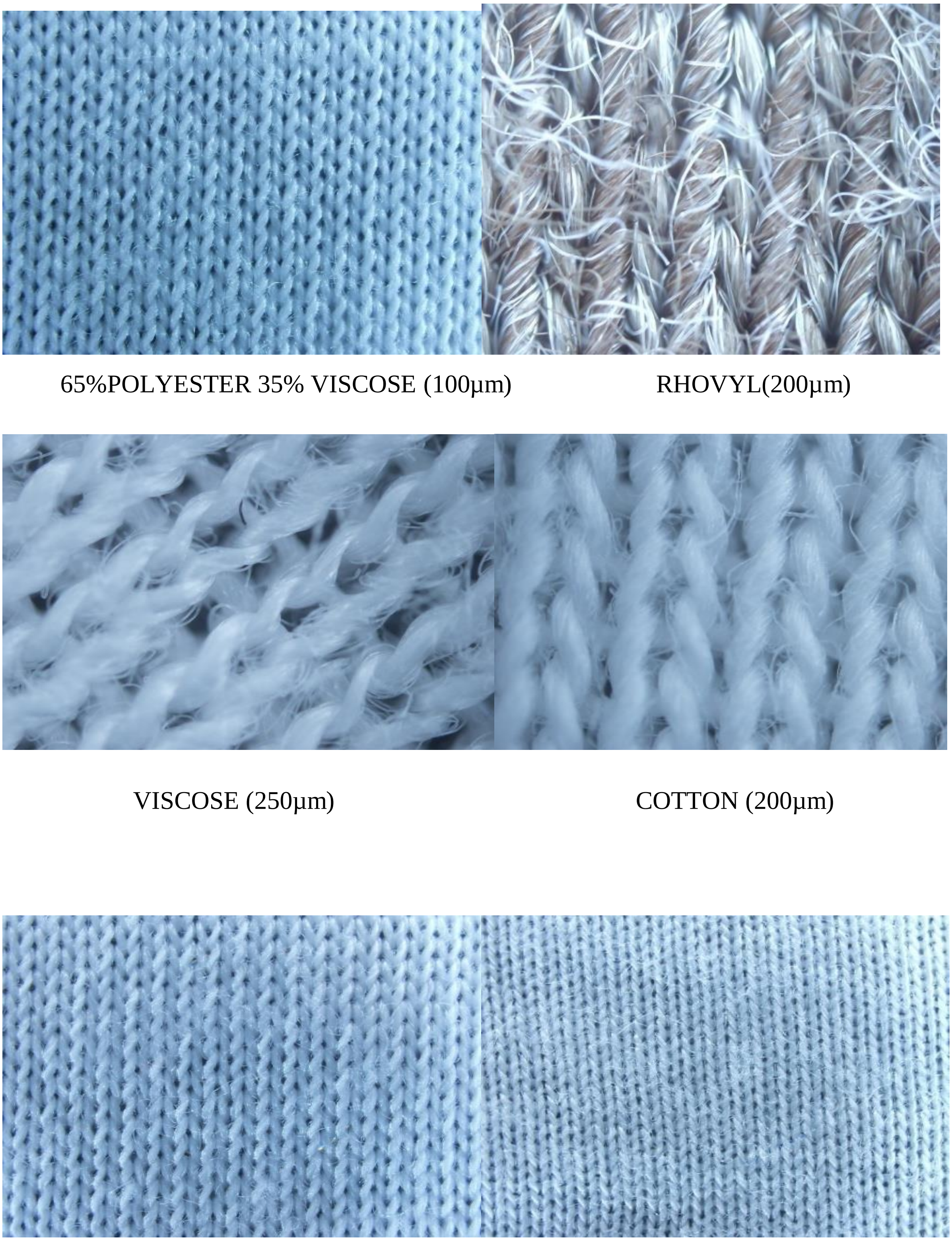


Figure 32: microscopic view of different samples (10x magnifications)

The microscopic view for different knitted fabrics presented in figure 32 indicate some of its properties: it is obvious that Mrib and Msj have porous structure while coolmax and wool have tighter structure. Also, CPE and PE have tighter structure than cotton and viscose.
PP has loose stitches while RH has tight stitches.

II. Thermophysiological properties

Based on the experimental methods, thermal comfort properties of different knitted fabrics were determined and displayed in Table 8:

Table 8 : Thermophysiological comfort properties of different knitted fabrics

Fabric structure	Fabric code	Thermal conductivity [10^{-3}W /mk]	Thermal absorptivity [$Ws^{1/2}$ /m²K]	Thermal resistivity [m² K/W]	RWVP %	Ret [m²Pa /W]	Regain value %
Single jersey	PES	42.88	114	16.94	72.18	2.48	0.681
	Msj	48	145	15.56	71.8	2.96	1.558
	P/V	41.86	119.4	18.52	70.34	3.14	1.053
	C/P/E	57.12	145.8	13.8	66.08	3.74	1.48
	P/E	62.04	162.8	11.1	70.72	2.6	0.72
	RH	41.78	135.4	18	70.28	3.1	0.604
	CM	63	192	8.22	79.44	1.68	0.336
Rib 1*1	Mrib	47.12	142.8	15.94	68	3.48	1.9
	VIS	53.32	142	17.88	71.26	3.04	2.036
	COT	46	128	21.1	68.7	3.52	2.798
	PP	49.1	133.4	16.96	79.04	2	0.34
	W	40.3	113.2	32.2	62.5	4.4	1.52

1. Air permeability

The air permeability is the measure of air flow passed through a given area of a fabric. The results are presented in figure 33:

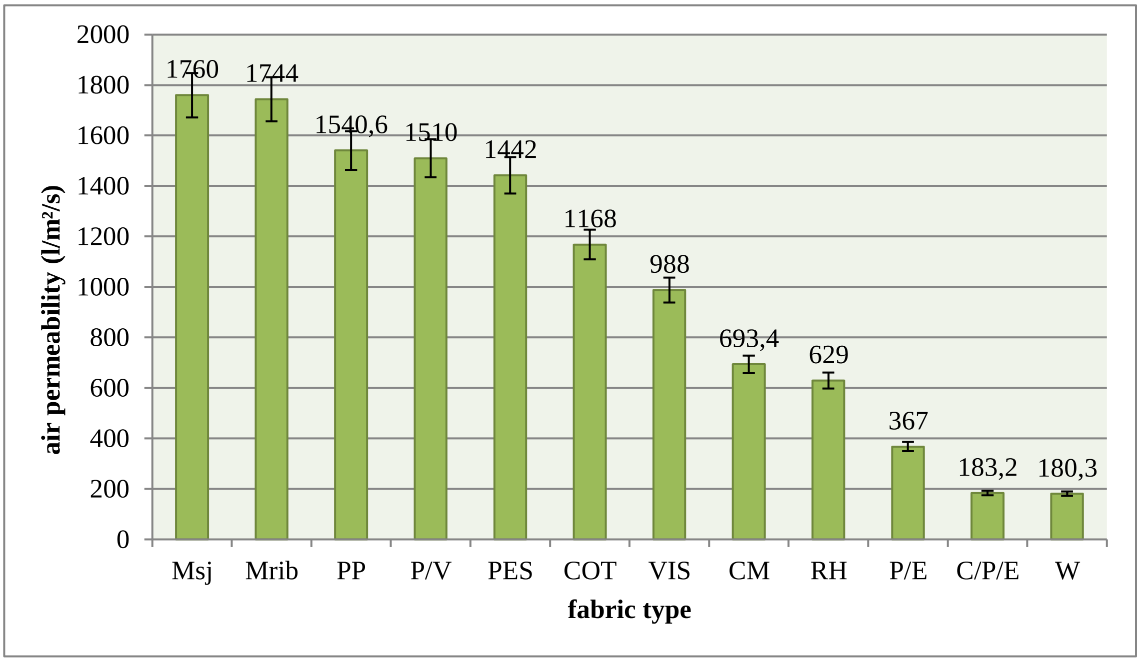


Figure 33 : Effect of fiber type on air permeability

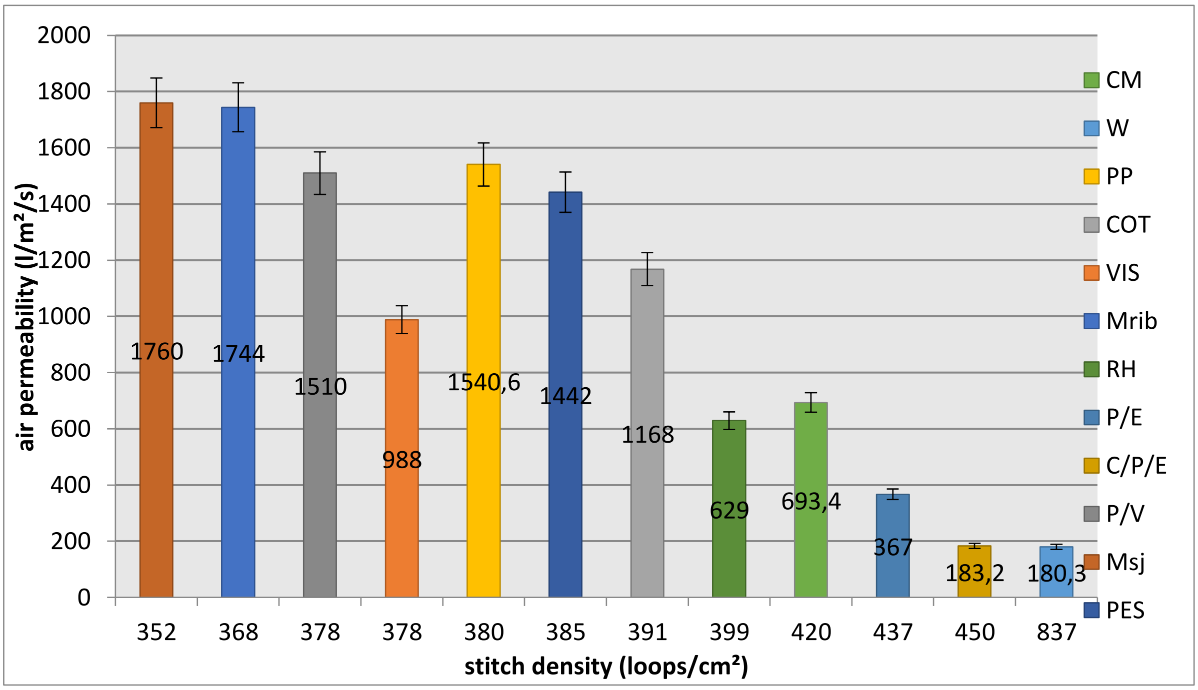


Figure 34 : Effect of stitch density on air permeability

It is clear from Figure 33 that the air permeability of fabric is inversely proportional to stitch density, the higher the stitch density, the lower porosity of the fabric, the higher the air permeability:

The air permeability is the lowest for the wool fabric, having the highest stitch density, while this value is the highest for the modal fabrics (Msj and Mrib) having the lowest stitch density values. It decreases as the stitch density decreases. Higher stitch density leads to more courses and wales which occupy more space, leading to smaller pores size. The decreased pores size leads to lower air permeability, this result can be confirmed with the microscopic view of Mrib and Msj presented in figure 32 showing the loose structure.

The results indicate also that for rib structures PP has higher value than VIS and PES; because PP has the lowest areal density, while for single jersey structure P/V has higher value of air permeability than PES and CM and lower areal density. Fabric structure and areal density directly affect the number of pores on the fabric.

The comparison of RH values with C/P/E and P/E values showed that RH has the highest value of air permeability but the lowest thickness value, thus the higher the thickness the more is the resistance to passage of air through fabric; lower air permeability.

As shown in the figure 34, despite having higher stitch density, cotton has higher air permeability values, that’s can be attributed to lower areal density value or because of the inter-fiber structure of cotton is more permeable.

