THE WICKING OF WATER THROUGH MULTI-LAYER FABRIC ASSEMBLIES

By

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The candidate confirms that the work submitted is her own and that appropriate credit has been given where reference has been made to the work of others

ABSTRACT

This thesis is concerned with the Transplanar wicking of water through multi-layer fabric assemblies, with particular reference to firefighters' under garments. The literature survey is concerned with a review of research work carried out on thermophysiological comfort and the heat and moisture transmission in relation to clothing.

This serves as an introduction to which the experimental work has been concerned with the design and construction of apparatus for the measurement of horizontal transplanar wicking (i.e. from a lower fabric layer to the adjacent upper fabric layers, laid horizontally). This apparatus has been constructed to allow the measurement of horizontal transplanar wicking under static fabric conditions, and another novel design has been built for horizontal transplanar wicking measurements under dynamic conditions. In addition a novel design of apparatus for the measurement of vertical transplanar wicking under static conditions has been designed and constructed.

A series of horizontal transplanar wicking tests have been carried out on a range of 1x1 rib polypropylene, Nomex, and Coolmax (polyester) knitted fabrics, and cotton and acrylic interlock knitted fabrics. The initial wicking of water into the fabric occurs in the fine inter-fibre capillaries within the yarn structure and then transplanar wicking occurs through contiguous inter-fabric contact points. The nature and number of these inter-fabric contact points in any two or more fabric layers has been demonstrated to depend upon the relative orientation of the fabric construction and the applied pressure. For these reasons some variability in the initial wicking stages of weft knitted fabrics is to be expected, as every two fabric layers in contact will exhibit different inter-fabric contact points.

A model of horizontal transplanar wicking has been proposed to explain the observed phenomena.

The type of water used (distilled) has been studied in comparison with deaerated and carbonated water, and been shown to have only a very minor influence on the initial rate of wetting and wicking.

An empirical hyperbolic equation has been proposed to explain the results of the horizontal transplanar wicking in a single fabric layer which relates the change in percentage fabric water content (%) in a single layer to the wicking time. In this way any fabric under study may be characterised by the initial rate of wicking and the theoretical maximum fabric saturation can be calculated. The effect of modifying the fabric surface structure by singeing, rubbing, and brushing has been compared with the untreated state for cotton interlock fabric. Disruption of the fine capillaries within the yarn appears to have an adverse affect on the rate of wicking, also the type of disruption. The maximum fabric saturation also appears to be affected by the type of surface disruption which may occur in everyday clothing wear.

Dynamic horizontal transplanar wicking exhibits greater transplanar wicking rates compared with the results on the same fabrics under static conditions. The results in each case are dependent upon which fabric type acts as the initial reservoir for transplanar wicking.

It was observed that for cotton fabrics that wet out rapidly in vertical transplanar wicking, the initial fabric layer always maintains a greater amount of water than the fabric layer below, whereas the reverse occurred in fabric that were slow to wet out.

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CONTENTS

CHAPTER 1.

INTRODUCTION.

1.1 COMFORT

1.1.1 THE BALANCE

The term 'Comfort' is a subjective property, with endless and ever-changing connotations. These range from the Oxford dictionary definition as ' freedom from pain, well-being' ,to 'an extension of physiology and psychology enabling the wearer to accommodate changes in the environment without a sense of stress' as described by Verma[1] . It is all a matter of balance, and one important aspect of comfort is 'thermophysiological comfort' or 'thermal comfort' (thermal neutrality). This can be defined as "a state in which man expresses satisfaction with the thermal environment, i.e. he would prefer neither a warmer nor a colder environment". Thermal comfort can be an aim in itself in line with other common demands for human well-being.[50]

Thermal comfort is related to the heat and moisture release of the human body, and in order to preserve the balance maintained by the body the creation of a microclimate as a buffer around the body against environmental conditions is necessary to assist in maintaining this balance.

A textile assembly that possessed suitable heat and moisture transmission properties would promote and maintain a feeling of thermophysiological comfort, thus maintaining the balance, and in turn maintaining the equation " heat produced equals heat dissipated."

1.2 THERMOPHYSIOLOGICAL COMFORT

The mechanism by which the body identifies the sensations of temperature is dependent on the information received from temperature receptors in the skin. These are widely distributed around the body, but mainly in the extremities. Temperature-sensitive nerve endings pick up temperature changes in and around the body.

1.2.1 REGULATION OF BODY TEMPERATURE

In order to understand thermal balance it is necessary to understand the mechanism by which the human body regulates body temperature in relation to environmental conditions and body activity.

The purpose of the thermoregulatory system of the body is to maintain an essentially constant internal body temperature of 37°C; therefore it can be assumed that for long exposures to a constant (moderate) thermal environment with a constant metabolic rate, balance will exist for the human body. This means in the ideal situation heat production will equal heat dissipation, and there will be no significant heat storage within the body.

The heat balance equation for this condition is[2]:

$$H - E_d - S_{ew} - E_{re} - L = K = R + C \qquad \text{----- [1]}$$

where H = the internal heat production in the human body

E_d = the heat lost by water vapour diffusion through the skin

S_{ew} = the heat lost by the evaporation of sweat from the surface of the skin

E_{re} = the latent respiration heat loss

L = the dry respiration heat loss

K = the heat transfer from the skin to the outer surface of the clothed body (conduction through clothing)

R = the heat loss by radiation from the outer surface of the clothed body

C = the heat loss by convection from the surface of the clothed body .

When the human body is in an environment in which the temperature is greater than the internal body temperature a sequence of events is set in motion in order to counteract it. The area of the brain that regulates body temperature sends impulses to the sweat (sudoriferous) glands and more sweat is produced.

As the sweat evaporates from the surface of the skin, the skin is cooled and the body temperature is lowered to the normal level of 37°C, maintaining the homeostasis of body temperature. This sequence of events is simplified in Fig. 1.

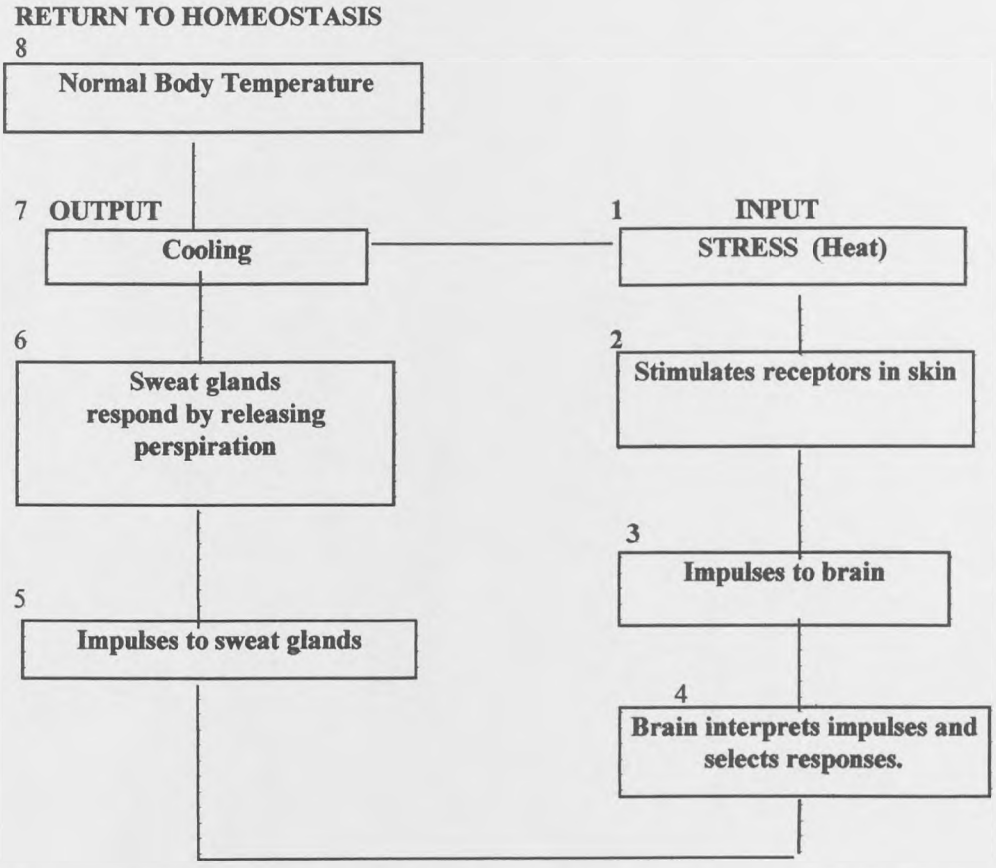


Fig.1 Role of the skin in maintaining the homeostasis of body temperature.[3]

1.2.2 PHYSIOLOGICAL TEMPERATURE REGULATION

The sensation of hot and cold is dependent on the information received from temperature receptors widely distributed in the superficial layers of the skin deep within the dermis. Nerve structures sensitive to temperature or temperature change are called temperature sensors, and these are sometimes known as the body's 'thermocouples' [3,4]. They can be found over the whole of the body, and exist at sites such as the extremities, in the fingers and toes, and the hands and feet to a lesser extent. Thermal sensation is most apparent in the nipples, chest, back and forearms. Certain areas of the skin are of more importance to heat balance, and the hands and feet play a particularly important role in regulating the body temperature. Although these areas appear relatively small (the hands = 5%, feet = 7% approximately of the total skin area)[8], the blood supply from full vasoconstriction to full vasodilation can change by 100-fold. Hands and feet can limit or increase the amount of heat brought to the surface. The amount of insensible perspiration per unit area of skin is a lot higher in the feet and hands than in the rest of the body, and the concentration of sweat glands is also higher in these areas.

Temperature changes in the environment and/or skin stimulate the nerve endings, sending a series of impulses along the afferent nerve, passing the posterior columns in the spinal cord and eventually reaching the sensory cortex in the brain. Along the way these impulses pass the hypothalamus, the main centre for temperature regulation in the body (see Fig. 2).

The nerve endings consist of two groups, cold endings and hot endings. These endings known as thermal receptors are sometimes referred to as free or naked nerve endings and are sensitive to changes in temperature , see Fig. 3.[9] A fall in temperature stimulates the cold endings and an increase in temperature stimulates the hot endings. When we are in a state of thermal comfort we are unaware of the temperature of our own skin. It is not said "my skin temperature" feels comfortable.[5] The nerve endings do not act as thermometers, but are only indicators of change , either an increase or a decrease in temperature.

Central temperature sensors are found chiefly in the hypothalamus, but there are also some in the spinal cord. It is thought that the spinal cord can also act as a temperature regulator in the event that the hypothalamus is damaged.

Heat-sensitive neurones are found in the anterior (preoptic) region of the hypothalamus. The neurones respond to changes in the temperature of the blood circulating through this organ. A change in blood temperature of as little as 0.01°C has been shown to stimulate this thermostatic mechanism.

Inputs to the hypothalamus from the temperature sensors arrive via various cells and are passed to centres controlling blood vessels, sweat glands, and the muscular activity of shivering. Heat production may also change as well as heat loss, modified due to these inputs. This temperature control can be described as a 'closed loop' with a feedback system [8] controlled automatically (see Fig 2).

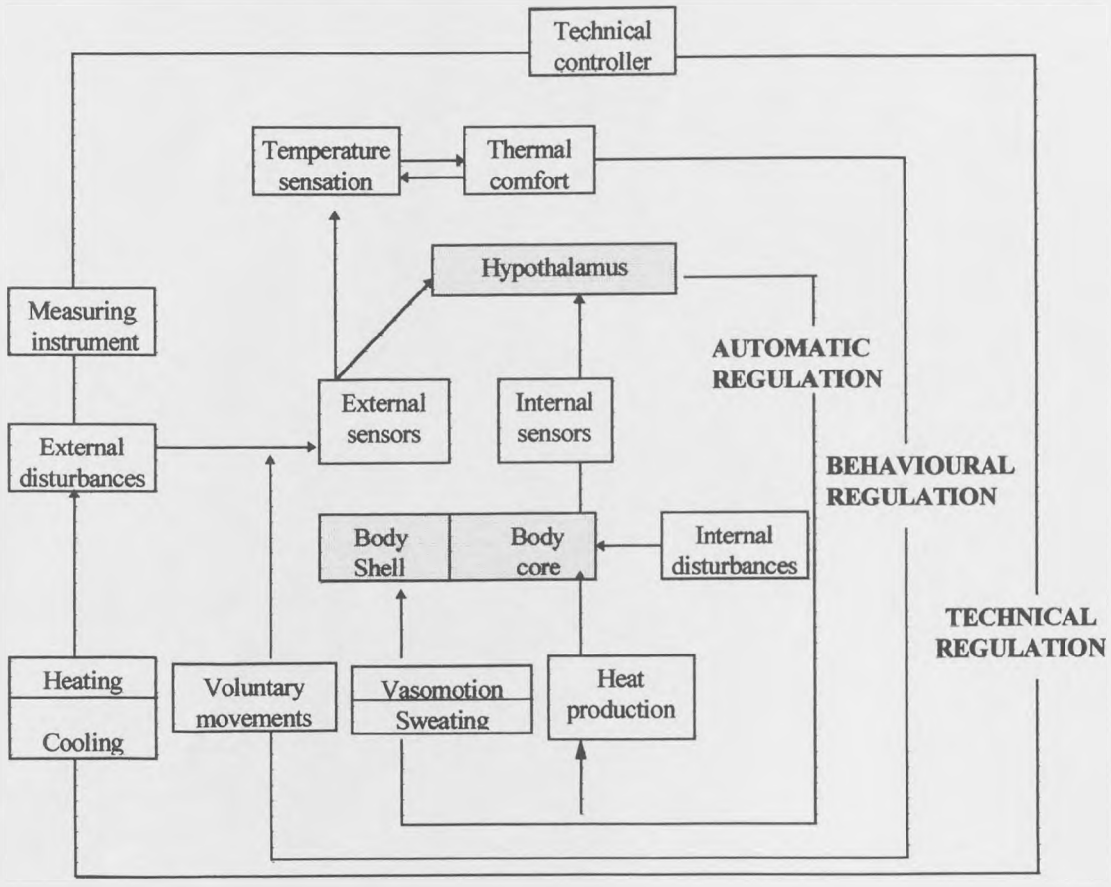


Fig. 2 Schematic diagram of automatic, behavioural and technical temperature regulation in Man[8]

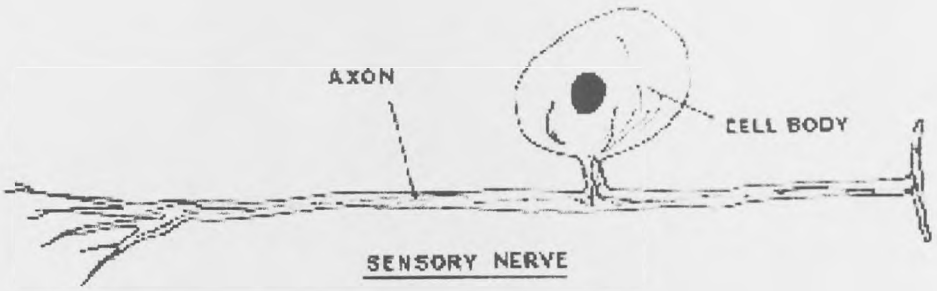


Fig 3. Sensory Nerve cell [7]

Body temperature is also related to levels of exercise, however mean skin temperature can be related to environmental temperature. The regulating system controls deep body temperature during exercise allowing increases in temperature to specific levels depending on heat production. At the same time the active control of cutaneous heat loss related to exercise levels takes place. This pattern of regulation differs from that of a body at rest. Moreover this exercise effect differs again from situations where the body temperature is changed by other means, such as changes in the surrounding environment.