2. Thermal conductivity

The thermal conductivity values for all fabrics were presented in table 8 and compared in figure 35:

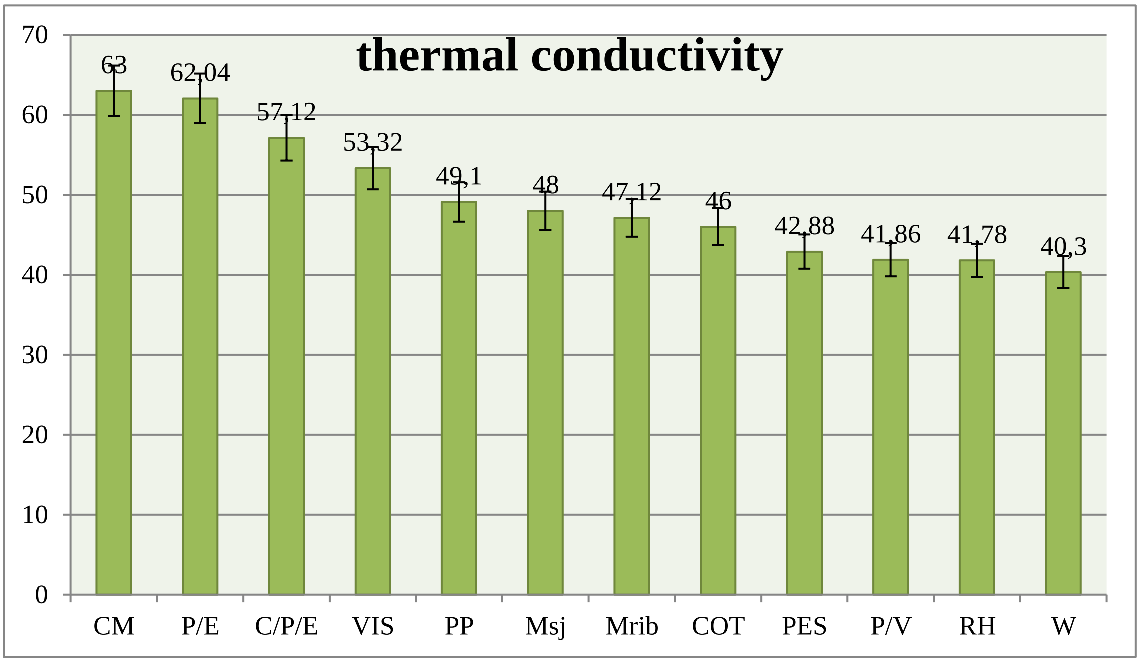


Figure 35 : Effect of fiber type on thermal conductivity

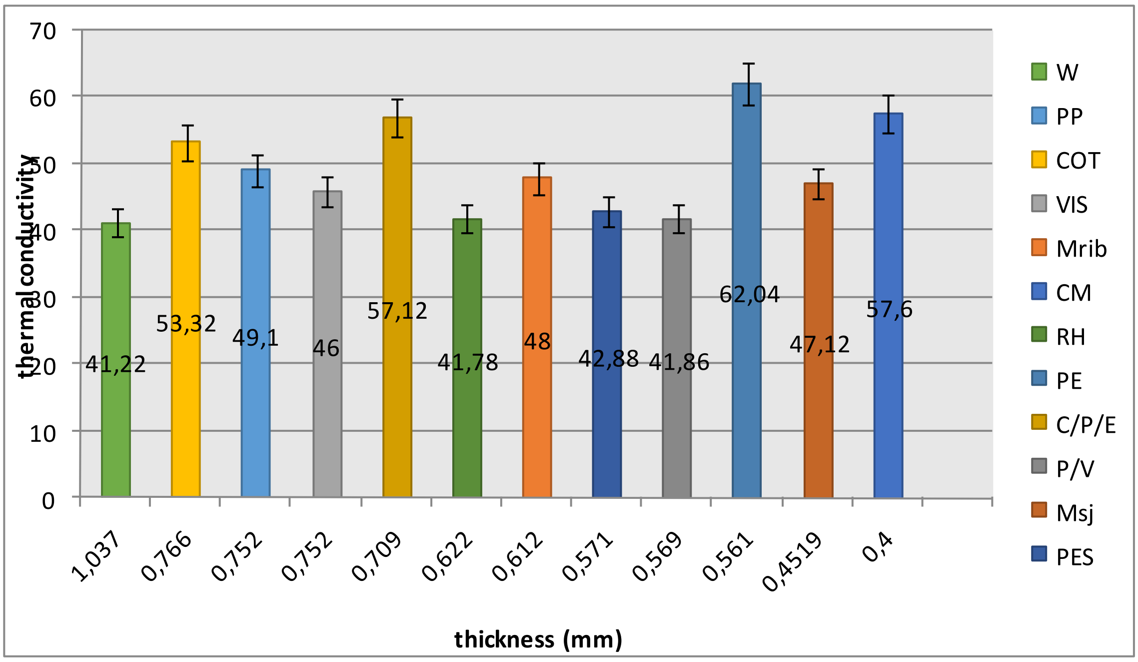


Figure 36 : Effect of fabric thickness on thermal conductivity

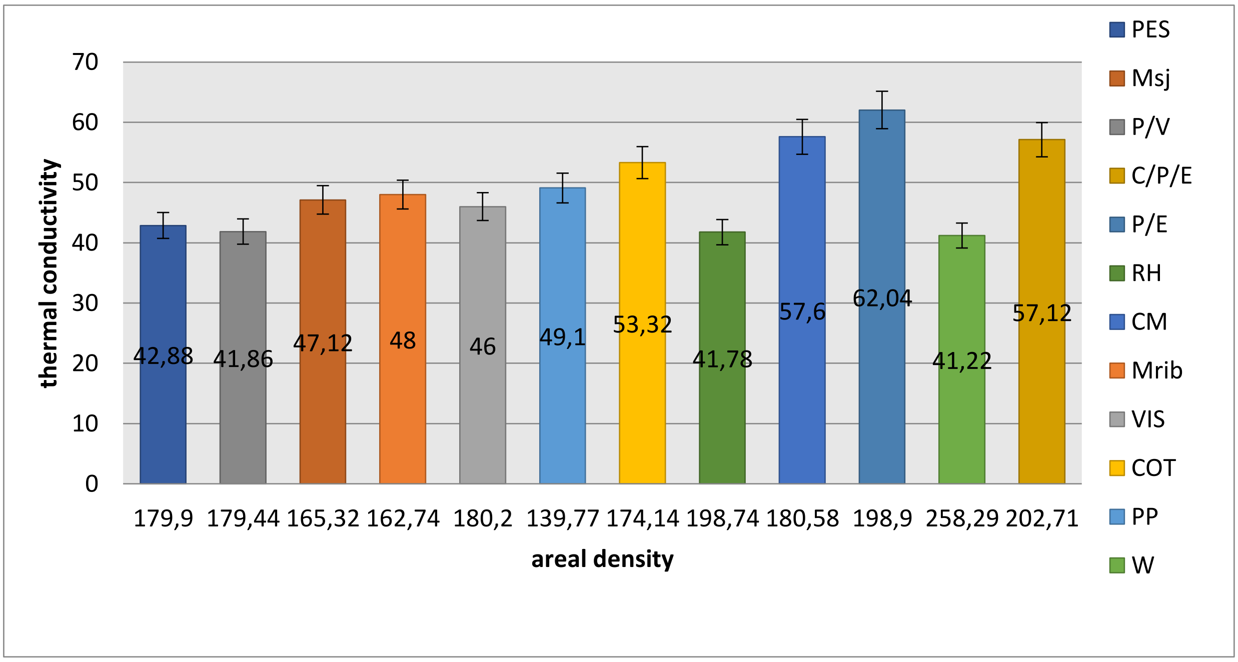


Figure 37 : Effect of areal density on thermal conductivity

Thermal conductivity is a material property that is described as the quantity of heat transmitted through the thickness of the material direction normal to the measured surface area. This property indicates the ability of fabric to conduct the heat coming from the source.

As shown in figure 36 the knitted fabric thickness has a significant influence on the thermal conductivity. It can be seen that regardless of the fabric composition, Wool has the lowest thermal conductivity, while CM has the highest value, this can be explained by the higher thickness of W and, the lower thickness of CM, thus more space to trap air inside the structure have relatively lower thermal conductivity.

COOLMAX has the ability to provide the best cooling effect while WOOL gives warmer feeling.

The fabric thermal conductivity can be discussed in relation to its porosity as a determining factor, figure 37 demonstrates that with the porosity increasing, the thermal conductivity becomes lower , what explains that despite PE, CPE and PES have the same knitted structure , PE and CPE have higher thermal conductivity than PES , thus PES has lower stitch density than PE and CPE , the presence of lycra increase the tightness (as shown in microscopic view figure 32) of fabric and stitch density due to the compact packing of yarns in the fabric structure , therefore less still air and higher thermal conductivity .

The conductivity of a fiber is higher when having the lowest air permeability;

Since viscose has lower air permeability value than cotton and higher thermal conductivity, this indicates that the ratio of fibers for the cotton fabrics is higher, so the air is mainly entrapped between fibers of the yarn.

According to the results Mrib has higher thermal conductivity than Msj, the thermal conductivity of knitted fabric constructed on rib machine higher than those constructed on jersey machine. This situation can be explained by the amount of fiber per unit area. While the number of fibers increases, the amount of entrapped air decreases.

The fiber conductivity also plays a role in determining the thermal conductivity;

Thermal conductivity of VIS higher than P/V, thus the use of polyester can decrease the thermal conductivity, this result also found by Gauthier Bedek et al.

RH has lower thermal conductivity than PP and the other synthetic fibers; as known that chlorofiber has insulating (low thermal conductivity) property that is better than most other fabric materials.

According to the results fabric thickness and porosity are significant factors for the thermal conductivity; tighter samples having higher weight, also have higher thermal conductivity values.

Structure can influence on thermal conductivity; rib structures, due to their high thermal insulation values (knits are thicker that retains more heat and air between body and garment), could be preferred for winter garments in order to protect from cold, since a lower value of thermal conductivity indicates a lower heat transfer from the skin to the fabric surface, this is usually associated with a warm feeling.

3. Thermal absorptivity

Thermal absorptivity values of all knitted fabrics were presented in table 8 and compared in figure 38:

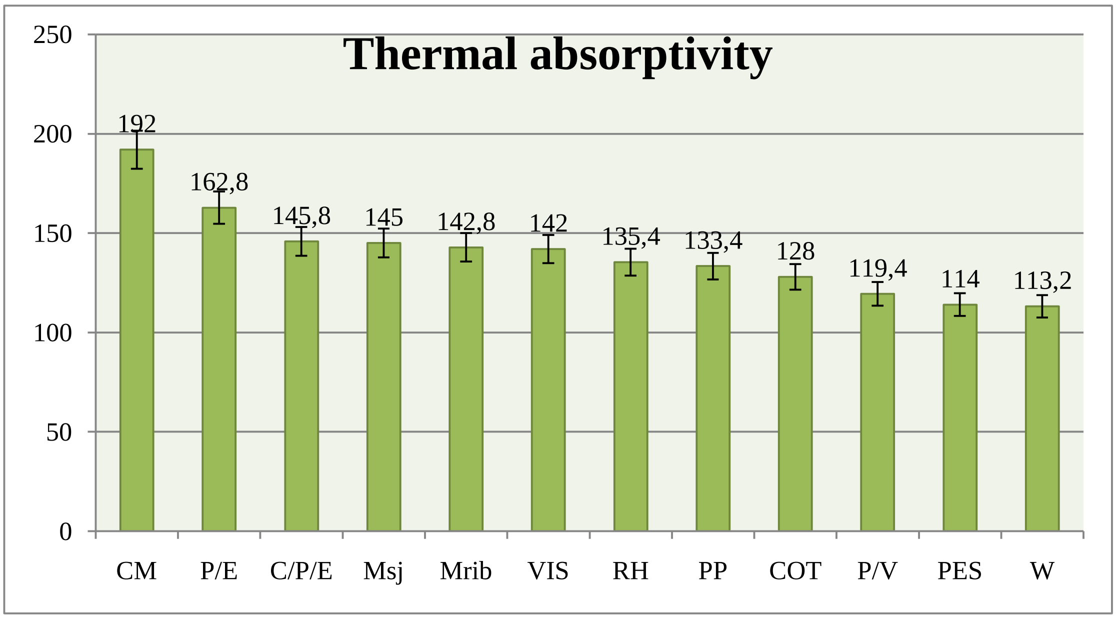


Figure 38 : Effect of fiber type on thermal absorptivity

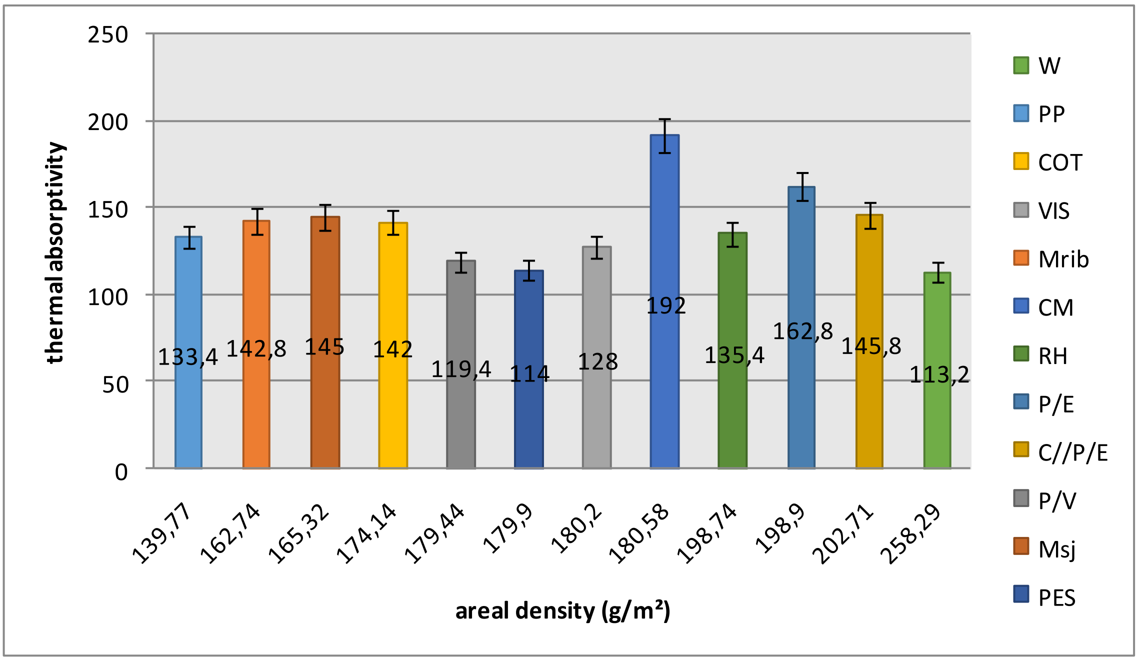


Figure 39 : Effect of areal density on thermal absorptivity

Thermal absorptivity was introduced by Hes. It is used for objective evaluation of a warm or cool feeling which is the first sensation during short contact with the fabric (Hes, 1987). Fabrics with low thermal absorptivity values give a warmer feeling while high value refers to a cool feeling.