As mentioned before body temperature in general is controlled mainly by the 'Hypothalamus', situated at the base of the brain, (see Fig.4) with a few subsidiary centres of control in the cerebral cortex, medulla and spinal cord.

Thermal control is dependent on the balance between two centres, one functioning to prevent excessive heat loss, and the other to prevent excessive heat gain.

The control centre for the prevention of overcooling is situated in the Posterior region of the Hypothalamus, close to the "**Corpora Mammillaria**" , and the other lies in the Anterior centre between the "**Optic Chiasma**" and "**Anterior Commissure**"(see Fig. 4).

It is the Anterior (Preoptic) centre, which is concerned with the prevention of over-heating. This centre controls evaporative cooling, and activity in this area induces panting in animals, and cutaneous vasodilation and sweating in man. It is thought that the anterior and posterior sites are connected, so that when one is active the activity of the other is depressed and vice versa. When the two sites are in balance a normal sensation of thermal comfort is achieved.[3,4,5]

This nervous system response fails if their capacity for adjustment is exceeded. If the core body temperature rises as a result of inadequate heat loss, sweating continues violently until this becomes exhausted, and subsequently over-heating takes over the body.

The reaction to a rise in external temperature is two-fold, firstly vasodilation of the small blood vessels in the skin occurs, increasing the blood flow and consequently increasing the amount of heat lost by radiation. Secondly there is an increase in the activity of the sweat glands caused by both the increased blood flow through the skin and the direct stimulation of the glands by the parasympathetic nerves.

The effect of strenuous exercise on the body is similar, a rise of the internal temperature of 1 - 2°C may occur and this rise in turn sets off the thermostatic mechanisms in the hypothalamus resulting in a 1 - 2°C drop in skin temperature.

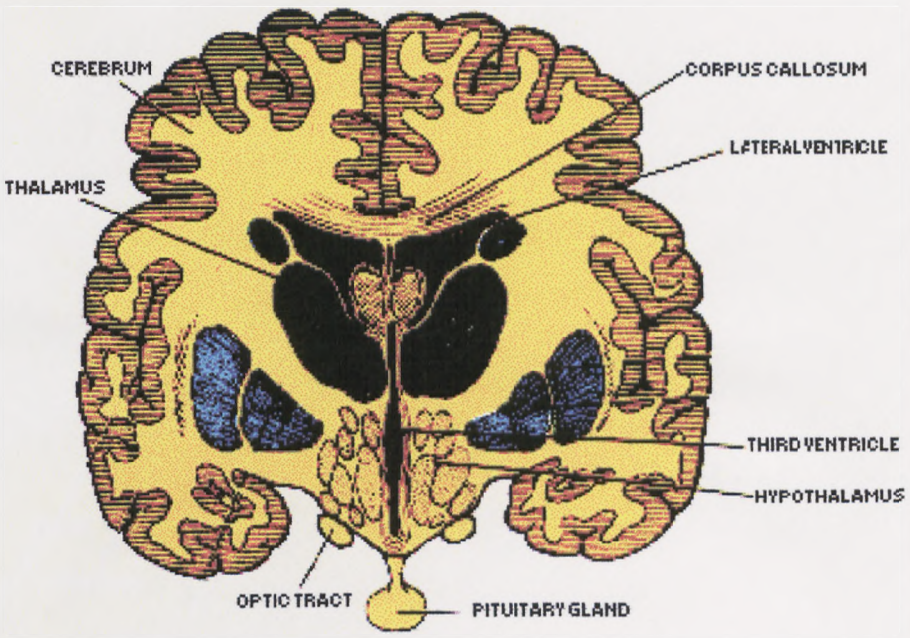


Fig.4 Thalamus - Frontal section showing thalamus and associated structures.[3]

1.2.3 FUNCTION OF THE SKIN

One of the largest organs of the human body is the skin. It occupies an area of approximately 19,354 cm^2 and varies in thickness from 0.05 to 3.0 mm[3,4]. The skin is composed of two layers, the '**Epidermis**' (outer layer) and the '**Dermis**' (inner layer). The functions of the skin are complex. Skin helps to control body temperature , prevents excessive loss of organic and inorganic material, stores chemical compounds, excretes water and salts, and receives stimuli from the environment.

The outer thinner layer or epidermis consists of epithelium and is cemented to the inner thicker layer or dermis. Within the dermis is an area known as the 'reticular region' (see Fig. 5). This region consists of fibres which permit flexibility and strength in all directions. It also contains blood vessels, collagenous and elastic fibres, and between interlacing fibre spaces are adipose tissue, hair follicles, nerves, and sweat glands.[4]

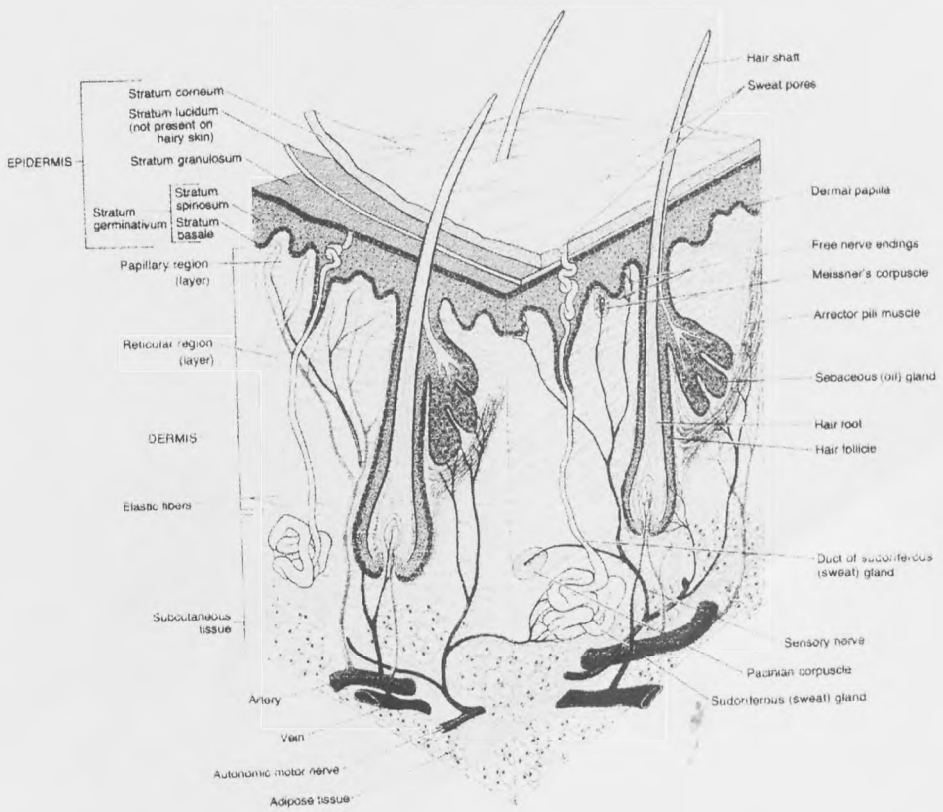


Fig. 5 Structure of the Skin and underlying subcutaneous layer [3]

1.2.3.1 Sweat Glands

These are found throughout the entire body and can be found in abundance in the palms and soles of the hands and feet. The density can be as high as 7620/cm^2, with other areas of high concentration such as the armpits and forehead[4].

Each gland consists of a coiled ball embedded in the dermis with the ducts extending through the epidermis to the surface to form the sweat pores. The base of the sweat glands are surrounded by a network of small blood vessels. In the auxiliary region the glands are of the simple branched type, elsewhere they are simple coiled tubular glands (see Fig. 5).

1.2.3.2 Insensible Perspiration

Under ambient conditions in which the air temperature is about 26.5°C , the human body at rest does not generally sweat , and in the absence of active sweating the body may still lose heat by insensible perspiration. The word 'perspiration' has become confused over the years with the word 'sweat' giving rise to the misconception that insensible perspiration and sweating have the same meaning. Insensible perspiration does not refer to the evaporation of liquid sweat, which comes from the sweat glands i.e. sweating. It refers to a diffuse evaporation of moisture vapour taking place all over the body surface almost continually from water which oozed through the blood vessels of the dermis by transudation to pass into the spaces between the cells of the epidermis.[5]

Insensible perspiration can be termed as heat loss by skin diffusion (E_d) [see the heat balance equation (equation [1], section 1.2.1)].

Water vapour diffusion through the human skin is one part of insensible perspiration which is not subjected to thermoregulatory control . The intensity of moisture vapour diffusion is assumed to be proportional to the difference between the saturated water vapour pressure P_s (mm Hg) at the skin temperature and the partial pressure of water vapour P_a (mm Hg) in the ambient air. [2]

The main barrier to moisture vapour diffusion is provided by two layers inside the horny layer of the skin, namely the Stratum Corneum Conjunctum and the Stratum Rucidum,(see Fig 5). In these layers the resistance to moisture vapour diffusion is assumed to be large in relation to the diffusion resistance of the clothing worn.

A rise in skin or ambient temperature produces a rise in the production of insensible perspiration, however the rate of perspiration will decrease with a rise in relative humidity (r.h%) at temperatures above 18.3°C[8]. It should be noted that when sweating starts insensible perspiration stops. This is because once the surface of the skin becomes wet the pressure gradient which brings about diffusion is reduced.

Under ordinary indoor conditions approximately one quarter of the heat lost by the body is due to the liberation of insensible perspiration, some 1200 ml. in 24 hours of which two thirds is derived from the skin and the rest at a rate of approximately 0.5g/min from the lungs. This is equivalent to a combined heat loss of approximately 20W/24h.

This equates to 32 ml/h. of moisture as water vapour is liberated from the whole skin area per hour, which in turn is equivalent to a heat loss of approximately 18.5 kcal./hour.

Table 1.
Partition of heat loss by different routes. [8]
(the importance of various modes of heat loss for an adult male averaged over 24 hours)

Mode of heat Loss		Total heat loss (%)
Insensible water loss		
by breath	11	25
by skin	14	
Radiation	37	66
Convection	29	
Warming of food and air and liberation of CO_2		9
		100 .

1.2.3.3 Function of Sweating

As previously mentioned the basic function of sweating is to assist in the regulation of body temperature. There are two ways by which water can be transported through the skin, namely insensible perspiration as discussed in section (1.2.3.2) and sweating.

Sweating is controlled by the autonomic nervous system, which is divided into two parts. These are differentiated by the chemical liberated from the nerve ending when they are working. Nerve endings in the sympathetic system produce adrenaline. In the parasympathetic system acetylcholine is formed. However in the case of sweat glands although the nerves are anatomically derived from the sympathetic system, the chemical they liberate is acetylcholine and not adrenaline.

Sweating is a sympathetic activity controlled by nerves which are cholinergic. adrenergic sympathetic nerves supply the sweat glands in the hands and feet. These sweat glands can take part in the sweating reactions to changes in the ambient temperature , however they also play a role in emotional responses and can show continuous secretion in the cold.

In man psychogenic sweating in response to emotional sweating is generally confined to areas of the palm, soles and axillas in a cool environment, while it appears on the whole body surface in a warmer environment. Furthermore as the body responds to mental or thermal stimuli, sweating increases on the general body surface, so that sweating on the palms and soles decreases or even disappears.

The composition of the sweat produced by these glands varies with the location in the body, reflecting the differences in structure. Sweat glands in the external genitalia and axilla regions produce a stronger smelling substance than that of the rest of the body. The cause of the secretions may also vary the composition, sweat produced by excess heat is more acidic than that produced by exercise, and the concentrations of salts and ions are also affected[7].

Sweat contains several waste products from the body, such as urea, breakdown products from muscle action such as creatinine and creatine, and most important of all salt (sodium chloride).[7]

Under normal circumstances salt is unimportant, but in hot environments where the amount of sweat is increased, the loss of salt is important. When the sweat glands are overworked the reabsorption of salt by the duct cells becomes impaired and this leads to further salt loss.

Salt (NaCl) and the products of muscle action are the main constituents of sweat with the addition of various minerals and amino acids. Fresh sweat is acidic, this is because it contains lactic acid and other amino acids which contribute to the acidic reaction. These amino acids join together to form peptides, polypeptides and protein molecules. The following amino acids have been detected in human sweat[7]:

ARGININE ; HISTIDINE ; THREONINE ; TYROSINE ; VALINE ; ISOLEUCINE; PHENYLALANINE ; ASPARTIC ACID ; GLUTAMIC ACID ; CITRULLINE.

Ammonia is also present , and this increases with bacterial decomposition of the urea in stale sweat. Small amounts of glucose are present, along with the following minerals, POTASSIUM, CALCIUM, MAGNESIUM, SULPHATES, PHOSPHATES and IRON, with sodium chloride as the most important mineral.[7]

1.2.3.4 Thermal Sweating

The aim of thermal sweating is to cool the body by increased evaporative cooling. Up to 1-2 litres or more of sweat can be produced in an hour by an individual acclimatised to working in a hot environment. However this can only be kept up for a short period of time. Under resting conditions sweat breaks out when the ambient temperature rises above 26.5°C. With an ambient relative humidity (rh) above 80% under these same conditions evaporation is impeded and the skin becomes covered in sweat. In tropical conditions with an ambient temperature of 37 - 51.8°C and a low r.h. of 5 - 25% moisture evaporation is very rapid and sweat may only show itself as crusts of salt on the skin. With heat acclimatisation the salt concentration in the sweat decreases. The vapour pressure of sweat depends upon its salt concentration, which, on the other hand, increases during the evaporation process itself.[9,4]

The sweating mechanism is easily fatigued. The ability to sweat at high rates decreases considerably during long exposures to heat stress near the limit of tolerance. It has been reported that sweating may decline by as much as 10 to 80% depending upon the environmental conditions. [5]

1.3 HEAT TRANSFER

1.3.1 MECHANISMS OF HEAT TRANSFER

Basic heat transfer can be described by the second Law of Thermodynamics which states : that free migration of heat energy is always in the direction from a body at a higher temperature to a body at a lower temperature[6]. It is also known that mechanisms of heat transfer are influenced by the temperature levels in the system. At low temperatures conduction is the main mechanism of transfer. In the case of a liquid the main mechanism of transfer is by convection. However at moderate temperatures another mode of transfer becomes apparent. The agitation of molecules by temperature increases gives rise to radiant energy, emitted in amounts determined by the temperature level of the molecules.

If the mechanisms of conduction and convection are contrasted with thermal radiation, it is found that the former are affected by temperature differences and very little by the levels of temperature, whereas the latter increases rapidly with increases in temperature. Therefore at low temperatures conduction and convection are the chief contributors to heat transfer and at higher temperatures radiation is the controlling mechanism of heat transfer.

The heat transfer occurring, taking account of the method of heat exchange, can be written as a simple equation[6] :

$$\mathbf{H = H_R + H_C = H_D + H_V} \qquad \text{----------[2]}$$

where : H = heat exchange
H_R = thermal radiation
H_C = thermal convection
H_D = thermal conduction
H_V = vaporisation

1.3.1.1 CONDUCTION

Conduction can be described as the flow of heat through a medium to an object which is in direct contact with it. Conduction can take place in solids, liquids and gases, although in the case of gases, it occurs only in circumstances where convection is limited or prevented from occurring. In solids intermolecular radiation may take part in the exchange. Sometimes it is difficult to separate the radiation through the pores of a solid object from conduction. Therefore the internal radiation is generally included in the definition of thermal conductivity.

In an object of uniform physical properties it has been determined that the amount of heat which flows from a warm surface to a cooler one is proportional to the length of the path, the nature of the object, and the thermal gradient[6,27].

In equation form many authors have applied it to the problem of the conduction of heat from the interior of the body to the skin, and hence the following equation has been developed [6]:

$$H_D = \frac{KA\,(T_2 - T_1)}{d} \times t, \text{ gm . cal.} \qquad \text{------- [3]}$$

where :

H_D = quantity of heat conducted
K = thermal conductivity, a constant which depends upon the material
A = area of the conducting surfaces
T_2 and T_1 = temperature of the warm and cool surface
t = time
d = thickness of the conductor.

However the basic law of heat conduction is[27] ;

$$q = k \frac{A}{L} \Delta t \qquad \text{------- [4]}$$

where :

q = rate of heat flow per unit time
L = thickness of plate
Δt= temperature difference
k = thermal conductivity
A = area in unit time.

1.3.1.2 CONVECTION

The next mode of heat transfer, convection is the exchange of heat between hot and cold objects by the physical transfer of heat via the liquid or gas with which the object is in contact. This method of transfer depends upon the existence of a liquid medium between the hot and cold objects and the streaming movement of warm molecules from the hot to the cooler object.

Natural convection can be termed as the transfer of heat via the air flow near a heated object. Since the density of the air near the object is lower than the main body of air, the differences in gravitational forces cause an upward flow of air near the object. Heat is conducted through the gas layers and carried away by bulk motion or convection. Although termed as natural or free convection, both convection and conduction are involved in this mechanism. An equation for basic convection was proposed by Newton and this is often referred to as "Newton's Cooling Law" [27] ;

$$q = hA \cdot \Delta t \qquad \text{---------- [5]}$$

where : q = rate of heat flow per unit time
A = area in unit time.
h = surface coefficient of heat transfer
Δt= temperature difference

1.3.1.3 RADIATION

Radiation is a method of heat transfer that can be defined as an exchange of thermal energy between objects depending on the temperature and the nature of the surface of the radiating object. At temperatures below approximately 537°C radiation is not visible to the naked eye, but is recognised by the feeling of heat when a hand is held near a slightly warmer object. When the quantity and quality of radiant energy emitted per unit time is dependent solely on the temperature of a body the radiation is called "Thermal Radiation". For total radiation the following equation can been used [27];

$$q = \sigma A T^4 \qquad \text{---------- [6]}$$

where : q = time rate of heat flow
σ = constant of Stefan-Boltzmann's law
T = Absolute temperature (K)

Agitation of the molecules of a substance by heat emit radiant energy, the amount of which is determined by the temperature level and passage of the molecules for absorption by a distant receiver of the radiation. The temperature at which thermal radiation accounts for approximately one half of the total heat transmissions is dependent on the emissivity of the surface or the magnitude of the convection coefficient[27].

Radiation takes the form of electromagnetic waves, and there are several physical laws which describe this method of heat transfer. Some of these laws relate to temperature and the nature of the surface of the emitting object. When radiant heat comes into contact with an object some energy is absorbed by the object , some is transmitted through it, and the remainder is reflected away. A perfect "black body" is considered to absorb all, and reflect no, radiant heat[6,8].

1.3.1.4 EVAPORATION

Evaporation is described as the conversion of a liquid or solid into a vapour. This method requires heat energy and therefore some heat transfer is necessary. There are many types of evaporation. In general molecules from a liquid surface in contact with a gaseous environment leave the surface and mix with the gas. Conversion of a solid directly into a vapour , without the formation of a liquid is termed "sublimation" and is another type of evaporation.

In the case of a liquid transforming into a vapour ,the boiling of water may be taken as an example. Vapour forming at the liquid surface is invisible at first and becomes visible when the heat is increased. With further increases in temperature boiling starts and just below the water surface steam bubbles rise and burst forming vapour just above the surface. Due to the presence of solid particles this is called "nucleate boiling" sometimes simply called ordinary boiling. Another type of evaporation is described as " Film boiling", and this occurs when water is spilled on a hot surface and the water droplets 'dance' on the surface for some time without sensible evaporation occurring. Just below the surface of each water droplet a film of superheated steam exists and this serves as thermal insulation between the heated surface and the water, and this is what stops the rapid evaporation of the bulk of the water.[29]

1.4 HEAT TRANSFER/TRANSMISSION IN THE HUMAN BODY

Heat transfer or exchange between the human body and the environment is a vital part of the human thermal regulatory system (Homeostasis). It may take place by one factor, or by a combination of conduction, convection, radiation and evaporation depending on the situation. Because of the possible combinations heat exchange between the skin and the environment can be difficult to define.

In the evaporation of vapour (sweat) from the surface of the skin heat is absorbed at the surface by the phase change from moisture vapour to liquid sweat that creates a temperature difference and initiates heat transfer. Even if the skin surface is not wet the evaporation of insensible perspiration affects the heat and mass transfer process. When the surface of the skin is not in contact with another surface conduction cannot take place. Radiation may also take place whenever radiation from the skin surface is allowed to radiate to other surfaces. [8, 2]

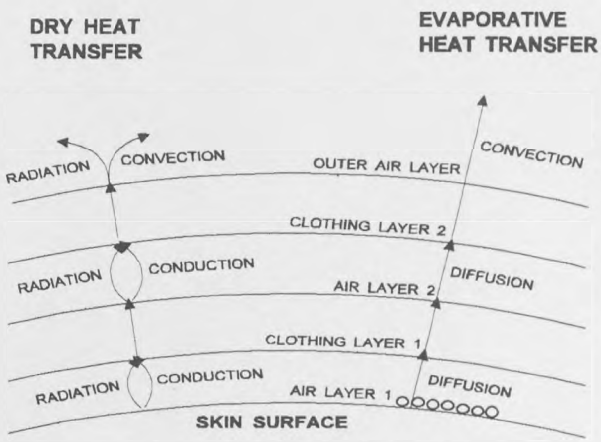


Fig. 6 Diagram of heat transfer from the skin surface to the environment[38]

1.4.1 CONDUCTION IN THE HUMAN BODY

This is a mechanism by which heat is exchanged directly from surfaces that are touching. Heat exchange in the regulatory system of the human body can account for approximately not more than 1 - 2% of the total heat exchange, and this only plays a minor role in heat exchange with the body surface and its environment[2,8].

However it is thought that conduction does occur in heat exchanged within the body's central 'core'. The central core consists of the main organs of the body, heart, lungs etc. The surrounding tissue of the core forms a shell of skin, fat, and superficial layers of muscle. This shell can be at varying temperatures and thickness depending on the heat exchange processes occurring at the skin surface in relation to the environment, and the metabolic activity in the body core (see Fig 7). A 'comfortable' condition is induced by a mean skin surface temperature of approximately 33 - 34°C. This is obtained by heat being conducted from the core through the tissues of the shell to the surface. A covering of clothing provides further insulation and an intermediate layer between the skin and the environment.

In an equilibrium state, body heat exchange with the surroundings may be considered in two distinct parts.

Firstly there is heat exchange through the tissues and clothing, and secondly this heat is lost through transfer from the surface of the clothing to the environment, (see Fig. 6).

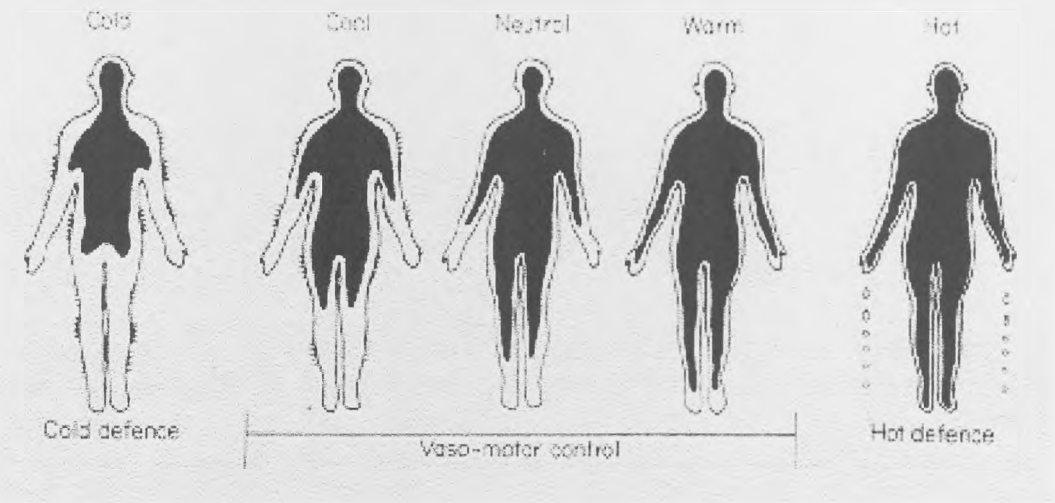
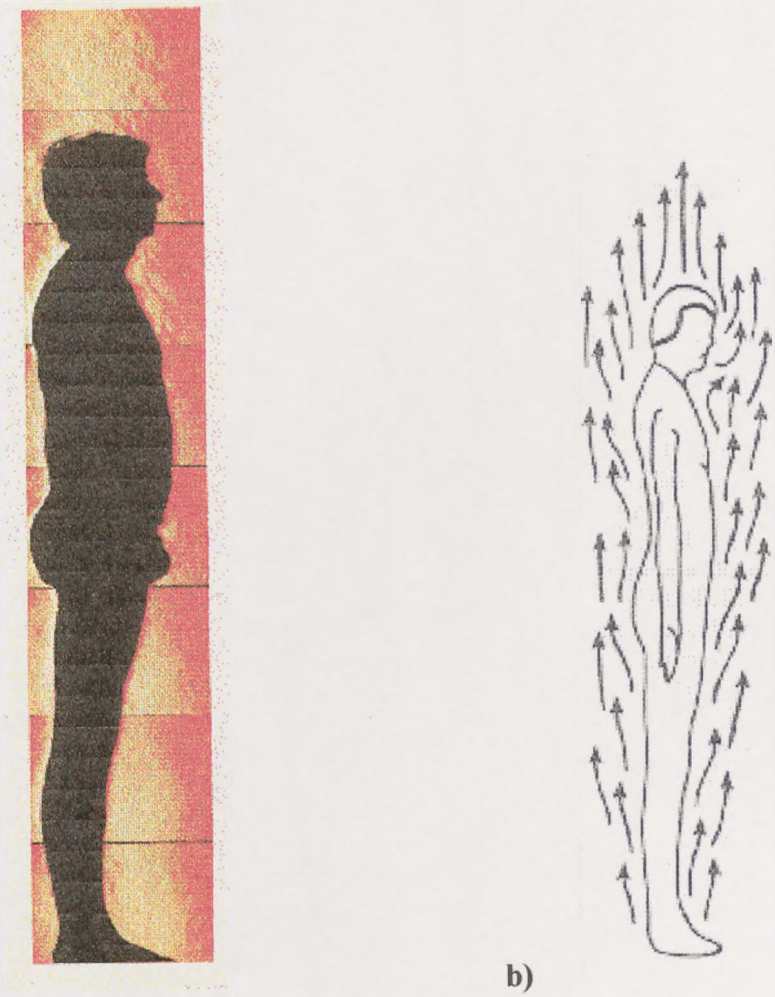


Fig 7. Representation of the size of the central constant temperature 'core' in conditions ranging from hot to cold. (In cool, neutral and warm conditions temperature regulation is affected by vasomotor control. In hot conditions, sweating becomes necessary, and in the cold , shivering is evoked. [8]

1.4.2 CONVECTION

Convection is the exchange of heat or energy from a warm body or clothing with the surrounding air. This causes the surrounding air to become heated and buoyant and rise under the influence of gravity to form a natural convection boundary layer around the body (see fig 8).

Convection can occur freely in 'still' air or by forced convection when the body is either in an air stream or moving. About 15% of body heat can be lost to the air and approximately 3% to nearby cooler objects such as clothing.



a) b)

Fig 8. a) Composite Schlieren photograph of the boundary layer flow over a standing nude subject at a room temperature of 22°C.

b) Diagrammatic representation of the natural convective boundary layer flow generated around a standing subject. [8]

The exchange of heat between the surrounding environment and the human body is dependent on two factors ;

(i) the difference in temperature between the body surface and the air; which determines the heat absorbed or given up by a unit mass of air coming in contact with the skin;

(ii) the air movement; which determines the mass of air coming in contact with the surface.

Convection is a mechanism usually thought to operate only in a fluid, and of course the body is not a fluid. However the circulatory system within the human body does contain fluid of high thermal capacity which acts as a regulated convection system. This assists the equalisation, conservation, or dissipation of heat from the human body when needed.

1.4.3 RADIATION

This physical process of heat loss is also an important mechanism. Heat loss occurs because the human body is surrounded by cooler objects. In a room temperature of about 21°C approximately 60% of heat loss through the skin can take place by this method. However heat loss by radiation usually occurs from freely exposed surfaces, and is not an active mechanism from skin surfaces close together, for example the inner aspects of the thigh and the axilla. From the heat equation viewpoint the skin can act as a "perfect black body" - i.e. a perfect emitter and absorber of heat , but this aspect is dependent on the colour of the skin. Of course this is of very little importance once the body is out of the sunlight.[5]

All radiant heat emitted from the human body lies within the infrared wavelengths. This type of energy is invisible to the human eye , and no human emits radiant energy in visible wavelengths.

In relation to 'man' there are two types of radiant heat exchange ;

(i) the high temperature, short wavelength radiation emitted by the sun or other objects e.g. open furnaces;

(ii) the low temperature, long wavelength radiation associated with the human body, objects such as walls, ceilings and hot water radiators (indoors), and the outdoor environment where temperatures in the existing scale are not very different from the human body.

Some objects termed " grey bodies" reflect a small, but equal amount of light of all wavelengths. Objects which are black or almost black for some radiation and not for others are called coloured objects, and it is into this category that the human skin and most clothing fall. The human skin regardless of its actual colour is considered to approximate to 'a black body' for the range of wavelengths in which it radiates. However it is the area of the body exposed to the environment that is effective in contributing to heat loss by radiation. Areas such as under the arms, between the fingers, between the legs and under the chin radiate to adjacent surfaces and therefore cannot contribute greatly to the overall heat loss[8].

1.4.4 EVAPORATION

An important method by which heat exchange occurs is through evaporation, which is the main mechanism by which the human body regulates the body temperature in warm conditions. A general definition is the diffusion of water vapour across the boundary layer once liquid sweat has been converted into the vapour phase.

In order to avoid overheating by excessive energy storage, excess heat energy must be dissipated by the evaporation of sweat. During strenuous activity a dominant role is played by evaporative cooling in maintaining a thermal balance or homeostasis. The sweat rate can be finely tuned over a wide range of energy production. Metabolic heat production can vary from about 100W at rest to over 1kW during violent exercise. The sweat rate can reach levels of up to 1.5 litres/h in unacclimatised people and as much as 4 litres/h for people acclimatised to heat. At these sweat rates the levels of maximum heat energy that can be lost are 1kW and 2.7kW respectively . For each gram of water that evaporates from the body surface 0.58 Kcal of heat is extracted. In order for evaporative cooling to take place sweat must not run off the surface as liquid without evaporating.

The liberation of heat from the body by evaporation is wholly dependent on the rate at which the body can secrete sweat and the evaporative capacity of the environment i.e. upon the relative humidity (r.h.). In the event that the humidity of the climate or microclimate is, or becomes too high it may not be possible for the surrounding air to absorb water vapour at the same rate at which the skin is producing it. Thus sweat droplets will settle and roll off as liquid without contributing to the evaporative process, and as a result the heat extraction will be lower.