Figure 38 shows that similarly to thermal conductivity CM, P/E and C/P/E have the highest thermal absorptivity values while W has the lowest value, these results can be explained by the thermal conductivity property of such fabrics, Thus Coolmax give cooler feeling at first touch with the human skin than W, and P/E give cooler feeling than CPE.

According to the findings Msj, Mrib and VIS have higher values than COT, it can be said that regenerated cellulosic fabrics may give cooler feeling to the human with their high thermal absorptivity values than cotton. Cotton give warmer feeling at first touch with the human skin.

In the case of synthetic fibers, PES has the lowest value; less than PP and RH however, it is revealed that polyester fabrics may give a warmer feeling to the human, while RH gives cooler feeling than PP.

Cotton as natural fiber show higher thermal absorptivity values than PES. As was stated by Pavlović et al. It is generally accepted that textile products produced from natural fibers provide higher thermal absorptivity and cooler feeling, and this situation makes them convenient for hot summer clothing.

It can be observed at the same time that thermal absorptivity values were contrary to our expectations and to its equation [$b= (\lambda\ \rho\ c)^{1/2}$]: when thermal conductivity or areal density increases as shown in figure 38; it wasn’t found that thermal absorptivity increases too in all cases. That might be explained in terms of the surface property of a fabric as it has a great influence on this sensation.

4. Thermal resistivity

Thermal resistivity values were presented in table 8 and compared in figure 40.

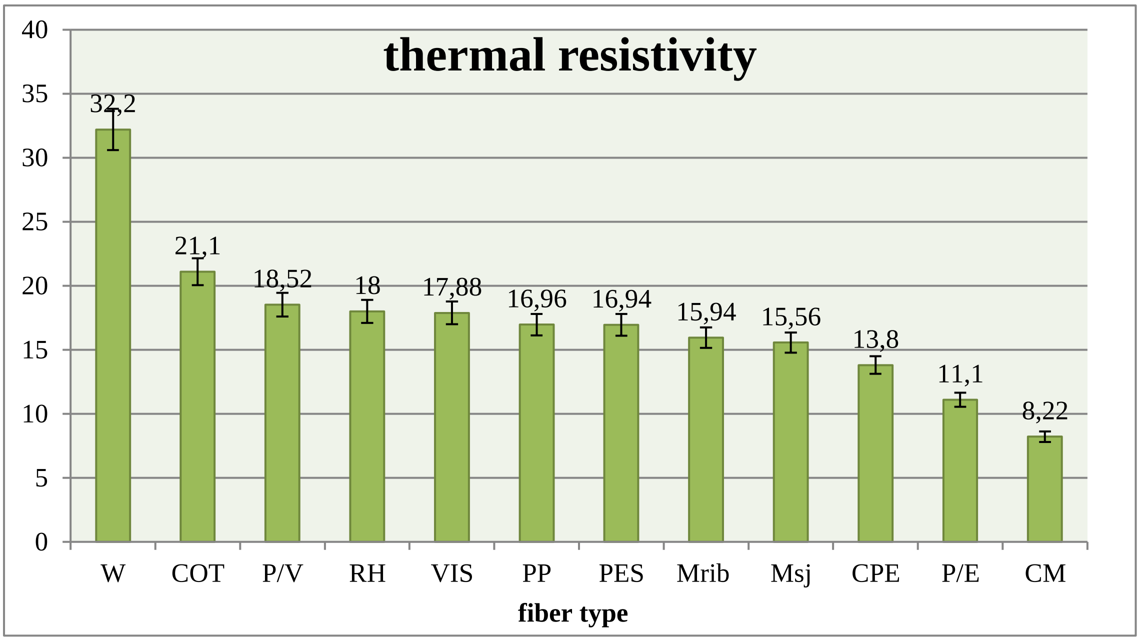


Figure 40 : Effect of fiber type on thermal resistivity

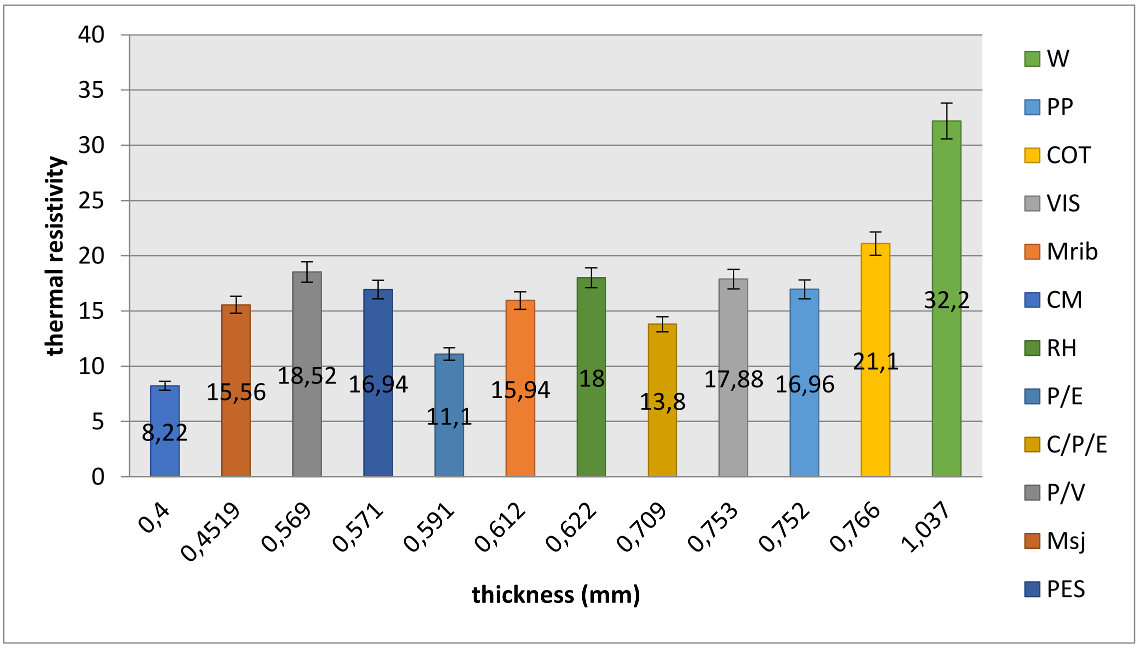


Figure 41 : Effect of fabric thickness on thermal resistivity

Thermal resistivity is a measure of a material's ability to prevent heat from flowing through it under certain climatic conditions, if the thermal resistance of clothing is low, heat energy will tend to gradually decrease, giving rise to a cool feeling.

Thermal resistance results presented in figure 40 showed that CM has the lowest value, followed with P/E and C/P/E while W has the highest value. In fact, thermal resistance, which is a measure of insulation value of fabrics, is the reciprocal of thermal conductivity value.

As the thermal resistance value of fabric increases, heat transfer from human body to environment decreases and the temperature in the microclimate increases.

Wool gives the best insulation capacity while Coolmax gives the cooler feeling.

The test result revealed that PES has lower value than RH, PP and P/V; considering the lowest thickness value. Thermal resistance is directly proportional to the thickness of the fabric ($R = h/\lambda$; where R - thermal resistance, h - thickness, λ thermal conductivity).

The decrease in fabric thickness influences fabric porosity due to corresponding decrease in fabric volume, thereby decreasing the amount of air in fabric. Since the volume of air enclosed is much higher than the volume of fibers, the insulation is dependent more on thickness of material than on fiber type, RH has an important insulation value while PES give a cooler feeling.

The results found that, despite Msj has lower thickness than P/E and CPE, it has the highest thermal resistivity value, this can be explained by the lowest value of areal density. In fact, the tightest fabrics having the highest areal density gives the highest thermal conductivity values so lower thermal resistance values.

Considering cellulosic fibers, cotton has the highest value while Modal has the lowest value of thermal conductivity. The fabrics produced from regenerated fibers have generally low thermal resistance values. This is also in agreement with the results of Tausif et al. Thus, Modal and viscose gives a cooler feeling while cotton is a better insulator.

5. Relative Water vapor permeability

Figure 42 presents the ability of transmitting moisture vapor from the skin defined as the water vapor permeability for different knitted fabric type:

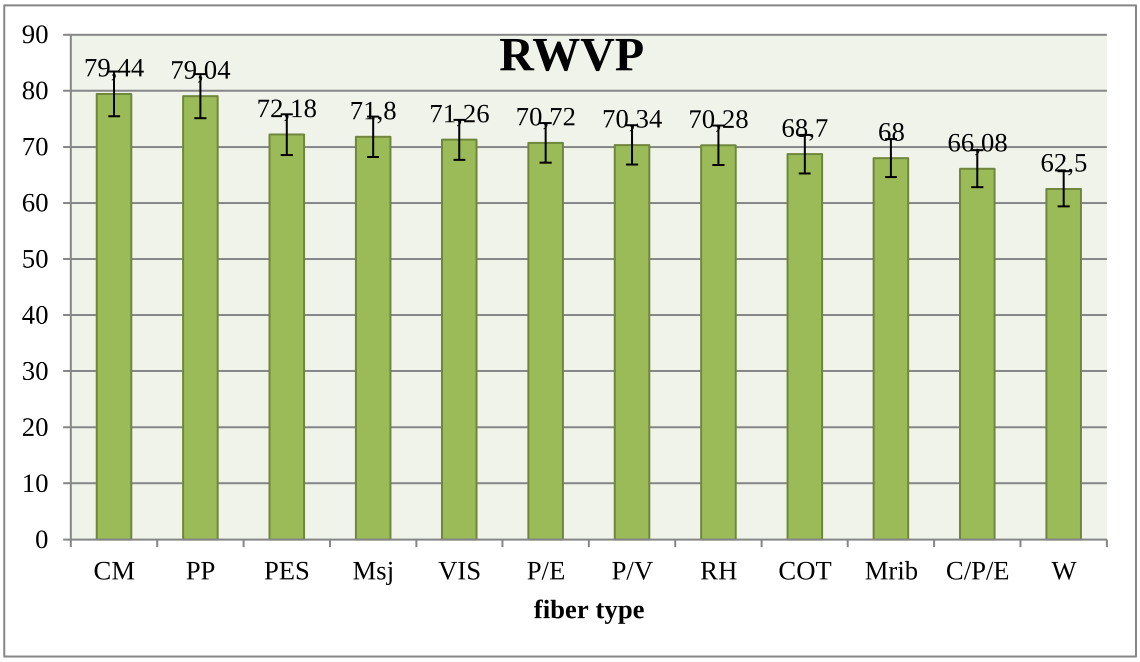


Figure 42: Influence of fiber type on RWVP

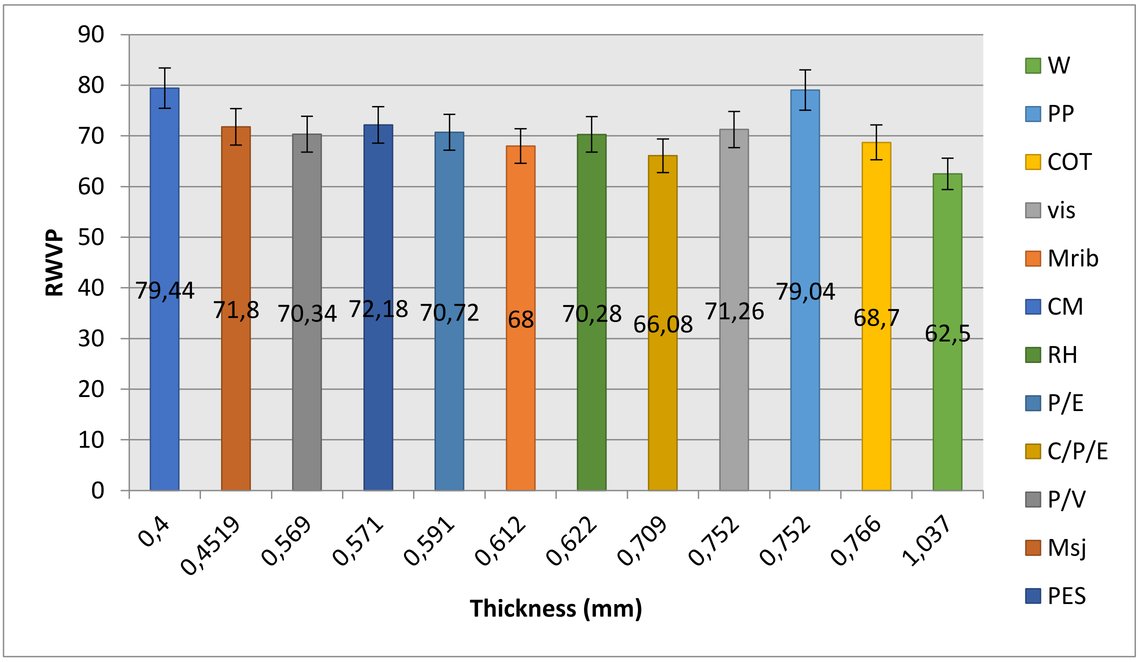


Figure 43 : Effect of the thickness on RWVP

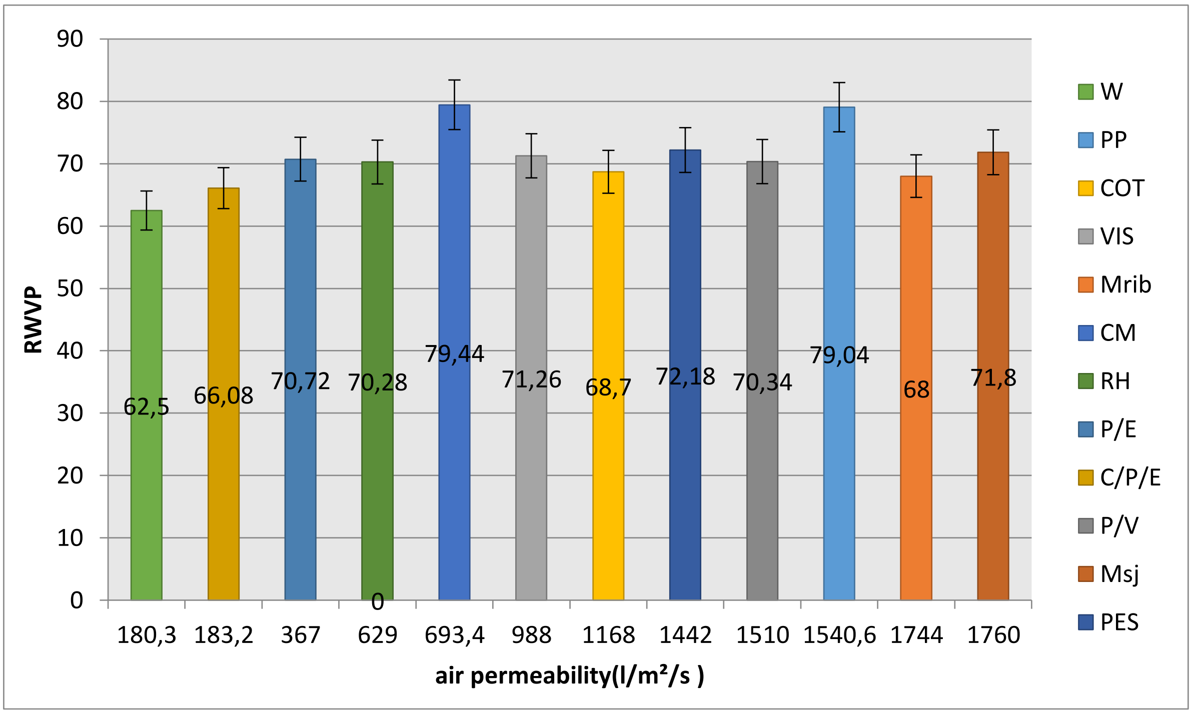


Figure 44 : Effect of air permeability on RWVP

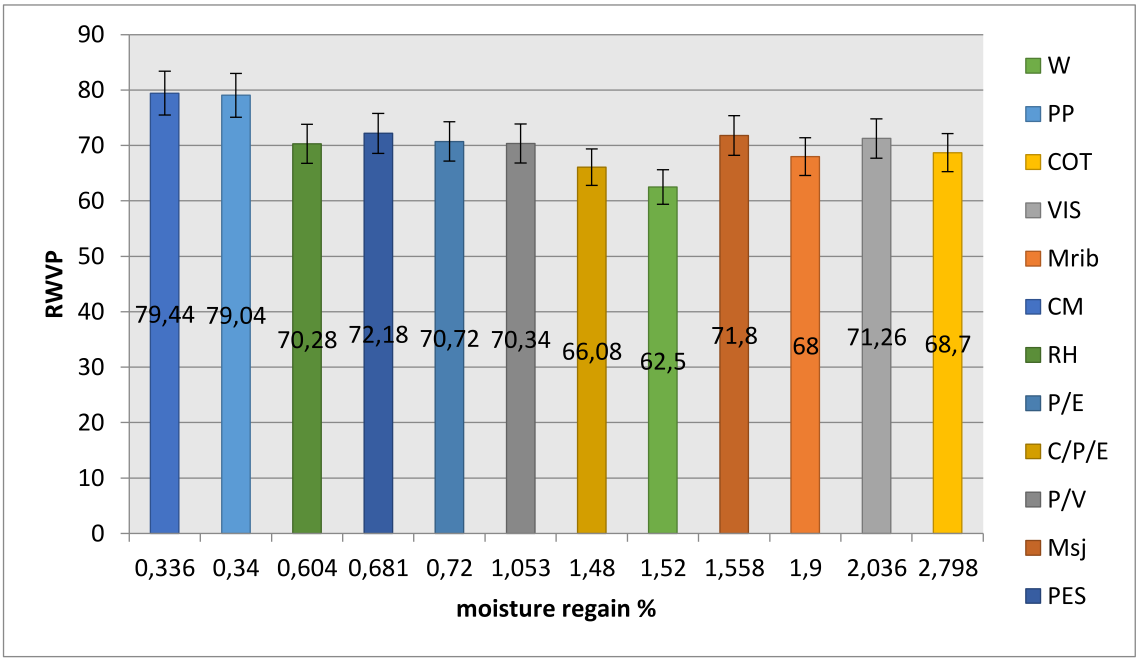


Figure 45 : Effect of moisture regain on RWVP

The results showed that Coolmax have the highest RWVP, while Wool have the lowest value.

The values found by CM and W are explained by the thickness values; in fact, RWVP increase when decreasing the fabric thickness (figure 43 presents the influence of thickness on RWVP value). When the fabric thickness decreases the porosity increases and therefore, the diffusion of vapor through inter yarn spaces becomes rapid and RWVP becomes important. Besides wool is a hygroscopic fiber that can retain water vapor molecules more than any other fibers.

Thus, the high RWVP of coolmax indicates the air movements through the fabric produce a cooling drying effect and the low RWVP of wool produce high insulation and warmer feeling.

The cotton has lower RWVP than viscose, what confirms the fact that increasing thickness effect on water vapor transmission. Cotton fibers retain water vapor and give less cool feeling than viscose.

The highest values of PP and PES comparing with other types of fabrics, regardless to thickness, can be explained with the fact that PES and PP are hydrophobic fibers; Therefore, hydrophobic fibers, having a bad ability to absorb moisture, making the absorption and diffusion of water vapor through the fabric substrates very difficult.

It can be seen from the figure 42 that P/V have lower RWVP than PES, and CPE have lower value than COT; It may be explained by decreasing the polyester percentage and blending it with another hydrophilic fiber that can affect the permeability of fabric. Thus, blended fabrics retain water vapor molecule better than pure synthetic fabrics and give warmer feeling.

Despite of having higher thickness, PP has higher RWVP values than RH, according to figure 44 RH has lower air permeability value and a tighter structure; the water-vapor permeability gives some information about the breathability of fabrics; the higher air permeability indicates the higher porosity and the facility of diffusion.

Although of having higher air permeability value and lower thickness, Modal has the lowest RWVP value of cellulosic fabrics. The result obtained can be attributed to its higher moisture regain value as shown if figure 45. In fact, hydrophilic fibers retain water vapor molecules and could even swell to reduce the porosity of the fabric.

Besides, the low RWVP of CPE is attributed to its low air permeability and high stitch density; the higher stitch density value means smaller holes in the fabric that creates higher resistance for entering water vapor molecules.

6. Water vapor resistance

Water vapor resistance (R_{et}) indicates how much a textile can allow the passage of water vapor through it. Figure 46 presents the results found:

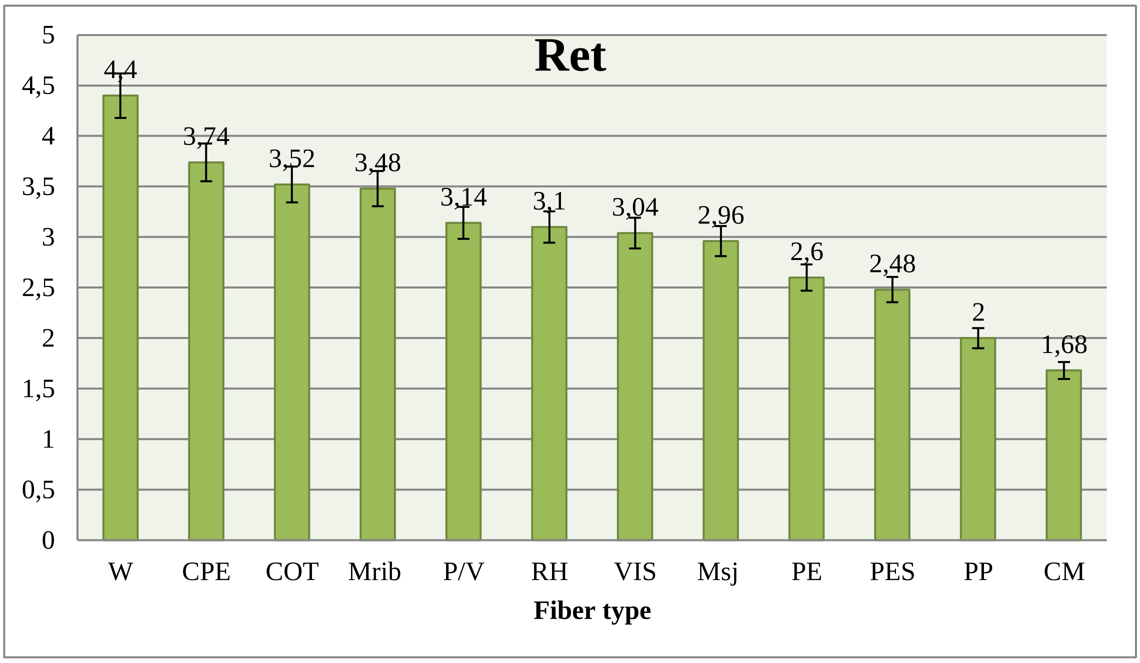


Figure 46 : Effect of fiber type on Ret

The increasing of Ret indicates that fabric has less breathability and more resistance for vapor transmission through the fabric;

Wool has the highest Ret while CM have the lowest value, coolmax and PP allow water vapor transmission easily than wool and CPE, because of the lower porosity of these fabrics.

CM and PP are the most breathable fabrics, while W and CPE have less breathability.

Viscose and modal have higher Ret value than COT, can be explained with the hairy structure of cotton fibers which may restrict the passage of water vapor and then make it less breathable than regenerated cellulose.