However there are less important mechanisms by which smaller amounts of heat can be lost. When the skin is not wet and active sweating is not present evaporation from the skin will still take place. It is a combination of diffusion of water vapour and evaporation of water during expiration that leads to smaller amounts of heat loss. This is known as insensible evaporation. Further heat is lost from the body during the warming of food, air taken in, and CO_2 that is expired during respiration (see Table 1). [6]

1.5 ENVIRONMENTAL EFFECTS ON THE BODY TEMPERATURE.

1.5.1 EFFECTS OF ENVIRONMENTAL HEAT.

Work performance can be greatly effected by environmental heat. In hot conditions the body temperature may rise and an individual may experience discomfort from increased skin temperature and sweating, and this can affect the performance of many physical tasks.

In some industries and public service organisations workers can be exposed to severe heat, usually in the form of radiation. In steelworks, ceramics factories and glassworks high levels of radiant heat can be produced. In the service industry such as fire fighting, all the forms of heat can be present.

A further effect of high environmental temperatures is that as work continues the rate of sweating decreases. Sweat gland fatigue is instigated at an early stage with exposure to hot conditions ; the peak sweat rate is reached as soon as body temperature has risen. From here on the sweat rate begins to decrease. As work continues the body temperature will continue to rise and work performance will begin to decline. If a worker continues to work in a hot environment when their sweat rate is deteriorating they may become liable to a serious condition known as heat stroke. Experiments carried out in Singapore[8] revealed that performance in hot conditions may still fall even without a rise in body temperature ; one possible explanation could be that the increase in discomfort might distract the worker.

1.6 COMFORT IN PROTECTIVE CLOTHING

1.7 HEAT AND FLAME PROTECTIVE CLOTHING

A wide variety of industries use heat and flame protective clothing to protect their employees from heat produced from a fire/heat flux. Most clothing is designed to protect the wearer for a few extra seconds to allow escape from a flash fire. The types of protective clothing available range for example, uniform/coveralls ; fire-fighter station uniforms ; fire-fighter turnout clothing , to chemical protective clothing (encapsulating suits).[21]

1.7.1 THE ROLE OF MOISTURE IN PROTECTIVE CLOTHING

1.7.1.1 THE EFFECT OF MOISTURE ON HEAT AND FLAME PROTECTIVE CLOTHING.

The human body's first line of defence against heat stress is to flood the skin with the excess heat, thus, as the temperature of the body core increases more heat is passed from the core to the skin. As a large proportion heat can be liberated by the evaporative process, sweat production is increased on order to increase sweat evaporation. Unfortunately evaporation through clothing is often extremely difficult, and almost impossible in the case of protective clothing as these are normally constructed to prevent heat and moisture entering the clothing assembly from the environment. As the skin approaches the core temperature we have what is called " Convergence". A person with a skin and core temperature difference as low as 2°C will probably collapse with heat exhaustion.[11]

As internal body temperatures increase with the combination of external temperatures and metabolic heat production from the work being performed moisture evaporation will decrease as the amount of sweat produced on the skin surface increases. Once sweat is deposited on the skin as liquid moisture evaporation will effectively cease. There is now a layer of liquid between the skin surface and the first layer of clothing. Evaporation is not taking place and therefore the removal of heat is severely reduced, and some cases not occurring[8].

Most articles of heat-and flame-protective clothing are constructed to prevent heat, flame and moisture/liquid from entering the clothing system for a short period of time, but not indefinitely. The presence of water on the outside of the clothing system may have some effect on the protective efficiency of the system, however the presence of liquid within the clothing system so close to the wearer, must have a more detrimental effect on the wearer.

Thus the role of moisture/liquid is two-fold. In the form of moisture it is initially essential for the removal of excess heat. However excess moisture which turns into liquid does not contribute to the body thermoregulatory system, and its presence in the microclimate may have a detrimental effect on the wearer.

1.7.1.2 MICROCLIMATE v ENVIRONMENTAL CLIMATE

The environmental climate can be described as a combination of thermal properties such as temperature , air movement, radiation intensity and humidity. The microclimate is normally that intermediate area between the skin and an intermediate medium, i.e. clothing, however it can also be the area between clothing/ fabric layers, thereby creating multiple microclimates. In most cases of single layer structures the skin temperature is higher than the external ambient air temperature , therefore sweat evaporates from the skin surface, condenses on the fabric surface, spreads throughout the fabric and finally re-evaporates to the outside environment, (see Fig 9).

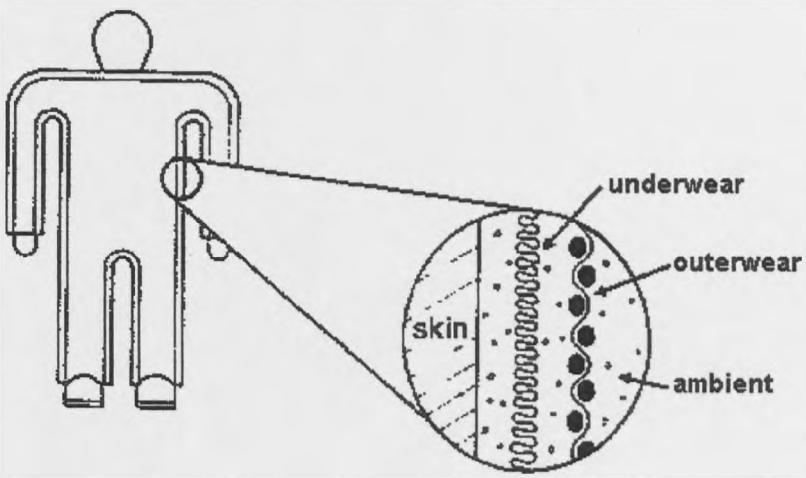


Fig. 9 Buffering of evaporated sweat between clothing-layer[25]

Of course the atmosphere within the various layers in a multi-layer structure can be vastly different (see Fig. 10). For example the area nearest the skin, the first microclimate can be made up three different moisture concentrations, and Hong et al [20] describe these moisture concentrations as follows:

i. - C_s - the area nearest the skin, the moisture concentration to be assumed as fully saturated ;

ii. - C_m - the next area just above this is described as the microclimate between fabric and skin surface;

iii. - C_i - and this is the layer at the inner fabric surface (see Fig 10)[20]

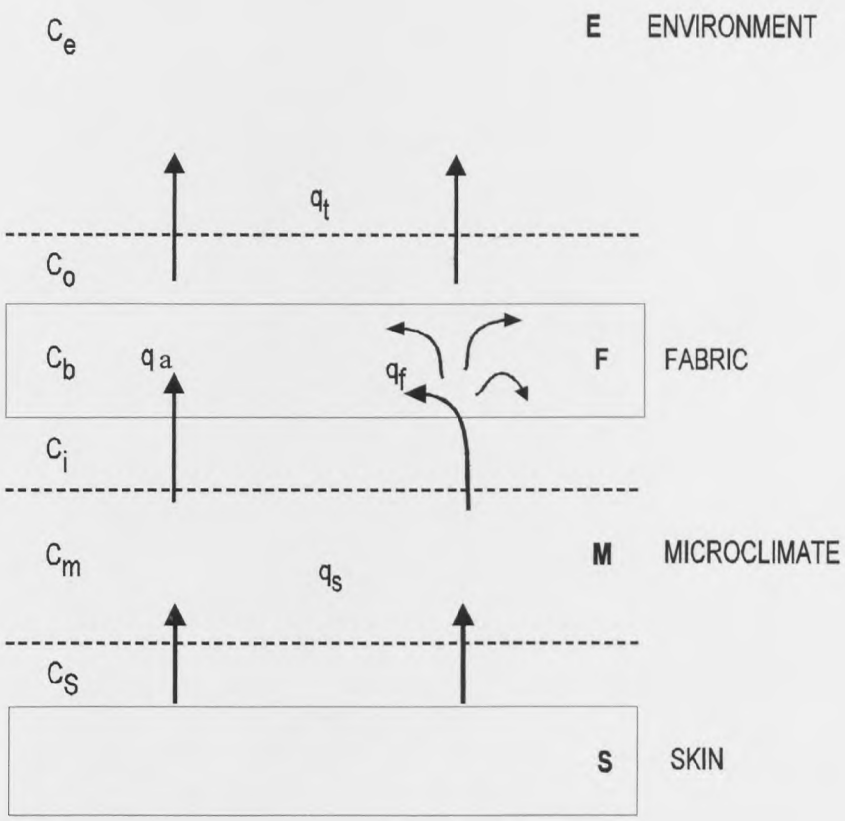


Fig. 10 Cross-sectional representation of the Skin-Microclimate-Fabric-Environment System[20]

where :

C_o – Moisture concentration at the outer surface.

C_e - Moisture concentration of environment far above clothing system, this remaining a constant.

C_b - Moisture concentration in the bulk of the fabric.

q_s - moisture flux from the skin.

q_f - moisture flux along the fibre surfaces.

q_a - moisture flux through open air spaces in the fabric.

q_t - moisture flux from the fabric to the air.

These multilayer surfaces must be considered as three-dimensional (3D) objects. The skin surface is not smooth and flat, but is made up of capillary bridges, grooves and hairs. Fabric surfaces are also 3D in configuration and are not smooth and flat, but also made up of surface fibres with trapped air between them[20,46,47]. Following the conclusions of Hong et al.[20] a proposed multi-layer system devised in this work is described diagrammatically in Figure 11, with the moisture concentration decreasing from skin to microclimate(1) through microclimate(2) into the air of the outside environment.

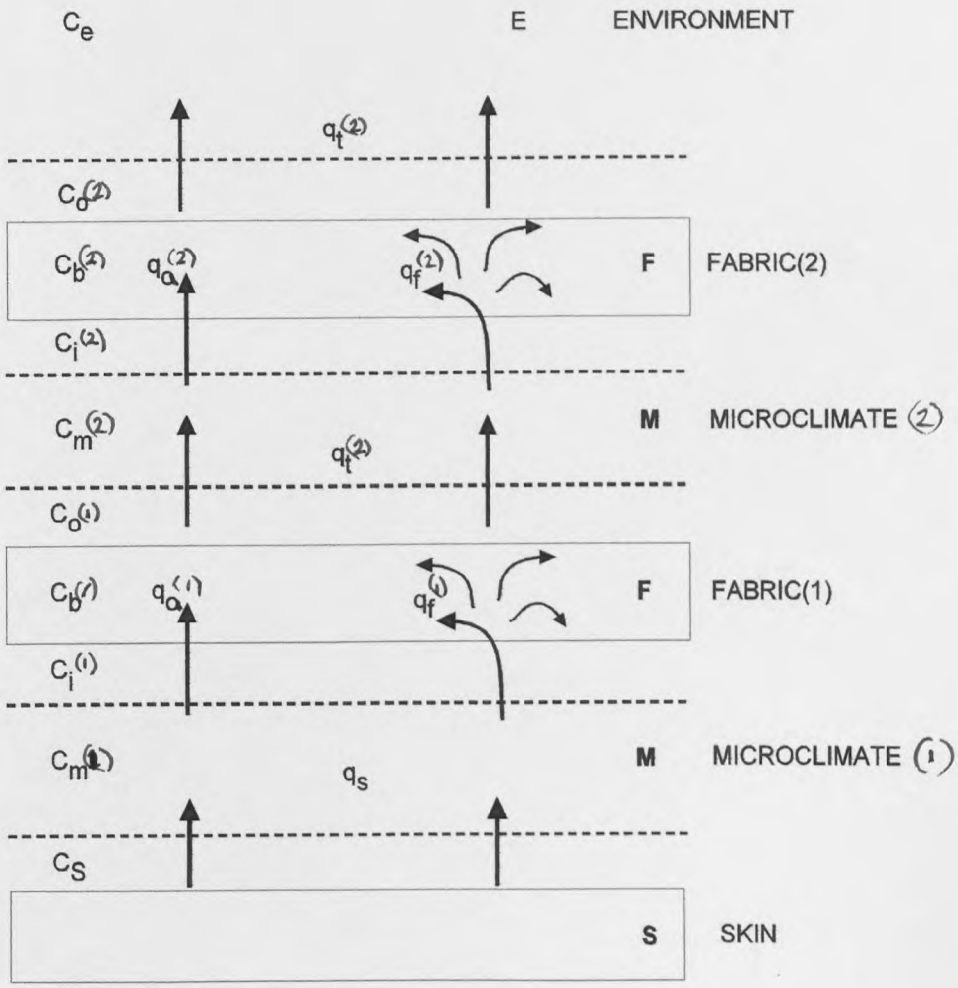


Fig. 11 Proposed model of a theoretical Microclimate in a Multi-layer assembly

1.7.1.3 HEAT STRESS

In the absence of sufficient body cooling, rapid temperature rises cause "Hyperprea" and slow deep breathing , this lowers alveolar $C0_2$ tension and raises the blood pH. Blood pressure may be lowered with exposure to mild heat, but bodily exposure to more intense heat causes a rise in the systolic pressure, and the diastolic pressure may also increase but to a lesser extent. As the body temperature rises sweating begins to decrease, and if cooling of the body is not achieved sweating can then be inhibited. The individual may have dry skin with a rapidly rising body temperature, and heat stroke will then become inevitable. This is a dangerous condition and once the body exceeds a temperature of approximately 42°C death may be likely. At 43°C and above permanent brain damage can occur, while recovery from temperatures of 44°C and above are rare (see Fig. 12). All these symptoms come under the heading of heat stress, and prevention of this condition can be greatly influenced by the garments worn during situations requiring heat and flame protective clothing.[8]

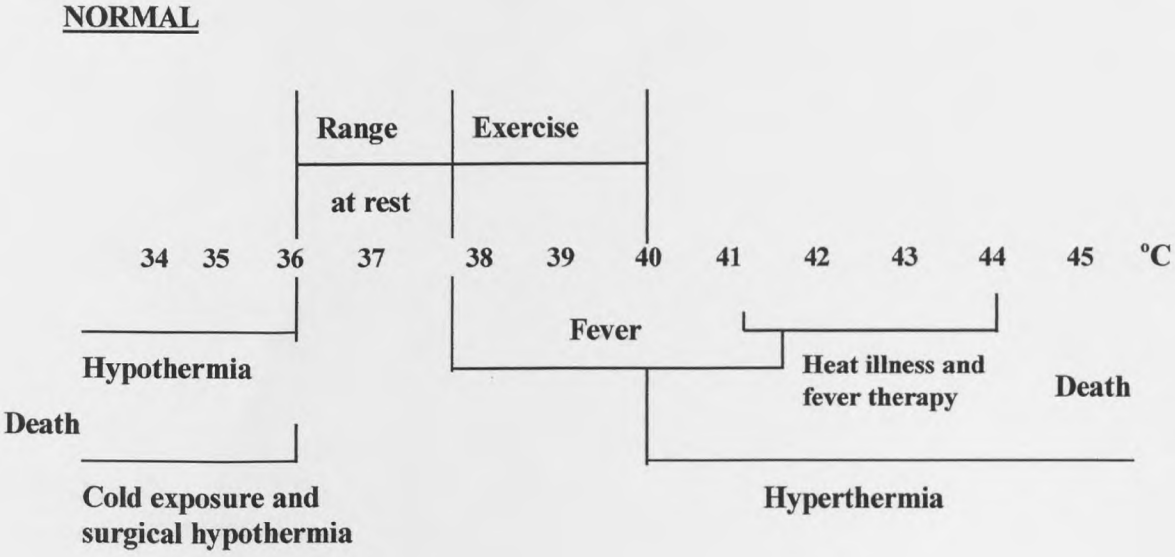


Fig 12. Range of body temperature. (The usual range is from approximately 36 to 40°C ; at temperatures above 41°C there is an increasing risk of death.) [8]

Ten minutes working in a fire-fighting situation can be equal to 8 hours working with a pick and shovel. After 10-12 minutes a person can become completely exhausted even if they are in good physical condition. However heat stress is not a condition limited to fire fighters both in the public and the private sectors, but chemical emergency response, foundry work, waste incineration and boiler room workers are also all subjected to heat stress, even fighter pilots.[10]
Heat stress can occur from the interaction of three factors : the heat produced during work, the clothing worn during the work , and the operational environment.