PES has lower value than P/E, that has lower Ret than P/V, can be attributed to reducing the polyester percentage in the fabric, in fact polyester fibers have high RWVP. PES has the lowest value what makes it better for moisture transport and more breathable.

As presented in the figure 46; regardless to the fabric structure; RH is less breathable than PES and PP despite having lower thickness, this result can be attributed to its higher areal density and higher stitch density, so lower porosity and therefore higher Ret.

III. Moisture and liquid properties

1. Moisture regain

Moisture regain is the amount of liquid absorbed by the fabric

Figure 47 presents the results found;

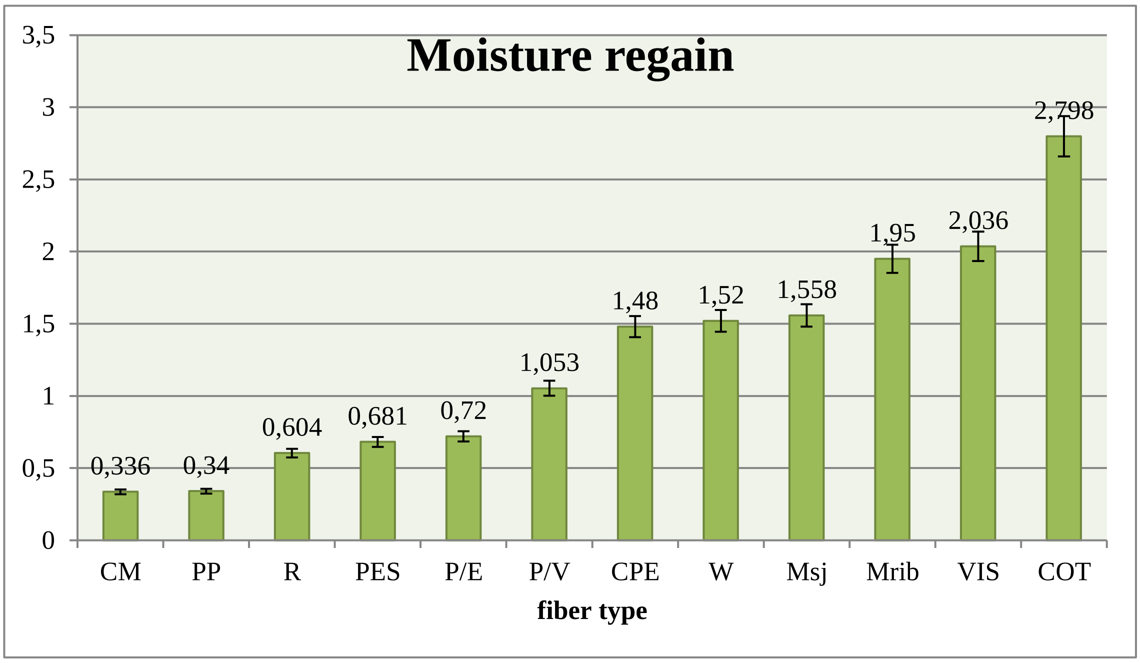


Figure 47 : Effect of fiber type on moisture regain

As shown in figure 47, cellulosic fabrics have the highest moisture regain value, can be explained by the hydrophilic character and the high surface energy of cellulosic fibers. Despite having the lowest RWVP, wool has less moisture regain than cellulosic fabrics;

probably because of the thin lipid coating that is chemically bonded to the surface of wool fibers, what makes it hydrophobic and doesn't absorb water drops easily.

CM, PP, RH and PES have the lowest values, due to its hydrophobic character, synthetic fibers do not have the tendency to absorb moisture, while blending it with hydrophilic fibers can improve the moisture regain, like CPE and P/V; as the cellulosic fibers proportion increases in the fabric number of waters absorbing group increases, leading to higher hydrophilicity, which comes as higher moisture regain of the material.

2. Moisture Management Tester

Liquid transport properties of knitted fabrics, which have different raw materials, knitted structure and tightness, were examined. The results of moisture management properties of fabrics used are summarized in Table 9:

Table 9 : Mean values of MMT test results

Knitted structure	Fabric code	Wetting time top (sec)	Wetting time bottom (sec)	absorption rate (%)	Wetted Radius (mm)	Spreading Speed (mm/sec)	Accumulative one-way transport (%)	OMMC
Single jersey	PES	3.15	3.04	37.6	25	3.55	420 .32	0.701
	MSJ	3.15	3.98	44.01	20	2.96	252.50	0.503
	P/V	9.3	8.1	42.23	10	2.52	274.73	0.54
	CPE	8.39	2.43	40.84	15	3.23	199.60	0.45
	PE	4.32	2.81	38.61	20	3.71	362.06	0.64
	RH	4.62	2.06	43.2	25	4.34	240.48	0.696
	CM	8.94	2.06	32.44	30	4.86	530.4	0.732
Rib 1*1	M RIB	3.93	4.07	44.75	20	3,41	204.72	0.408
	VIS	20.4	8.14	44.32	20	2,38	99.96	0.43
	COT	1.54	3.09	55.62	15	0.65	98.3	0.32
	PP	3.89	4.35	37.12	25	3.16	380.41	0.51
	W	3.18	3.37	46.11	5	0.96	136.30	0.560

2.1. Wetting time

Wetting top time (WTt) and wetting bottom time (WTb) are the time period in which the top and bottom surfaces of the fabric just start to get wetted respectively after the test starts. Figure 48 shows the mean grades of the WTt and the WTb of the fabrics.

Wetting time range values were compared using the grading scale, which is a 5-point scale, according to AATCC test method 195 (1-5).

The grades of the indexes are: 1(≥120) = No wetting, 2(20-119) = slow, 3(5-19) =Medium, 4(3-5) =Fast and 5(<3) =very fast.

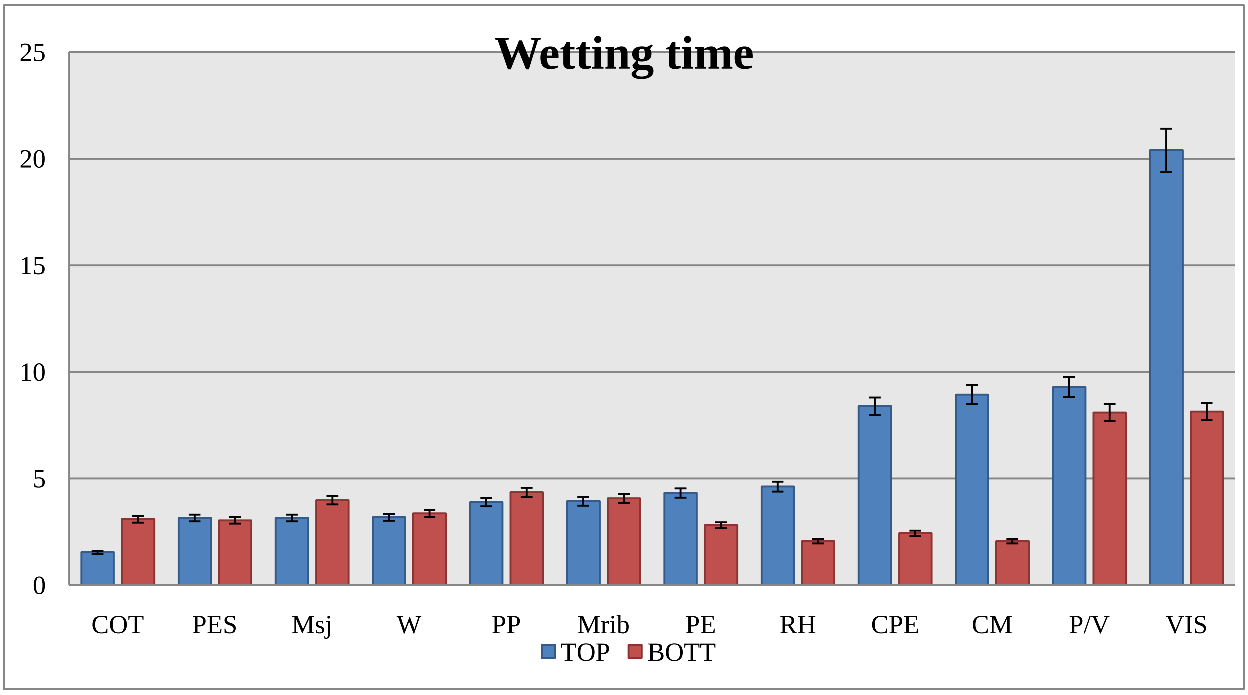


Figure 48 : Influence of fiber type on wetting time

From Table 9 and Figure 48, it can be seen that rib structure fabrics: W, Mrib, PP have fast wetting time in both top and bottom surfaces. VIS has the slowest wetting time in both top and bottom surfaces due to its thickness and mass per unit area. Both CPE and CM have almost equal grades in top and bottom wetting time.

Considering its hydrophobic effect, CM gets wet slowly but due to its cross-sectional shape it transports moisture very fast away from the skin to dry fasts.

Cotton has faster top wetting time than the bottom, showing that when the test liquid was dropped to the fabric surface, the cotton absorbed and transported liquid to bottom surfaces slowly: cotton fiber has a hydrophilic property, meaning that its surface has bonding sites for water molecules.

Cotton has a similar wetting time as PES in the bottom surface, but at the same time it has significantly faster wetting top time. Due to absence of any water-bonding groups, polyester fibers perform better in moisture wicking whereas cellulosic fibers are slow in transporting liquid because of the hydrogen bonding with water molecules.

As indicated from the results, CPE has slower top wetting time than the bottom, it can be explained by the proportion of polyester that makes the surface wetting slower, but the cellulosic proportion make the transfer to the bottom easier, for the same reason P/V has faster top wetting time than bottom.

In terms of wetting time index, the fact that the bottom surface becomes wet in a longer time than the upper surface shows that liquid is transported from one side to other slowly; in our case; COT, Msj , Mrib ,PP and W gets wet in the bottom side slowly , the results can be explained with the fact that cotton ,modal and wool are hydrophilic fabrics , while PP has important thickness value, it takes more time to absorb water drop for higher thickness fabrics than thin fabrics .

2.2. Absorption rate

Absorption rate is defined as the average moisture absorbency of the top and bottom surfaces of the fabric within the pumping time (20 sec). The absorption rate of fabrics used in the experiments were shown in figure 49.

Absorption rate range values were compared using the grading scale, which is a 5-point scale, according to AATCC test method 195 (1-5).

The grades of the indexes are: 1(0-10) = very slow, 2(10-30) = slow, 3(30-50) =Medium, 4(50-100) =Fast and 5(>100) =very fast.

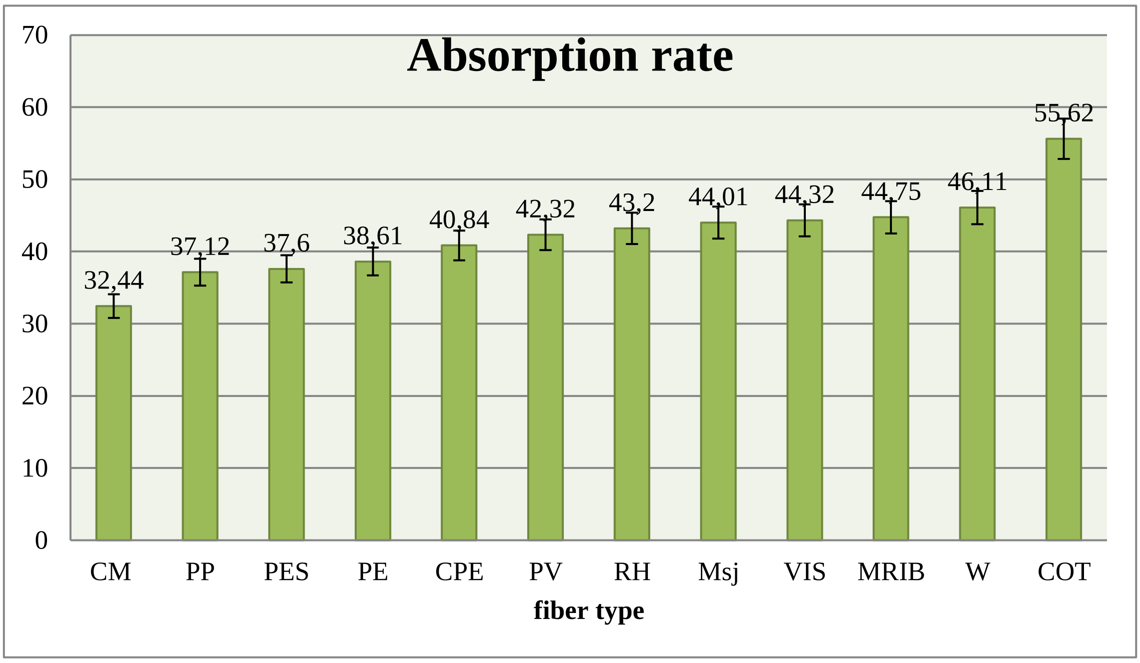


Figure 49 : Influence of fiber type on absorption rate

For cellulosic fibers, COT showed very fast absorption rate while modal and viscose have medium absorption rate. Cotton has better absorption than other cellulosic fibers because it's higher hydrophilicity. Viscose has higher absorption than modal, this might be explained with its higher thickness, thus thicker fabric can provide more space to accommodate water.