A fire-fighter can produce 100 Watts of heat at rest and 150 Watts in a fire situation.(1.163 watts = 1000 calories/ hour). The heat production rate at a fire scene has been estimated at a time-weighted average of between 300 and 400 watts. This estimate includes short periods of light activity (150W) ; longer periods of moderate work, such as laying hoses, or building searches wearing BA equipment (250W) ; and shorter periods of peak work, such as hauling hoses upstairs, working with ladders and venting with axes (500W or more).[12,54]

Protective clothing designed to protect people from increases in environmental temperatures, also increases body heat production. Insulation from temperatures greater than skin temperature is essential, however at air and radiant temperatures less than skin temperature this insulation may prevent the body from losing this extra heat produced from greater physical activity. In addition protective clothing may also interfere with the evaporative cooling process of the body.
Lastly the possible environment at a fire scene can be at air temperatures approximating 260°C (500^{O}F), but has been known to reach 982°C (1,800°F)[12].
The importance of comfort is borne out in an US report compiled by the USFA (United States Fire Administration) in 1990 stating that of 105 line-of-duty deaths in 1990, in the USA only one was caused by thermal injury sustained from a fire. More than 50% of the deaths were caused by heart attacks.[13] The comfort properties of protective clothing can thus be designed to help to relieve physical stress, or contribute to heat stress by trapping body heat.

Past studies have determined that a reduction in heat stress can be achieved, in a number of ways. Three of these approaches are directly related to the design and construction of protective clothing, and these are :

- Reduction of dynamic loading (restriction of body movement by the garment)
- Reduction of static loading (garment weight).
- Use of materials that provide high levels of moisture vapour/liquid movement in conjunction with acceptable levels of thermal insulation.

The experimental project described in this thesis is concerned with the third approach , namely , to prevent high levels of heat stress it is important to prevent the wearer from environmental and metabolic overheating. This would mean aiding the natural cooling system of the human body by assisting the movement of moisture/liquid within the clothing system.

At present heat-and flame-protective clothing are generally designed as a multi-layer system, usually incorporating three layers, with each fabric layer performing a different function in the protective garment. This multi-layer structure comprises an outer waterproof/flameproof layer ; a moisture barrier layer ; and a thermal barrier layer. What is worn underneath the protective garment can be almost as important as the protective garment itself.[48,49]

Research in recent years has determined that secondary protection in conjunction with the normal protective outer garment can provide an 'optimum protective ensemble' as described by Lord [50]. The combination of the fabric properties of the clothing worn beneath the protective outer layers can be very important and should be considered with the protective outer garment as an overall system.

It is considered that the right combination of fabric layers would help in the reduction of heat stress, and as a potential transport system for reducing the amount of heat produced and stored within the inner layers of this clothing system.

Therefore an understanding of the mechanisms of liquid/moisture transmission between fabric layers is important in conjunction with the factors which influence these properties.

This project investigates the mechanisms and factors which influence liquid/moisture transmission in multi-layer fabric systems. Knitted fabrics have been the fabrics most worn underneath protective clothing, in the form of tee-shirts and under-wear.

With this in mind weft knitted fabrics have been the main focus of this experimental investigation.

CHAPTER 2

2.0 LIQUID/MOISTURE TRANSMISSION IN TEXTILE MATERIALS

2.1 MECHANISMS OF LIQUID/MOISTURE TRANSFER

2.1.1 Migration

Migration is the transport of either liquid water or water vapour molecules along a fibre surface. The ability of a fibre to facilitate this is dependent on its surface hydrophilicity or affinity for water (see Figure 14). Other factors include the textile finish applied and the fibre substrate.[33]

Since $1m^2$ of substrate can contain approximately $100m^2$ of potential fibre surface a great deal of water can be transported via a textile by this mechanism.[33]

However this is also dependent on the amount of fibre surface available for sorption.

2.1.2 Capillary Action

Capillary action describes the water rise in a narrow tube, fissure or channel. The interstices in a fabric represent the capillaries or channels within a fabric system. This mechanism works on the principle that, the narrower the capillary tube, the greater the capillary action.

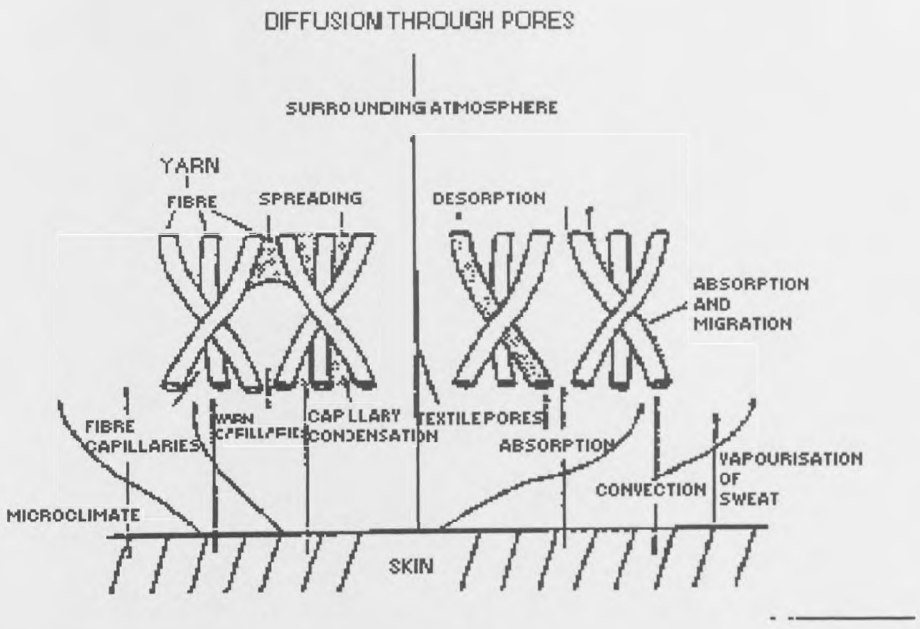


Fig. 14 Mechanisms of Moisture transport in Textiles. [33]

2.2 LIQUID / MOISTURE TRANSFER THROUGH SINGLE & MULTILAYER STRUCTURES

Liquid transmission through clothing assemblies can be made up of a series of sub-mechanisms based on the types of wicking processes that take place within a clothing system.

The experimental work described in chapter 3 and 4 of this thesis is concerned initially with horizontal transplanar wicking, however in any clothing system a number of wicking processes take place at the same time, all of which may contribute to liquid transfer. These are listed below :

(i.) transplanar wicking in the horizontal state ;

(ii.) transplanar wicking in the vertical state ;

(iii.) planar wicking in the horizontal state ;

(iv.) planar wicking in the vertical state ;

(v.) transplanar wicking in the horizontal state with interfabric movement ;

(vi.) transplanar wicking in the vertical state with interfabric movement ;

(vii.) planar wicking in the horizontal state with interfabric movement ;

(viii.) planar wicking in the vertical state with interfabric movement.

All these processes can occur at any point in a clothing system either separately or in combination, whether the human subject is in a horizontal or vertical state.

All these processes produce a very complex transport system, see Fig. 15.

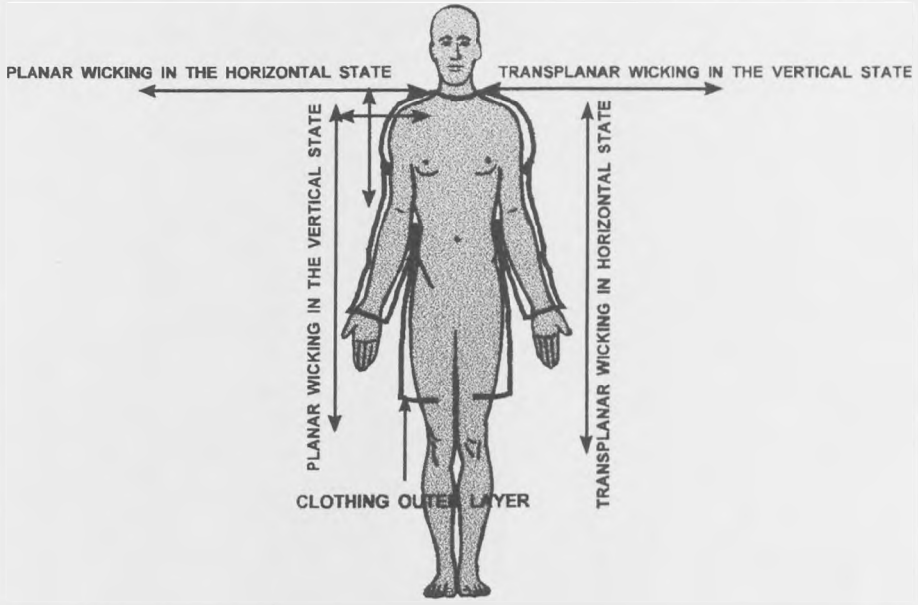


Fig. 15 Wicking mechanisms involved in a Clothing system

2.2.1 WETTING AND WICKING

Wetting and wicking are complex phenomena and are intrinsically linked with each other, and this is particularly so when a fibrous assembly is involved such as a fabric.

Wetting is described as the displacement of the fibre-air interface with a fibre-liquid interface. The definition of wicking or wickability has changed slightly over the years, and become more refined. Wicking was defined as "the ability to sustain capillary flow " by Harnet and Mehta[22] in the 1980's , while later Kissa [15] described it as "A spontaneous transport of liquid driven into a porous system by capillary forces", but also says " wicking is a result of spontaneous wetting in a capillary system." The latter definition incorporated the two methods of liquid transmission ,and stated that wetting precedes wicking.

However, in general, wetting describes the mechanisms that occur in a substrate during its initial contact with a liquid, with wicking describing the processes that occurs after wetting.

2.2.1.1 WETTING

Spontaneous wetting is a dynamic process and is the migration of liquid along the surface of a fibre or solid to reach a state of thermodynamic equilibrium. Forced wetting involves mechanical forces to increase the fibre-liquid interface beyond the static equilibrium. Wetting involves the replacement of air with liquid and various mechanisms such as immersion, adhesion, spreading, and capillary penetration may occur simultaneously.

Many studies have been carried out to apply a number of equations to describe the various stages of wetting. For example the solid-liquid boundary can be described by the Young-Dupré equation,[14,65]

$$\gamma_{SV} - \gamma_{SL} = \gamma_{LV} \cos\theta \qquad \text{---------- [7]}$$

where γ denotes the interfacial tension ; the subscripts S,L, and V denote solid, liquid, and vapour surfaces respectively, and θ is the equilibrium contact angle.

The term $\gamma_{LV} \cos\theta$ has been called the specific wettability or adhesion tension [14,15,61,62,63,64]. Although this equation is only relevant to a drop of liquid resting on a smooth homogeneous impermeable non-deformable surface, this equation is widely used to explain the wetting and wicking mechanisms in textiles. However it must be noted that when the contact angle is made the focus of the wetting process the conclusions drawn may be incorrect, for as Kissa [15] points out, textile fibres do not have ideal surfaces. Wetting is further complicated by surface roughness, heterogeneity, and the fact that the whole wetting mechanism is dynamic.

The contact angle thus becomes a dynamic contact angle in such systems corresponding to the instantaneous velocity of a moving meniscus.

Therefore the contact angle formed by a static liquid as used in the Young-Dupré equation can be very different from a dynamic contact angle (i.e. the contact angle of a moving liquid front).

On the other hand , Ghali et al.[15] describe wetting and wicking as one process, mathematically represented by Darcy's equation :

$$V = \frac{k \, dp_c}{\mu \, dx} \qquad \text{---------} \quad [8]$$

This equation relates to the liquid flow in response to the capillary pressure where:

V = velocity of liquid (cm/s)
k = permeability (cm^2)
μ = (g/cm s) viscosity of advancing liquid
p_c = capillary ($g/cm\ s^2$)

In the case of fabrics the wetting ability of a fabric is almost directly linked to the wetting properties of the related fibres, and in turn these are related to the fibre surface and the liquid properties. Using these properties Hsieh [17] theorises that the wetting characteristics of 100% cotton , polyester, Nomex, viscose and secondary cellulose acetate woven fabrics can be derived from the characteristics of their single fibres, demonstrating that the wetting property of a single fibre is similar to the wetting properties of the fabric of the same fibre type.

This property is described by its liquid contact angle[17] :

$$\theta = \cos^{-1} \frac{F\omega}{p\gamma} \qquad \text{--------} \quad [9]$$

where, p = fibre perimeter.

$F\omega$ = Force exerted on a fibre while in contact with a liquid

γ = Liquid surface tension

Experimental results from Hsieh demonstrated a straight forward method for determining fabric wetting contact angles , offering the advantage of simultaneous detection of dynamic liquid transport.[17,43,74]

2.2.1.2 WICKING

As mentioned before wetting precedes wicking, and in order to spontaneously transport liquid within an textile assembly, wetting must first occur. Once again there are various equations associated with this phenomenon. Kissa explains that for the process to be spontaneous, free energy has to be gained. This occurs when the interfacial energy of the fibre surface in contact with vapour (air) and liquid, γ_{SV}, exceeds the interfacial energy between the liquid and the fibre surface, γ_{SL} [14,65].

$$Wp = \gamma_{SV} - \gamma_{SL} \quad \text{---------- [10]}$$

where Wp denotes the work of penetration, and the measure of energy needed for capillary penetration.

Due to the difficulty in measuring γ_{SV} and γ_{SL} independently Kissa has used the Young – Dupré equation [Equation 7], which expresses the difference between γ_{SV} and γ_{SL}. With measurable quantities γ_{LV} and Cos θ [Equation 10] suggests that when Wp is positive for spontaneous capillary penetration, γ_{SL} Cos θ, must also be positive. γ_{LV}, is always positive, so therefore Cos θ is positive also, and the contact angle θ must be between 0° and 90°. Drawing to a similar conclusion in relation to capillary penetration with capillary pressure the Laplace equation [equation 11][14,15] has been used to describe the forces occurring in a capillary when a liquid wets the walls of a capillary and a meniscus is formed. The pressure difference ΔP across the curved liquid – air interface caused by the surface tension of the liquid can be denoted by the equation : [14,15,70]

$$\Delta P = \gamma_{LV} ({}^1/R_1 + {}^1/R_2) \quad \text{---------- [11]}$$

In a capillary with a circular X-section, the radii of the curved interface R_1 and R_2 are equal.

$$\Delta P = 2\gamma_{LV} / R \quad \text{---------- [12]}$$

In the case of a completely wettable capillary wall, the assumption is that the liquid-vapour interface is a hemisphere and R = r , where r = capillary radius :

$$\Delta P = 2\gamma_{LV} / r \qquad \text{---------- [13]}$$

In the case of a capillary wall that is not completely wettable :

$$r/R = Cos\ \theta \qquad \text{- ---------- [14]}$$

substitution in equation 14 gives :

$$\Delta P = 2\gamma_{LV} Cos\ \theta / r \qquad \text{---------- [15]}$$

and so for the capillary pressure to be positive $Cos\ \theta$ must also be positive , and therefore the contact angle must be between 0° and 90°. Capillary pressure is inversely related to capillary radius. Because capillary spaces in fabrics are not uniform an indirectly determined capillary radius is used for radius 'r' [14,15].