Wool has medium absorption rate but higher than synthetic fibers, the quick absorption of water explained by the high thickness of wool and the low fabric porosity comparatively less entrapped air in the structure.

Coolmax has the lowest absorption rate, due to its low thickness and hydrophobic character. For blended fabrics the results indicate that when the percentage of polyester decrease, the absorption rate increase case of PE, CPE and PV.

RH and PP have medium absorption rate, in fact synthetic fibers absorb only a comparatively small amount of moisture, because of their hydrophobic character.

Absorption rate depends on the fiber composition of fabric. Synthetic fibers like polyester and polypropylene are used for manufacturing of different variety of fabrics. Cellulosic fibers tend to absorb and retain body moisture, whereas synthetic fibers tend to improve wicking away from the body leading to evaporation of the moisture.

2.3. Maximum wetted radius and spreading speed

The maximum wetted radius range values were compared using the grading scale, which is a 5-point scale, according to AATCC test method 195 (1-5).

The grades of the indexes are: 1(0-7) = No wetting, 2(7-12) = small, 3(12-17) =Medium, 4(17-22) =large and 5(>22) =very large.

The spreading speed range values were compared using the grading scale, which is a 5-point scale, according to AATCC test method 195 (1-5).

The grades of the indexes are: 1(0-1) = very slow, 2(1-2) = slow, 3(2-3) =Medium, 4(3-4)=Fast and 5(>4) =very fast.

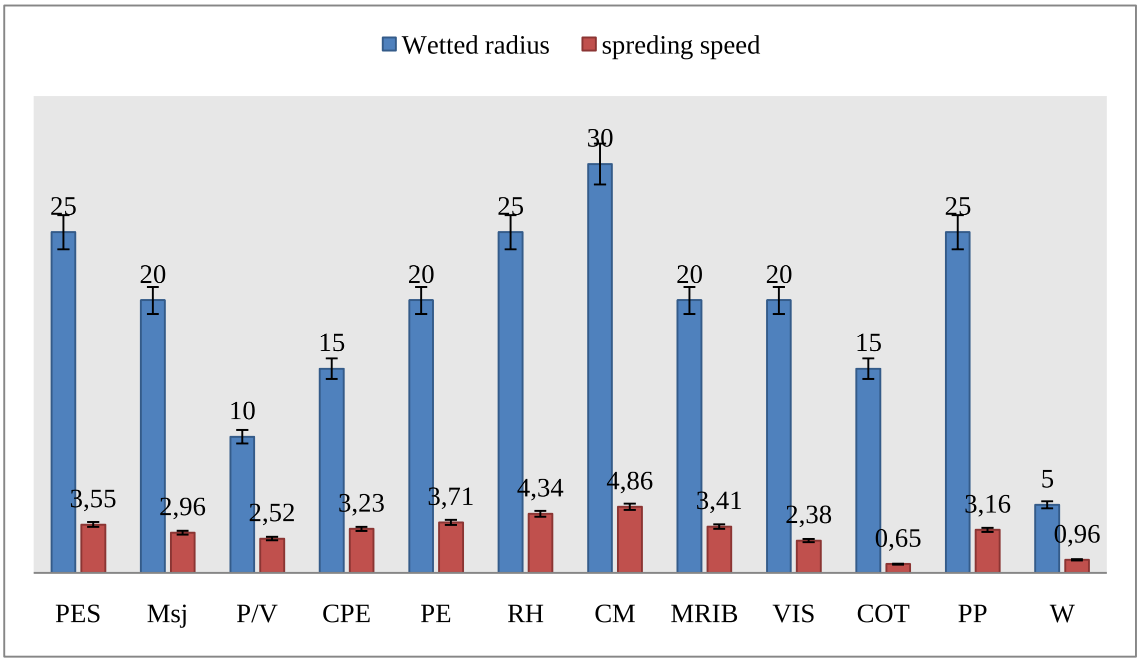


Figure 50: Effect of fiber type on wetted radius and spreading speed

Maximum wetted radius and spreading speed indicates the ability of liquid spreading, evaporation over a larger area and, the drying ability of the textile structures. Higher the maximum wetted radius and spreading speed of the fabric, greater the evaporation and lesser time the fabric takes to dry.

Figure 50 presents the wetted radius and spreading speed values, the figure indicates that Coolmax has a very large wetted radius and very fast spreading speed what makes it a fast-drying fabric and responsible for the cool feeling of the skin, while wool has poor wetting radius and very low spreading speed this probably caused by the highest value of thickness and lower porosity what makes it a very slow drying fabric.

Results for synthetic fibers indicate that PES, RH and PP have a very large wetted radius and fast spreading speed. In fact, hydrophobic fabrics do not absorb the test liquid and can transfer the liquid moisture through the surface of the fibers by capillary wicking means that liquid sweat can be easily and quickly transferred from next to the skin to the outer surface. While cellulosic fibers COT, VIS and Modal presents a medium wetted radius and slow to medium spreading speed what indicates the slow dryness and moisture spreadability of cellulosic fabrics.

The results reveal that P/V has slower spreading speed than PES and smaller wetted radius, can be explained by the hydrophilic character of viscose, some of liquid is absorbed by the fibers and penetrates into the fiber structure which decreases the moisture spreading, blending polyester with hydrophilic fiber can improve the moisture absorption and spreadability. For the same reason, CPE has fast spreading speed and medium wetted radius while 100 % cotton has slower spreading speed and wetted radius, the result attributed to the hydrophobic character of polyester and elastane proportion that can help to transfer the liquid away from the skin.

2.4. Accumulative one-way transport index (AOTI)

The one-way transport capacity range values were compared using the grading scale, which is a 5-point scale, according to AATCC test method 195 (1-5).

The grades of the indexes are: 1(<-50) = Poor, 2(-50-100) = Fair, 3(100-200) =Good, 4(200-400) =Very good and 5(>400) =Excellent.

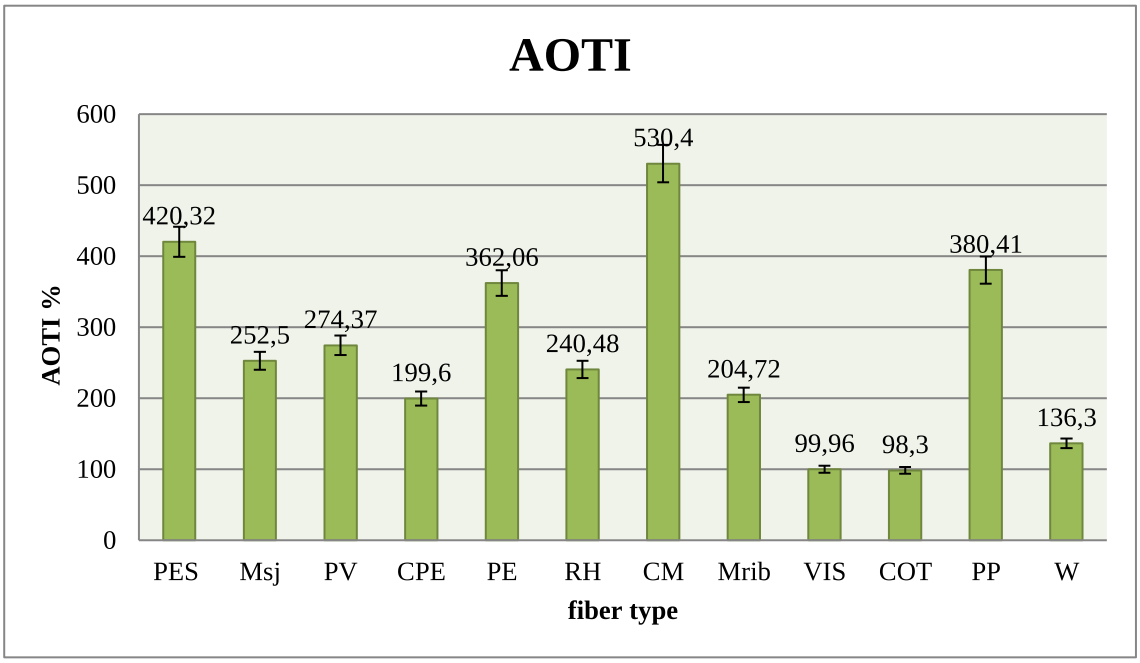


Figure 51 : Effect of fiber type on AOTI

The accumulative one-way transport is the difference in the accumulative moisture content between the two surfaces of the fabric. AOTI reflects the one-way liquid transport capacity from the top (inner next to the skin) to the bottom (outer) surface of the fabric.

The figure 51 shows the results for the AOTI comparing to the grading scale. For synthetic fabrics Coolmax has excellent AOTI, PES, PP and RH have a very good AOTI, Cot has fair AOTI while CPE havs better value due to the proportion of polyester. Comparing cellulosic fibers, cotton has the lowest value and Msj has the highest value because of its loose structure.

For blended structures, P/V and P/E have lower AOTI than PES, can be explained by the hydrophilic effect of VIS and the tighter structure of P/E, in fact if the fabric tightness increases, the porosity decreases; consequently, fabric permeability decreases.

Comparing to naturel fibers, synthetic fibers have higher AOTI, wool and cotton have fair to good AOTI.

2.5. OMMC

The OMMC range values were compared using the grading scale, which is a 5-point scale, according to AATCC test method 195 (1-5).

The grades of the indexes are: 1(0-0.2) = Poor, 2(0.2-0.4) = Fair, 3(0.4-0.6) =Medium, 4(0.6-0.8) =Fast and 5(>0.8) =Very Fast.

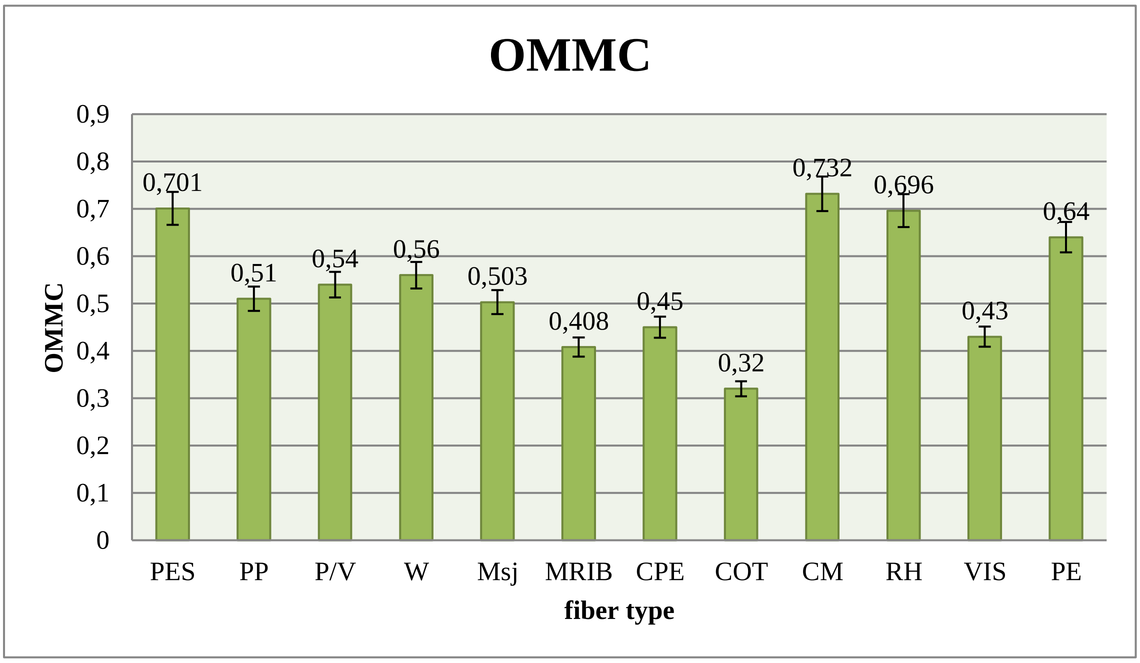


Figure 52 : Influence of fiber type on OMMC value

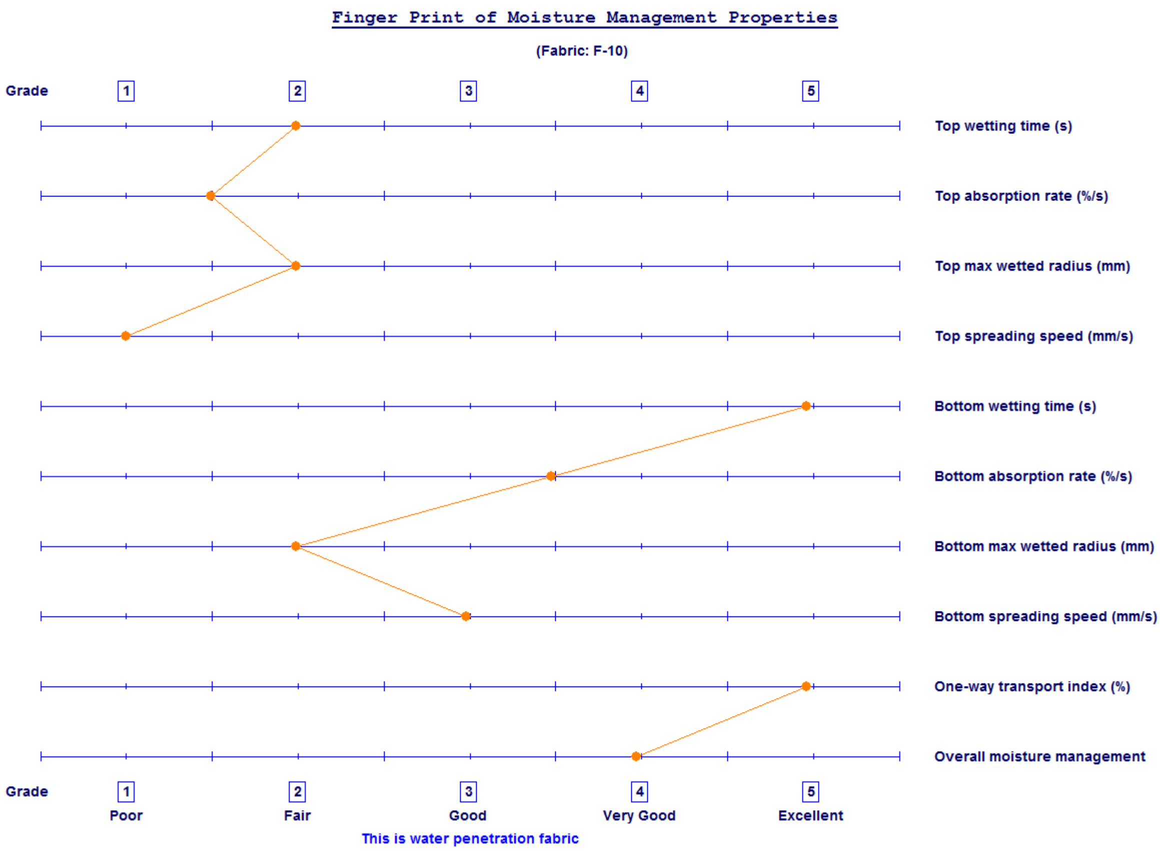


Figure 53 : OMMC results for Coolmax

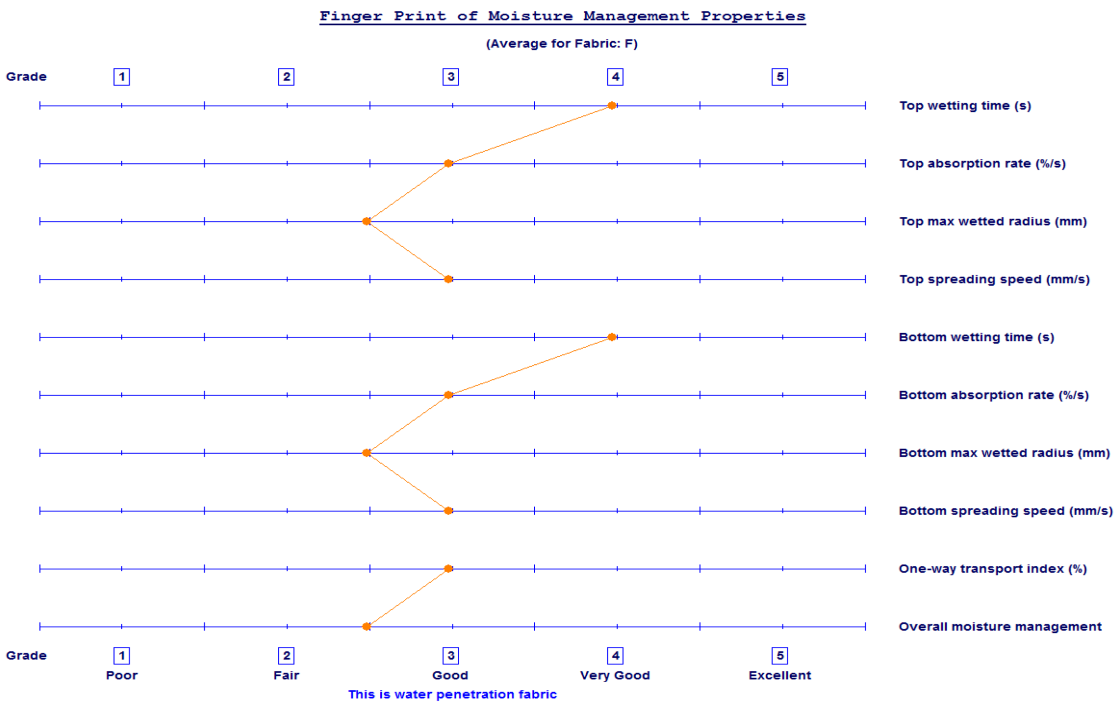


Figure 54 : OMMC results for wool

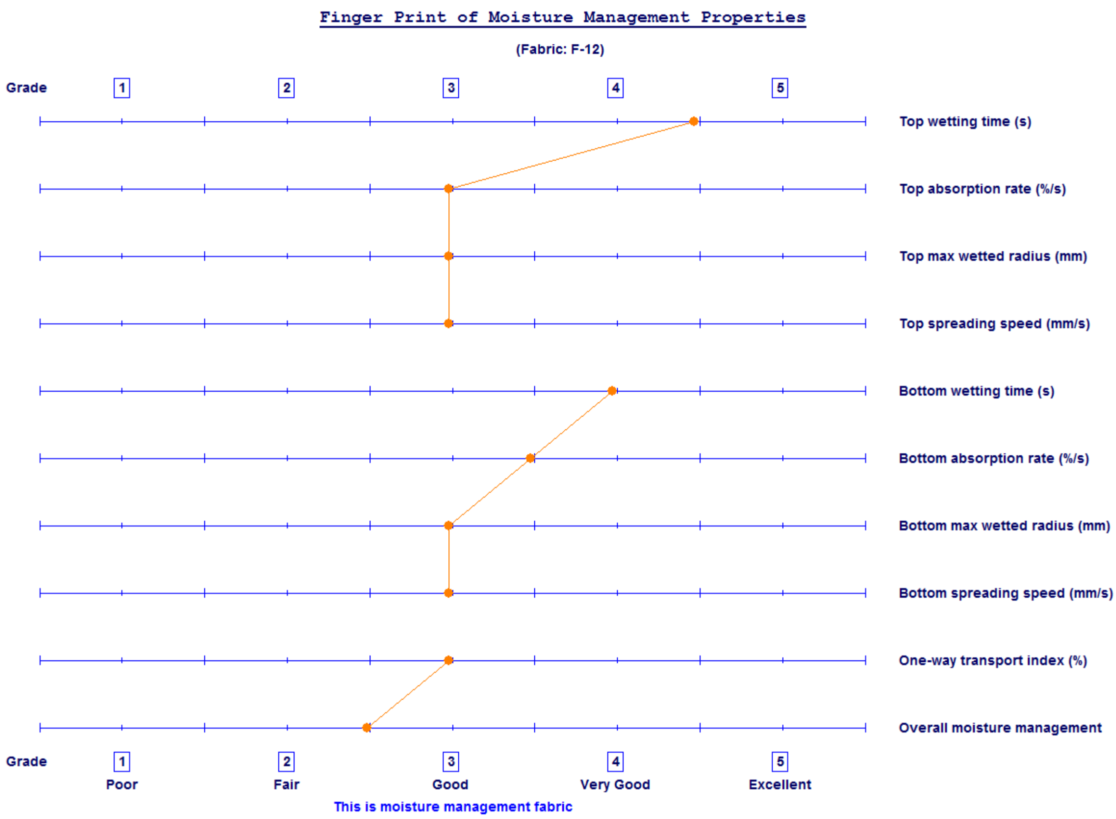


Figure 55 : OMMC results for Cotton

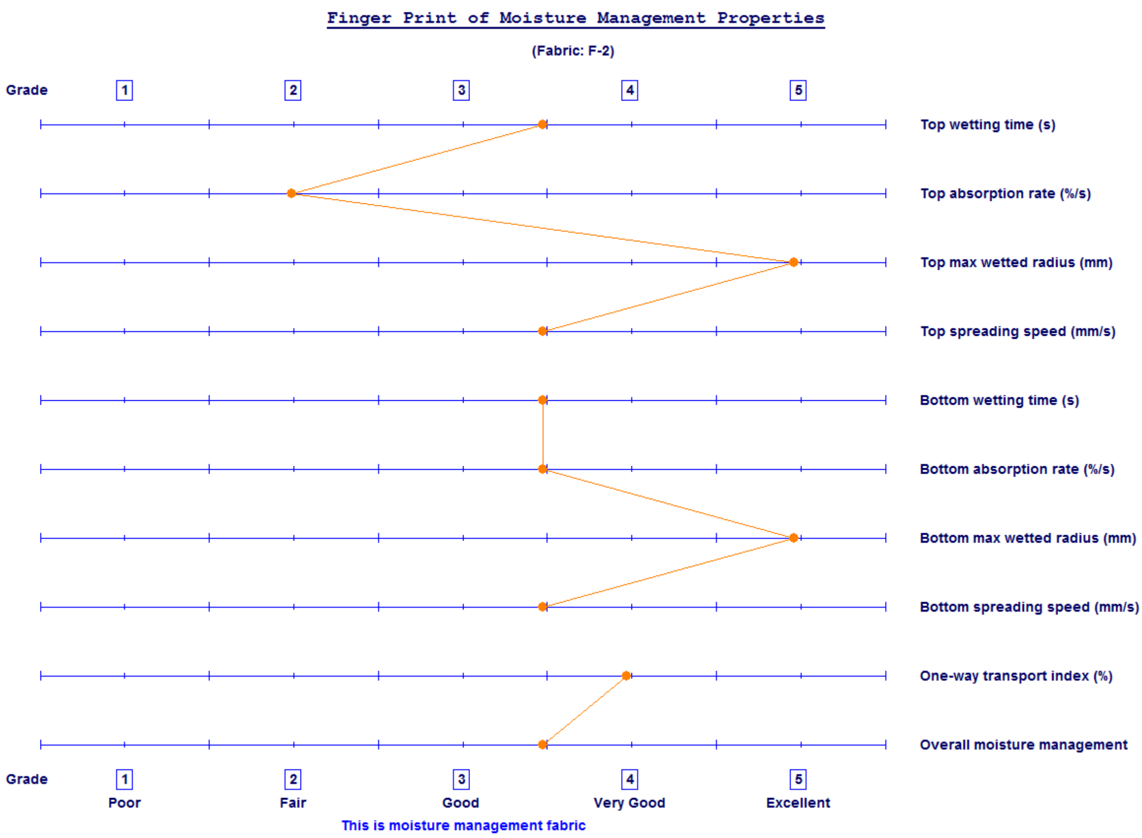


Figure 56 : OMMC results for Polyester

OMMC is an index to indicate the overall capability of the fabric to manage the transport of liquid moisture, which includes three aspects of performance: the moisture absorption rate, the one-way liquid capability and the accumulative spreading speed. OMMC values of the fabrics are given in figure 52.

The values are compared with the grading scale. The higher the OMMC is the higher the overall management capability of the fabric.

From the results it can be stated that Coolmax has the highest OMMC and the highest AOTI (fast according to the grading scale), showing that liquid sweat can be easily and quickly transferred from the skin to the outer surface. It could be due to two main attributes of the coolmax fiber; lower contact angel and multichannel cross-sectional geometry, so Coolmax is a moisture management fabric as shown in figure 53.