The theory of wicking has been described as follows ; in a single capillary the liquid front advances stretching the meniscus of the liquid until elasticity and inertia of the flow are exceeded. The meniscus then contracts pulling more liquid into the capillary thus restoring the equilibrium state of the meniscus. This may occur in a series of jumps due to the irregularity of capillary size. Theoretically capillaries have been visualised as a series of parallel capillaries in a fibrous assembly to facilitate this theory in fabrics.

The textile fabric can be described as three capillary systems by which liquid may be transported into the main fabric matrix. This system is mutually perpendicular, with each system representing the warp directions in the fabric plane ($\mathbf{C_w}$) , the weft direction in the fabric ($\mathbf{C_f}$), and the direction through the fabric thickness ($\mathbf{C_t}$) , see Fig. 16.

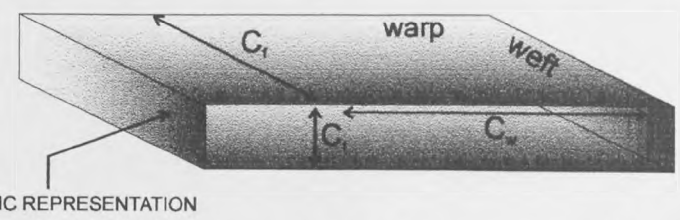


Fig.16 A theoretical representation of Capillary systems within a fabric

It is through these three types of capillary system that liquid travels and the wicking process is dependent on the characteristics of (C_w), (C_t) and (C_f) [39].
The capillary system of the fabric matrix can be vastly different from cylindrical capillaries. These may be neither cylindrical, or closed at either end or sides due to their formation by inter-fibre or inter-yarn spaces, see Fig 17.

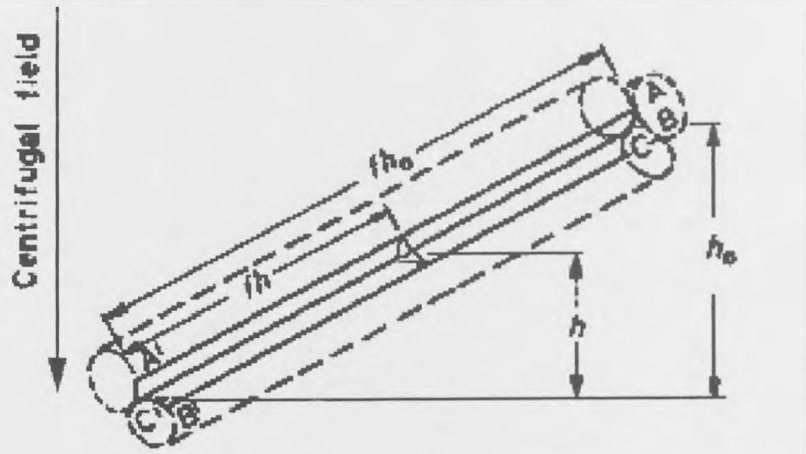


Fig. 17 Capillary channel formed by groups of contiguous fibres. [34]

Channels leading from one face of the fabric to the other differ from the capillaries found running from one end to the other of the fabric plane. This difference in geometric construction and therefore capillary characteristics causes differences in capillary migration.

Wicking is affected by the shapes and surfaces of fibres, although in the past the belief that fibre shape does not affect wicking is now only thought to be true for single fibres. The shape of a fibre affects the yarn and in turn the fabric, influencing the size and geometry of the capillary spaces within the fibres and the fabric. The rate of wicking is determined by the geometric irregularities present which allow the meniscus to reach an edge and flatten.[34]
Work carried out by Hsieh[17] on liquid transport in a porous medium has determined that pore size distribution and connectivity have a great influence. An important aspect is the connectivity, or the geometric pathways by which the pores(capillaries) are interconnected. However pore connectivity cannot be easily quantified or described.

The event sequence for liquid advancing through a pore with curved walls as this would occur in a fibre, yarn or fabric may be represented by figure 18:

a) just before contact ;

b) configuration can not occur unless the advancing contact angle were equal to 180°;

c) configuration has the proper angle (bearing in mind that the liquid is being forced to move);

d) the meniscus is curved to satisfy the contact angle requirement and enters the pore. No matter what the value of the contact angle is the meniscus shape must be concave[18].

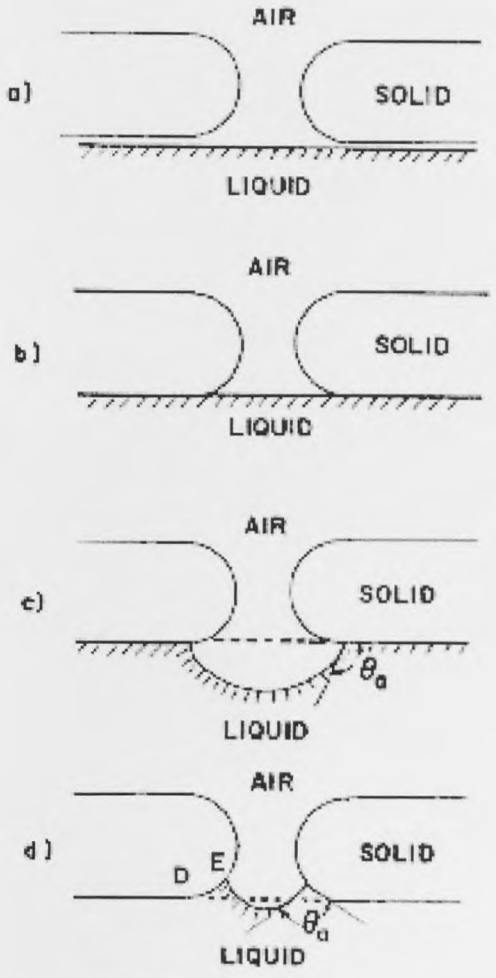


Fig. 18 Initial contact of a liquid with a doughnut-hole-shaped pore.[18] (a) Liquid surface just before contact with the pore. (b) Not acceptable due to θ_a constraint. (c) Not acceptable because portion of liquid mass cannot vanish. (d) Acceptable because liquid mass is conserved and θ_a constraint satisfied.

As the liquid front advances up the pore or capillary the meniscus changes shape from concave to convex (see Fig. 19).

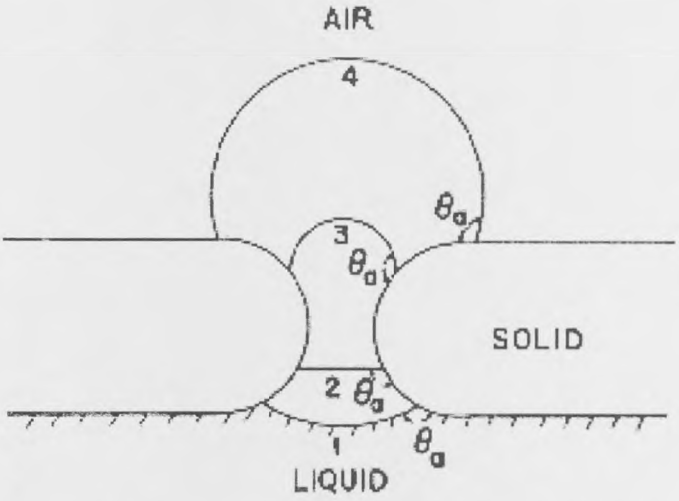


Fig. 19 Liquid surface changes shape from concave to convex as it advances through a pore with an hourglass profile. [18]

Inter-fibre spaces (pores) may or may not be interconnected and their distribution will also affect the liquid movement towards smaller pores ; this can lead to the draining of previously filled spaces in preference to these smaller pores. The occurrence of fibre swelling also affects capillary liquid capacity in inter-fibre spaces, and the reduction in wet fibre strength can lead to collapsed pores and a decrease in liquid holding capacity.

Wicking in a fabric may occur from a limited or unlimited amount of water. Wicking from a limited reservoir may take the form of a drop of water on a fabric surface, while wicking from an unlimited source can be described as 'immersion transplanar wicking' or 'longitudinal wicking'. Based on the interaction of the fibres Kissa [14] has further developed these wicking processes into four categories :

I : Wicking of a liquid - no significant diffusion into the fibre surface.

II : Wicking accompanied by diffusion of the liquid into fibres or into a finish on the fibre

III : Wicking accompanied by adsorption on fibres.

IV : Wicking involving adsorption and diffusion into fibres.

2.2.2 FACTORS INFLUENCING WICKING

Wicking in general is influenced by the inter-fibre spaces. These in turn are affected by the fibre type and the substrate assembly or structure. The fibre length, width, shape and alignment all have a great influence on the quality of the capillary channels in the inter-fibre spaces.

The type of assembly or structure (i.e. nonwoven, woven or knitted) of the substrate will determine the alignment, distribution and size of the pores present. For example in woven structures the capillaries will be directed along the warp, weft and in a smaller degree the thickness of the fabric. These pores can be intra-fibre, inter-fibre, and inter-yarn with the smallest being intra-fibre pores. These can be discontinuous between adjacent fibres. The density and structure of yarns in woven fabrics can greatly influence the dimensions and structure of inter- and intra-yarn pores. Inter-fibre pores can be either inter- or intra-yarn structures. Inter-yarn pores can be similar in size to fibres and in some cases larger than yarns.

The overall complexity of fabric pore structures must therefore include the complex structural variables, pore size distribution, pore connectivity and total pore volume. In spite of these complexities Hsieh has combined several fabric properties to describe the porosity of a fabric as the following equation[Equation 16] demonstrates[17] ;

$$\textbf{POROSITY } (\phi) = \frac{\textbf{1 - medium vol.}}{\textbf{bulk vol.}} = 1 - \frac{Pb}{Ps} \qquad \text{----------} \quad [16]$$

where Porosity is defined as the fraction of void space in a porous medium.

For fabrics, Pb = fabric density (g/cm^3)

Ps = fibre density

Pb = $\frac{\text{fabric weight}}{\text{thickness (cm)}}$ (g/cm^2)

Studies carried out on knitted fabrics include Robinson's work[82] on knitted interlock fabrics using methanol as the wicking liquid and experimenting with vertical wicking. He found that Washburn's equation[40] [equation 17] might not fit the wicking process in these fabrics due to :

- capillary channels in fabrics do not have circular cross-sections and are not uniform in cross-section along their length ;
- capillary channels differ in size and shape, and were interconnected.

$$\frac{ds}{dt} = \frac{\gamma r \cos\theta}{4\eta S} - \frac{gpr^2}{8\eta} \qquad \text{---------- [17]}$$

where γ = the surface tension of the liquid

η = the viscosity of the liquid

θ = the contact angle p = density

S = the distance travelled by the liquid g = gravity

Law [76] also modified Washburn's equation[40] (the hydrodynamic model) in order to fit results from horizontal wicking experiments on different types of knitted interlock fabrics in order to produce a prediction model which was :

$$x = at^{1/2} + bt + ct^2 \qquad \text{---------- [18]}$$

where x = wicking distance

t = wicking time

a = rate constant

b and c = fitted parameters

Maroufi[78] also used a similar test method and hydrodynamic model to study cotton interlock fabric after various finishing treatments. Observing the effect of different loop lengths, it was found that finer yarns with longer loop lengths wicked faster than fabrics with shorter loop lengths. Coarser yarns in fabrics with shorter loop lengths wicked faster than fabrics with coarse yarn and long loop lengths.

He also found that the equation fitted well with the vertical wicking performances of interlock fabrics.

The same apparatus was also utilised by Sungnoo[80] to observe vertical planar wicking in single jersey 100% cotton fabrics and cotton/elastomeric fabrics. Sungnoo investigated the effect of loop length and fabric direction on vertical planar wicking. Results from these tests agreed with Maroufi's observations with regards to loop length. It was determined that liquid flow occurred mainly in the intra-yarn channels in fabrics with long loops. Also at a particular loop size value the increase in loop size would begin to create a decrease in wicking rate. This was because the capillary pressure in the intra-yarn channels of a long looped fabric was higher than the pressure in the inter-yarn channels (loop spaces), this is borne out by equation 19.

$$\text{Capillary pressure} = \frac{\text{Capillary force}}{\text{Area}} = \frac{2\pi\, r\, \gamma\, \cos\theta}{\pi\, r^2} = \frac{2\gamma\cos\theta}{r} \qquad \text{----------[19]}$$

where liquid surface tension = γ; density = ρ; the advancing contact angle = θ; flows vertically through a capillary tube against gravity g ; the driving pressure = ΔP (is the capillary pressure minus the hydrostatic pressure)

Hydrostatic pressure = gpS, where S = distance travelled by liquid, therefore

$$\Delta P = \frac{2\gamma\cos\theta}{r} - gpS \qquad \text{----------[20]}$$

Also see equation 15.

Little work has been published on fabric movement during wicking, however this must be taken under consideration if one is to try and describe the processes occurring during garment wear.

Fabric movement during wear is a complex series of component movements. These can consist of movements parallel and perpendicular to the skin, and are further complicated where several layers are incorporated within a clothing assembly.

Barnes and Holcombe[36] investigated moisture absorption during fabric movement, and developed a model to describe one mode of movement, assuming the clothing is parallel to the skin. This can be seen in Fig. 20.

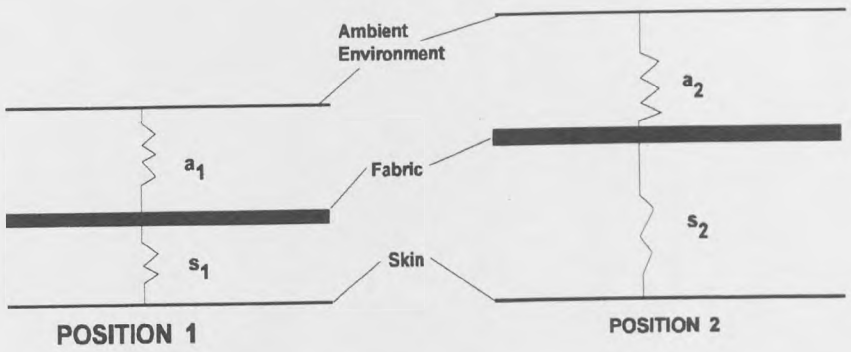


Fig. 20. A simple mode of fabric movement. The fabric is assumed to move repeatedly between the two positions shown above, spending a period t_p in each position. The vapour resistance between the skin and fabric is 's', and between the fabric and the ambient environment it is 'a', with subscripts to differentiate between values in the two positions.[36]

Barnes and Holcombe determined for an ideal sorptive fabric that moisture transport increases with movement. However in the case of nonsorptive fabric, fabric movement had no effect.

2.2.2.1 PLANAR WICKING

In most cases wicking in the direction of the fabric plane is where wicking occurs in a fabric hung in a vertical state. This method can also be known as longitudinal wicking. The fabric is partially immersed in a liquid to wet the fabric, and liquid transmission occurs up the substrate. There have been many studies carried out on this, with the distance travelled by the liquid front or the amount of liquid absorbed by the substrate being measured.[23]

In a vertically held fabric, wicking will be affected by gravity, and once capillary forces are balanced by the hydrostatic head, wicking ceases. The distribution of liquid in a vertically hung fabric may exhibit a pattern, especially when wicking is accompanied by absorption into the fibres.

2.2.2.1.1 Wicking From a Limited Reservoir

Wicking from a limited amount of liquid such as a drop of water on the surface of a fabric is made up of two phases with different kinetics[14,37,57] .