For synthetic fabrics, PES, PP and RH have medium to fast OMMC and good AOTI, medium absorption rate, large wetting time and spreading speed, indicating that knitted fabrics made from synthetic fibers absorb slowly liquid test, transport it away from the skin and fastly evaporate it, fabrics made of synthetic fibers are moisture management fabrics, this is confirmed with the figure 56.

Cotton has indicated fair OMMC and low AOTI , low to medium spreading speed but a good absorption rate and fast wetting time ; similarly to Modal's value but modal has faster spreading time and less absorption rate .VIS has showed a slow to medium wetting time but similar results as cotton, that indicates the ability of cellulosic fibers to quick absorbing water and transferring liquid (sweat) from the surface next to the skin to the opposite surface, but cannot easily evaporate it into the environment, cellulosic fabrics have similar OMMC results, they are considered as moisture management fabrics as reveals the figure 55.

As indicated in the figure 52, P/V and P/E showed slower OMMC than PES; The results show that as the PES content increases, the maximum absorption rate decreases whereas the spreading speed, AOTI and overall moisture management of the fabrics decrease. While in CPE blend, OMMC and AOTI decrease and absorption rate is higher, because of 60% cotton and the effect of elastane on fabric tightness. In fact, blending polyester with cotton or viscose can give better moisture management properties in knitted fabrics as compared to 100% polyester and 100% cellulose fabrics.

Increasing in cotton or viscose content results in increasing the moisture absorption rate wetting time but decrease in moisture spreading speed, maximum wetted radius and overall moisture management capacity, the blend ratio and fabric tightness influence the moisture management properties significantly.

Wool has a medium to good OMMC and good AOTI, also a good absorption rate but slow wetting time and spreading speed, considering its low air permeability, high thickness and its hygroscopicity, wool can absorb liquid test (sweat) but cannot diffuse it easily from next to skin surface to the opposite side and will accumulate on the top (slow dry), it is considered as water penetration fabric as stated in the figure 54.

3. Moisture absorptivity

Moisture absorptivity is expressed in terms of thermal absorptivity of the tested samples to simulate sweating; the figure 57 presents the important aspect of the 'warm–cool' feeling evaluation when a textile product gets wet.

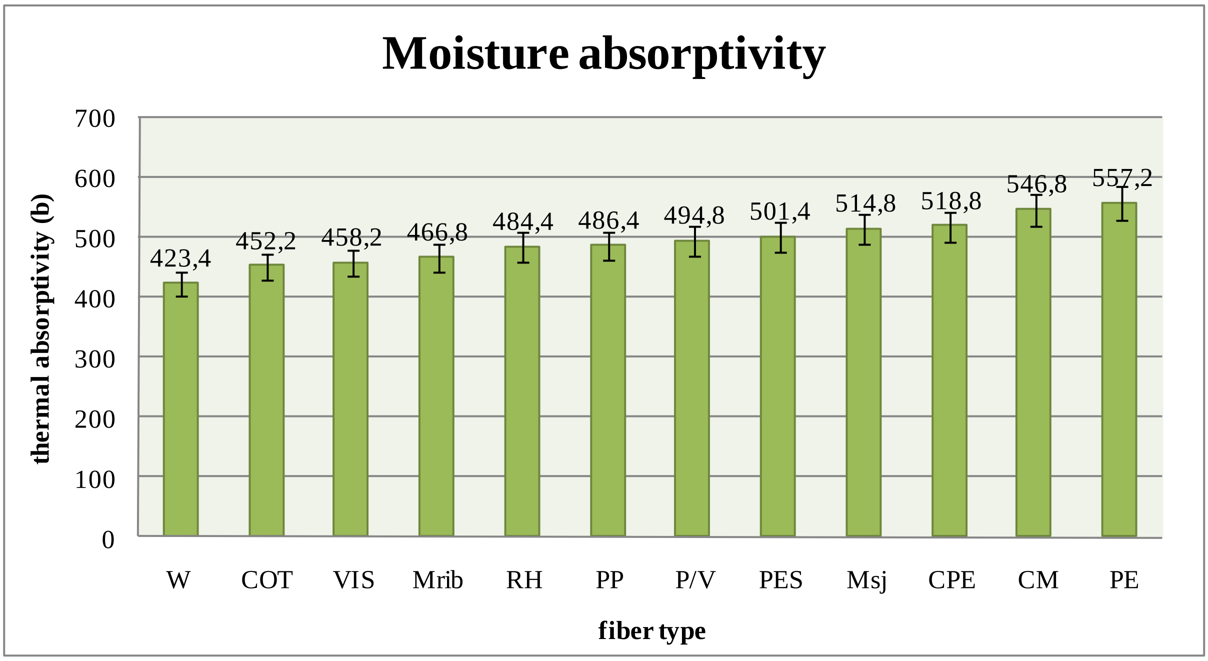


Figure 57 : Influence of fiber type on moisture absorptivity

When the fabrics absorb liquid from the skin simulator fabric (coolmax) and it gets wet, the thermal absorptivity values increase and begin to give cooler feeling (more than 500 W·s1/2·m–2·K–1) when decreasing, it gives the worse thermal contact comfort feeling in the case of superficial wetting.

As shown in the figure 57, P/E and Coolmax presents the highest thermal absorptivity value (the lowest moisture absorptivity); that can be explained by the low thickness and hydrophobic character, thus the test liquid is hardly distributed on the surface of fabric in contact with the skin, what gives a cool wet feeling to the skin.

While wool has the lowest value due to its high absorptivity, moisture is transferred to wool surface and distributed within the whole thickness, what gives a warm and dry feeling to the skin.

For cellulosic fabrics; Msj has lowest moisture absorptivity; because its low thickness and loose structure, it can evaporate the absorbed water located on the interface quicker than other cellulosic fibers, so the skin feels cooler but a little bit of wet.

Modal gives cooler feeling than viscose, which gives cooler and wetter feeling than cotton. Cotton fabric show substantially warmer and more pleasant feeling than those of CPE blend. This result can be attributed to the good hydrophilic characteristic of cotton fibers.

Cotton and wool have the highest moisture absorptivity and the lowest thermal absorptivity, in fact the absorbed liquid is spread within the whole fabric thickness what gives the effect of dry and warmer feeling to the skin.

In case of synthetic fibers; Polyester shows less thermal absorptivity than coolmax, RH and PP have lower thermal absorptivity than PES; This result can be explained by the hydrophobic character of these fibers, absorbed water can be easily spread and evaporate but it gives wet sensation to the human skin.

Conclusion

The purpose of this chapter is to analyse and determine the relation between knitted fabric properties , thermal and moisture properties, thus we attempted to discuss comfort related properties for the twelve knitted fabrics having different structure and raw materials , using the PERMETEST to simulate water vapor considering the air ventilation (walking condition 1m/s), the water vapor permeability and water vapor resistance were determined, to determine the thermal properties ALAMBETA was used, and MMT to simulate human moisture management.

For thermal properties we found that:

Wool has the lowest air permeability and coolmax has the highest value, also the influence of the thickness and stitch density on air permeability

For thermal conductivity and thermal absorptivity coolmax has the highest values while wool showed the lowest values and higher thermal resistance.

Wool gives warmer feeling and has a good insulation capacity while coolmax gives the cooler feeling.

For moisture properties:

Synthetic fabrics especially coolmax showed better moisture properties than cellulosic fibers: cotton, modal and viscose, in fact Polyester, rhovyl, polypropylene and blended fabrics have showed better wetted radius, spreading speed, AOTI and OMMC while cellulosic fabrics and wool have shown better absorption rate and wetting time, so the synthetic fabrics are slow absorbing and fast drying fabrics.

Because of their high hygroscopicity, cellulosic fabrics proved to be fast absorbing and slow drying fabrics what gives warmer feeling to the skin according to moisture absorptivity results.

General Conclusion

GENERAL CONCLUSION

This study aims to attribute a suitable use for each knitted fabric; for this reason, thermophysiological comfort of 12 different types of knitted fabrics was investigated. All fabrics having different raw materials and different structures were compared in terms of their air permeability, thermal conductivity, thermal resistance, thermal absorptivity, their water vapor permeability, water vapor resistance and moisture management properties that gives an idea about moisture wettability, absorptivity, spreadability and its dryness.

From the results found, wool has low air permeability (180.3 l/m²/s) because of its thickness, low thermal conductivity (40.3 10^{-3}W/mK), thermal absorptivity and high thermal resistivity, generally wool is considered as a good keep warm material and good insulator. Wool has slow wetting time and slow spreading speed, but good absorption rate, AOTI and OMMC. Thus, wool called water penetration fabric is a fast-absorbing moisture but slow drying fabric that gives warm dry feeling to the skin. It is the best fabric preferred for winter clothes.

For nearly close results, chlorofiber (RH) fabric is considered as a comfort wear and a warm keeper fabric, it has good isothermal property, keeping away cold air and acting as an insulator, because of its low thermal conductivity (41.78 10^{-3}W/mk) and low air permeability value (629 l/m²/s), important thermal resistivity and low RWVP. Medium absorption rate, slow wetting time, AOTI and excellent OMMC makes it a non-absorbent and fast drying fabric. It is therefore a good choice for next to skin office wear and for cold weather.

For cellulosic fabrics, cotton has good air permeability (1168 l/m²/s) value but less than modal, and higher than viscose (988 l/m²/s), an important thermal resistivity (21.1 m²K/W) comparing to modal (15.94 m²K/W for Mrib and 15.56 m²K/W for Msj) and viscose (17.88m²K/W) but lower thermal conductivity (46 10^{-3} W/mK) and thermal absorptivity (128 $Ws^{1/2}$/m²K). Cotton gives warmer feeling to the skin, than modal and viscose, but practically it is preferred to be worn in hot weather due to its moisture management properties, it has a slower wetting time, and higher absorption rate, medium to slow spreadability, AOTI and fair OMMC, what makes it a high absorbing and slow drying fabric better be used in summer clothing. While modal can be used as underwear fabric because of its higher breathability and moisture management properties.

For viscose, it is clear from the results that it has important thermal properties, gives warm feeling, and has high moisture properties, what makes it suitable for blouses, t-shirts, and casual dresses.

For synthetic fabrics:

Coolmax has the most notable values, it has good air permeability value (693 l/m²/s), the highest thermal conductivity (63 10^{-3}W/mK), thermal absorptivity (192 $Ws^{1/2}$/m²K) and the lowest thermal resistivity (8.22 m²K/W), giving cool feeling to the skin. It is considered as breathable fabric due to its low Ret (1.68 m²Pa/W) and higher RWVP (79.44%). Besides it is hydrophobic fabric and it has special shaped fibers structure that help to wick the moisture away from skin and evaporate it fastly, in fact it is preferred in case of intense sportswear where the skin is highly wet.

Polypropylene fabric is a breathable fabric thanks to its high air permeability (1540.6 l/m²/s), RWVP and its low Ret (2 m²Pa/W) value, it gives warmer feeling when first touches the skin comparing to regenerated cellulosic fabrics. It is revealed that from the regain value (0.34%) and the moisture management properties, that PP is a non-absorbent fabric with large spreadability it has slow wetting and absorption rate, medium OMMC but very good ATOI, what makes it a fast-drying fabric. Its thermal and moisture properties make it appropriate for thermal underwear, athletic uniformsand everyday fitness wear.

Polyester fabrics has almost the same thermal properties as polypropylene but better moisture properties, faster spreadability and dryness, it is breathable and give cool feeling to the skin, it is perfect for sportswear but uncomfortable for summer clothes because of its hydrophobic character.

For blended fabrics it is clear from the results that CPE has low breathability, because of its low air permeability (183.2 l/m²/s) and its high resistance for vapor transmission. Besides it has high thermal absorptivity (145.8 $Ws^{1/2}$/m²K) and low thermal conductivity (57.12 10^{-3}W/mK), what makes it a keep warm fabric. As stated in results it has better absorptivity than 100% polyester and better spreadability than 100% cotton, thus is a fast absorbing and fast drying fabric, it is perfect for socks and underwear.

It has been proven from the results that P/E has similar thermal properties than CPE, it has an important thermal conductivity (62.04 10^{-3}W/mK) and thermal absorptivity and low thermal resistivity (13.8 m²K/W), but higher breathability. As for moisture properties and regain, P/E has faster OMMC and less retention, what makes it less absorbing and quick drying fabric. It is preferred for athletics, swimwear and cycling suits.

According to the results P/V give warmer feeling to the skin than other blended fabrics and good moisture abilities, what makes it useful for winter clothing.

All synthetic fabrics are moisture management fabrics that have the ability to absorb moisture and wick it from the skin.

It is revealed from this study that thermal comfort properties depend not only for knitted fabric structure but also on its thickness, porosity and raw material.

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