Firstly the drop of liquid spreads and penetrates the fabric surface. If most of the water remains on the top surface of the fabric, capillary penetration is kinetically similar to that which occurs in wicking from the unlimited reservoir. During the second phase all the liquid is now within the fabric and spreads radially under capillary forces. Kissa defines this area of spread by the following equation [14,55,56]:

$$A = K(\gamma / \eta)^{\mu} V^{m} t^{n} \qquad \text{---------- [21]}$$

where V = initial volume of drop

μ ,m,n = are constants (with the value of $\mu = 0.33$; $n = 0.33$; $m = 0.67$)

K = capillary sorption coefficient which depends on the dynamic contact angle, the thickness and permeability of the substrate.

A = area covered by spreading liquid γ = surface tension of the liquid

η = viscosity of liquid t = spreading time

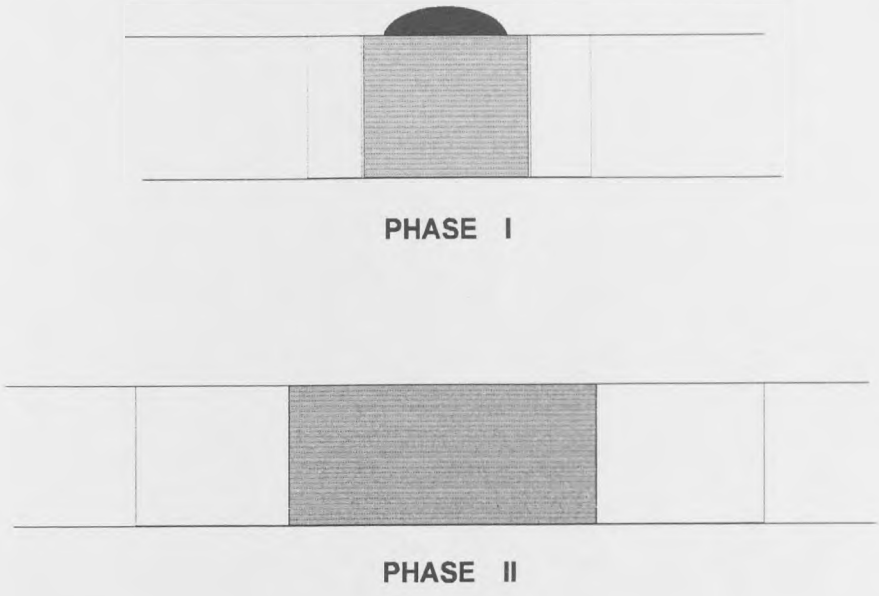


Fig. 21 Schematic illustration of the two phases of drop spreading of liquids in fabrics. [37]

It is at the first phase that the area of the spread is proportional to the square root of time. At the second phase the constants are 0.3 ;0.3 ;0.7 (μ ,n,m,) respectively for impermeable fibres only. For permeable fibres diffusion of the liquid into the fibres must be taken into account and results in the decrease of 'n', the increase of 'm' and 'μ', but all three parameters remain constant for specific fibre-liquid system.[14,55,56]

2.2.2.1.2 Wicking From an Infinite Reservoir

This can refer to wicking of a fabric during complete immersion. This causes the displacement of air from the inter-fibre and inter-yarn spaces, and allows the liquid to enter the fabric matrix. In a small sample this would cause it to sink in a large reservoir. Transplanar and planar wicking can also be included in this category.

2.2.2.2 TRANSPLANAR WICKING

Liquid transport perpendicular to the plane of the fabric, known as "Demand wetting or wettability", has also been termed by Miller and Tyomkin[16] as "spontaneous transplanar liquid uptake". This involves the transmission of liquid through a fabric from one side of the fabric to the other. Many tests have been developed over the years to investigate this phenomenon. Wicking has been split into two mechanisms described as spontaneous and forced, (see Fig. 22).

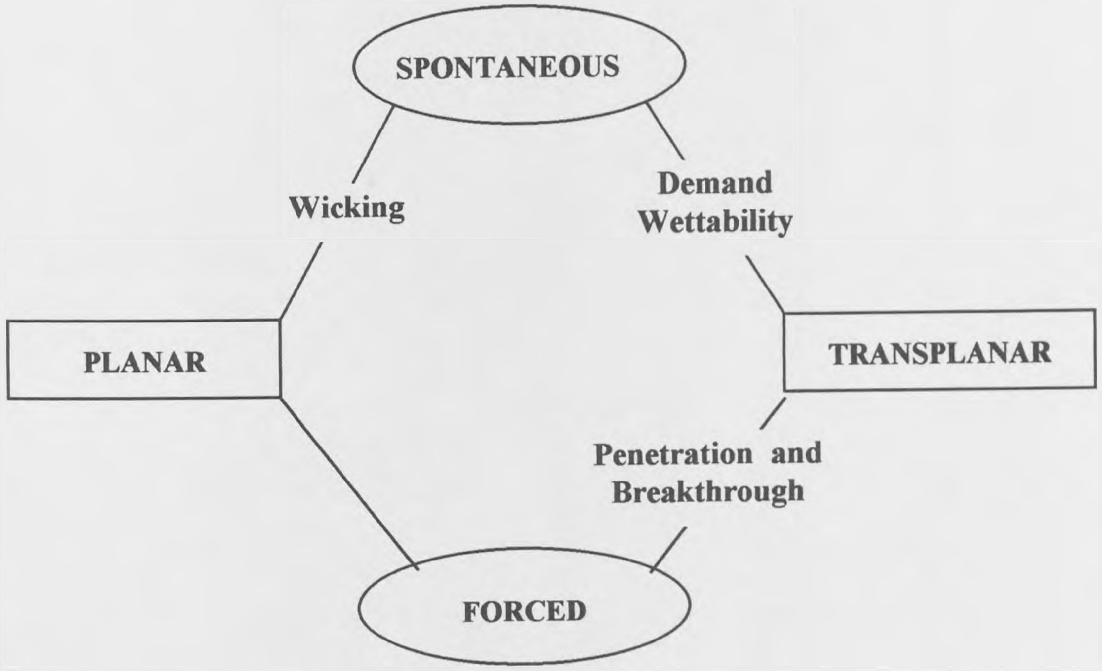


Fig. 22 Liquid/air displacement processes.[19]

Miller has also used Darcy's equation to describe wicking by forced flow into a porous medium[19] :

$$dV / dt = (KA / \eta\chi)\, \Delta P \qquad \text{---------} \quad [22]$$

where dV / dt = volumetric rate of penetration, A = macroscopic cross-sectional area of the network, K = permeability constant, η = liquid viscosity, χ = linear distance of penetration, and ΔP = external driving pressure.

Since liquid is displacing air within the network, the external ΔP will be reduced by the capillary pressure if the dynamic contact angle is less than 90°, and reduced if $\theta_a > 90°$.

2.3 MEASURING LIQUID/MOISTURE TRANSMISSION

Over the years the transmission of liquid within fabrics has produced a variety of experimental procedures for measuring wicking and wetting. Most have involved single layer investigation with some progressing to multi-layer structures, but almost none involving fabric movement during wicking.

2.3.1 PLANAR WICKING

A survey conducted by Harnett and Mehta[22] in the early 1980's on experimental methods for testing the fabric wicking process brought to light a series of methods that demonstrated the wicking mechanism.

Wicking in the planar direction was tested by the longitudinal wicking 'strip' test, using two standards available at that time, BS.3424 (method 21) 1973 - Determination of resistance to wicking, and DIN 53924 (1978) Determination of the rate of absorption of water by textile material (height of rise method).

DIN 53924 used a short test period of 5 minutes maximum ; used for rapid wicking fabrics. However BS.3424 had a very long test period of 23 hours, used for coated fabrics with very slow wicking rates.

However because these standards could not be used to compare heights of rise in different fabrics, unless the fabrics were of similar thickness and structure, the weight of liquid gained by a fabric at the end of the test was calculated and expressed as a percentage of the total fabric weight. (See Fig. 23)

Hollies et al[23] developed an alternative method, using a horizontal strip to measure the mass transfer rate and the simultaneous rate of the advance of the water front, (see Fig. 24).

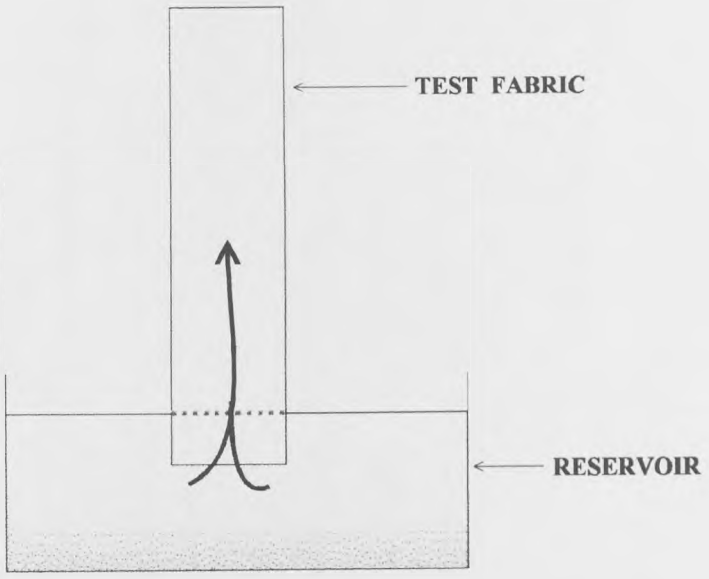


Fig. 23 Strip Test [22]

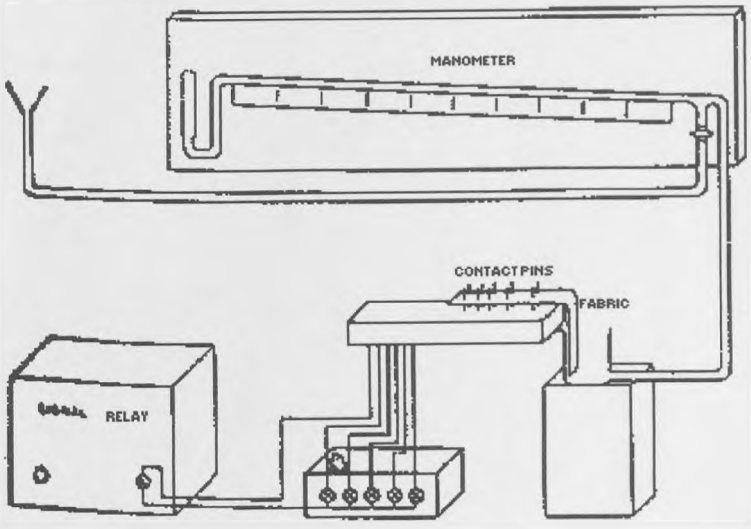


Fig. 24 The Horizontal Water Transport Apparatus [23]

Spot tests were also developed to test fabric wicking, and a modification of BS. 3554 (1970) - Determination of wettability of textile fabrics and AATCC method 39-1977 - Evaluation of wettability, have been devised along these lines. Liquid is delivered as drops from a 6mm height on to a horizontal fabric sample. The time that the drop takes from reaching the fabric surface to its disappearance by wicking into the fabric is measured and recorded, (see Fig. 25). This method was also modified [22] to replace the drop by a continuous supply of liquid. This was achieved by a saturated fabric wick or capillary tube in contact with the fabric sample.

The Siphon test also has no published standards. This method involves the use of a strip of test fabric as a siphon, with one end in a reservoir of liquid and at the other end the liquid is allowed to drain into a collecting beaker. The amount of liquid collected is recorded at successive time intervals (see Fig. 26).

Evaluation of the results from this method differed between researchers; Hardman[22] described its results as 'a rate of drainage' using the lapse time indicators of time at initial contact of the fabric with the liquid, and the time dropping commences as a measure of wicking.

However other researchers such as Hardman[22] and Tanner[26] have used the rate of mass transfer of liquid when a constant flow through the siphon has been achieved as an indicator.

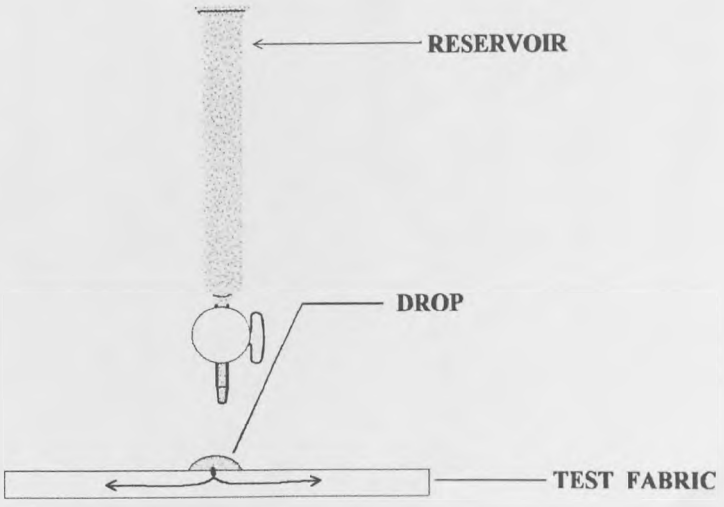
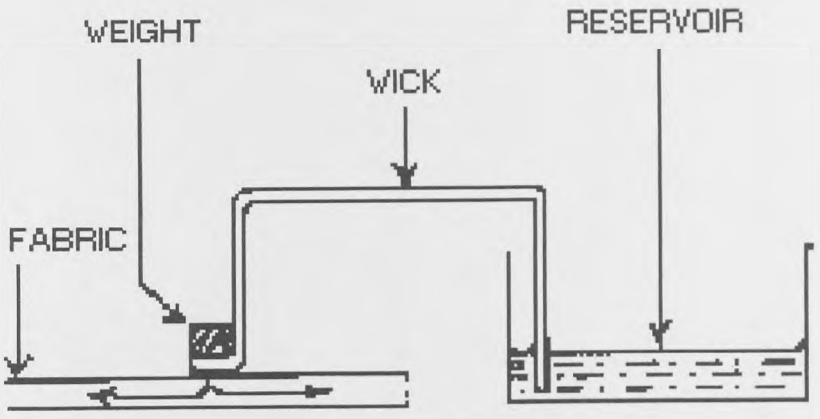
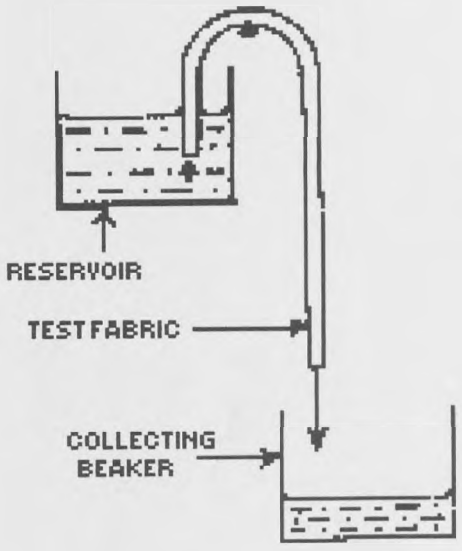


Fig 25 Spot Wicking test [22]



A.



B.

Fig. 26 Siphon Test (2 methods A and B) [22]

2.3.2 TRANSPLANAR WICKING

Transplanar wicking is sometimes known as wicking perpendicular to the fabric plane, but testing in this area has no published standards and various methods exist. In the 1950's, 1970's, and 1980's authors such as Buras et al. [30] , Korner et al. [31] and Harnett et al. [22] used the transverse wicking "plate " test or variations of it.

This method consists of a horizontal capillary tube. A simulated sweating skin surface is achieved by setting the level so that the plate is kept damp,(see Fig. 27). Test samples are placed on the plate with a defined pressure achieved by applying weights on the top. Results are determined by recording the position of the meniscus in the capillary tube at various time intervals as water is wicked through the fabric sample.

Variations of the test have been introduced as various criticisms of some aspects of the method have come to light [22]. For example it was thought that the decrease in resistance to flow imposed by the capillary tube could be overcome by replacing the tube by an air bleed system of constant lower resistance[22].

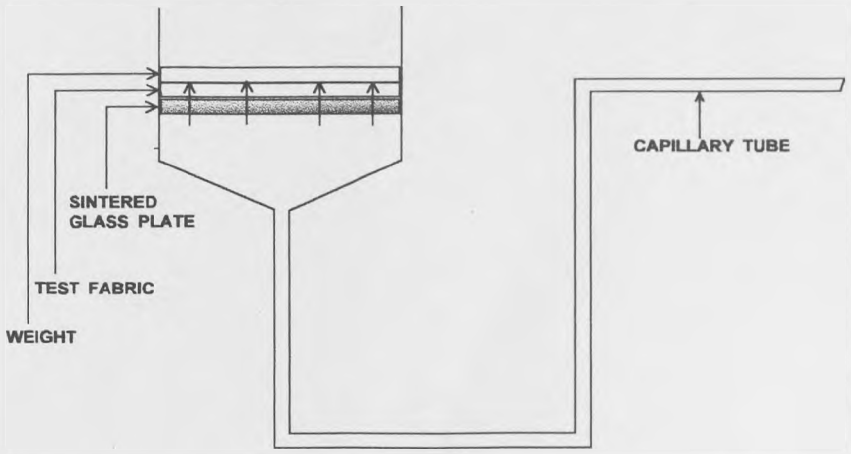


Fig. 27 Plate wicking test [22]

More updated methods of measuring transplanar wicking have incorporated multi-layer systems, such as the method devised by Yoneda et al. [32]. They have made use of a pressure sensor method to measure water uptake. This apparatus consists of a reservoir connected by a flexible rubber tube to a stainless steel cylinder. The cylinder is filled with ion-exchanged water, with a PTFE [Poly(tetrafluoroethylene)] perforated plate and cellulose filter paper on top ; this is the main section. Fabric samples are attached to the stainless steel plate and placed on the filter paper to cause water uptake. Detection of uptake is by a reduction of the water column pressure ; the change of pressure signals is then magnified by an amplifier and recorded, (see Fig. 28).

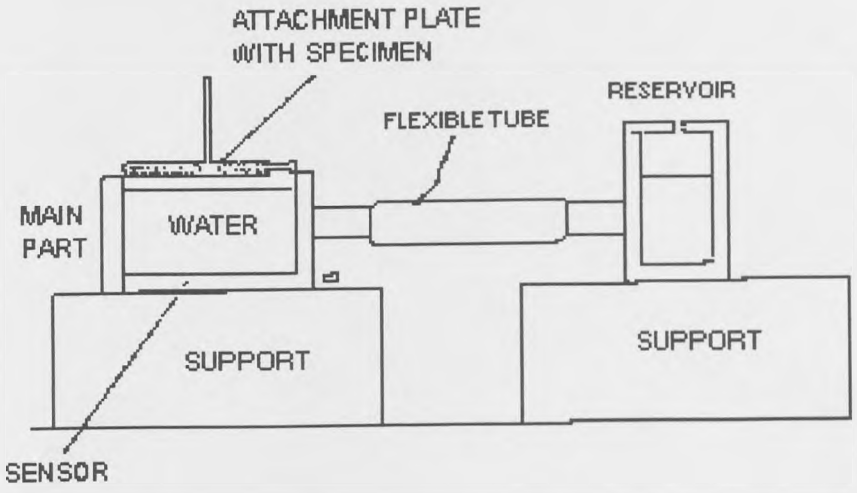


Fig. 28 Measurement System - by Yoneda et al. [32]

The technique more closely related to this investigation is the technique used by Miller and Tyomkin[16] based on the porous plate method, (see Fig. 14). This was used to determine the effect of negative pressure head height on the uptake rate in horizontal transplanar wicking. Based on Washburn's equation [equation 17], Miller and Tyomkin developed the following equation for their device :

$$\frac{dV}{dt} = \frac{\pi r^4}{8\eta x}\left[\frac{2\gamma\cos\theta a}{r} - hg\delta\right] \qquad \text{---------- [23]}$$

where V = Volume of water absorbed [m^3] h = height of elevation

δ = liquid density g = acceleration due to gravity

η = liquid viscosity x = distance within the pore

It was possible to replace $hg\delta$ by 'H' which equals the negative pressure head and therefore the following modified equation could be used by Miller and Tyomkin in their experiments :

$$\frac{dV}{dt} = \frac{\pi r^4}{8\eta x}\left\{\frac{2\gamma\cos\theta a}{r} - H\right\} \qquad \text{---------- [24]}$$

where H = negative pressure head (Kg/s^2m)

Another modified version of this apparatus was also utilised by Law[76] to study transplanar liquid transmission in knitted interlock fabric.

CHAPTER 3

3.0 INTRODUCTION

Chapter one has described the mechanism by which the human body regulates body temperature in relation to body activity and environmental conditions. The liberation of heat from the human body results in the loss of liquid from the body in the form of liquid or vapour. The formation of liquid within the clothing environment occurs only when the excess moisture released by the skin exceeds the vapour transmission rate of the clothing system. Liquid is then able to accumulate within the fabric layers.

It is the ability of a clothing system to transport liquid /moisture around the various layers that is of interest to this investigation. This ability is assisted by the various liquid/moisture transport mechanisms, which occur within a clothing system.

Figure 29 describes the main areas where sweating may occur on the human body, the extent of which is determined by the activity of the human body, the external environmental conditions, and to a smaller degree the internal environmental conditions (the microclimate) see section 1.7.1.2. Areas of more intense sweating, identified as the red areas on Fig. 29, are the palms of the hands , soles of the feet, and the forehead. Less intense sweating occurs over the rest of the body in the sedentary person, however in a more active person there will be increased sweating occurring all over the body[87,4,3]. This may be further increased by the type of activity being performed. In the case of the fire-fighter wearing heat and flame protective clothing and additional apparatus (i.e. Breathing apparatus [BA unit]), large amounts of sweat will be produced over larger areas of the body. This production is further increased by an additional rise in the environmental temperature produced by a fire.

The ability of the protective clothing system to remove heat and moisture from the body to the outside layers of the system may be compromised by the increased amount of sweat being produced, allowing more liquid to accumulate within the assembly layers impeding or halting the evaporative process.

Section 2.2 describes in general terms the many types of wicking process which occur in a clothing system in the form of **Vertical and Horizontal planar wicking** and **Vertical and Horizontal transplanar wicking**, see figure 15. In the past planar wicking, i.e. wicking along the plane of a fabric, has been investigated many times by many researchers[32,33,], and is explained in section 2 ; however it is transplanar wicking which is of interest in this experimental project and this is described in this section.

Figure 30 represents the various activities which may be occurring in the form of liquid/moisture transmission within a clothing system. Because different types of liquid/moisture transmission may occur within different areas of a clothing system, the various forms of liquid/moisture transmission may be considered in terms of the following :

- In a single or multi-layer assembly there may be continuous contact with the skin and/or within the clothing layers.
- There may be intermittent contact between layers (i.e. fabric with fabric or skin with fabric).
- There may be different pressures applied to the layers at different areas of the clothing system (in the shoulder area), i.e. fabric weight or equipment weight e.g. Breathing apparatus (BA) Fire-fighters.
- There may be movement within fabric layers, and between skin and fabric.
- Liquid transmission may occur in different states, horizontally or vertically and at varying angles in between, or a combination of all three.
- There may be different types of fabric movement i.e. backwards and forwards, circular, continuous or intermittent.
- The processes which occur at the folds of fabric, and layers of fabrics will be a combination of many of the above, plus the added dimension of a squeeze process occurring.
- Many of the above factors may occur in the clothing system of a sedentary subject, where very little bodily movement is occurring. This may influence the amount/duration of steady state or intermittent contact occurring within a system.

- In a more active subject the amount of steady state (continuous) contact and /or intermittent contact may be constantly changing as well as also increasing the amount of fabric to fabric, and fabric to skin movement.

All these factors contribute to the liquid/moisture transport system within any clothing assembly, whether it consists of one or more layer, see figure 30.

Fig. 29 A representation of the many areas where sweating may occur on the human body – at different levels.

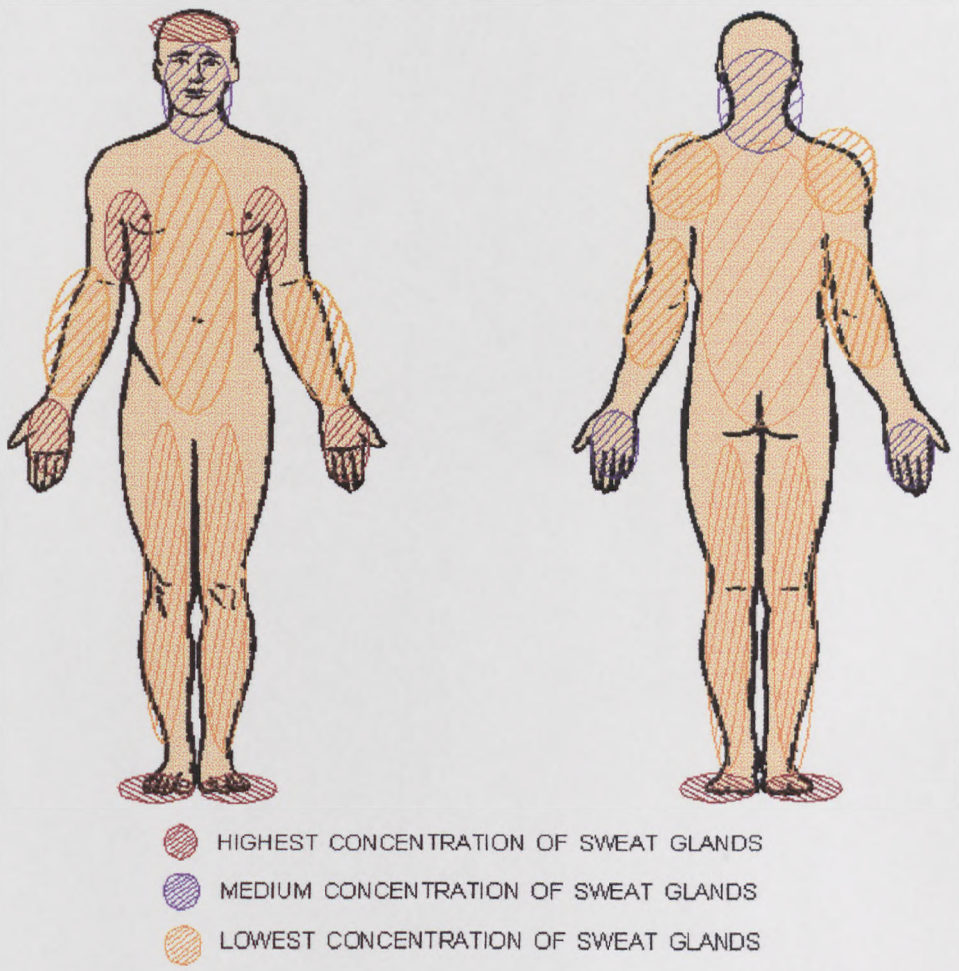


Fig. 30 A Representation of the many possible areas where wicking can take place – and the many variations and types of wicking processes that may take place within a clothing system.

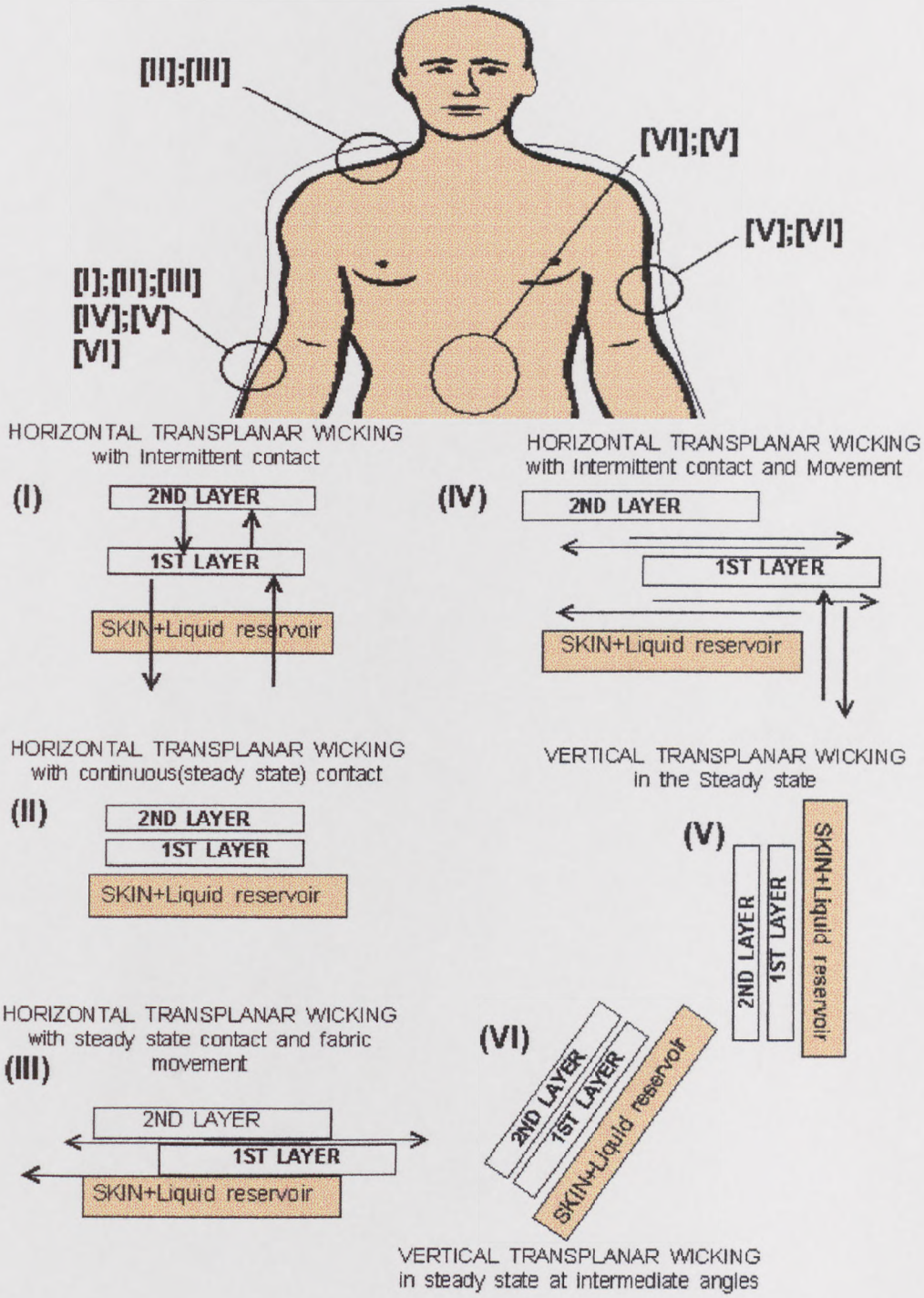


Fig. 31 A representation of the various wicking processes which may occur within a clothing system and the apparatus developed to simulate the processes - the Static Demand Wettability Apparatus and the Vertical Transplanar wicking Apparatus.

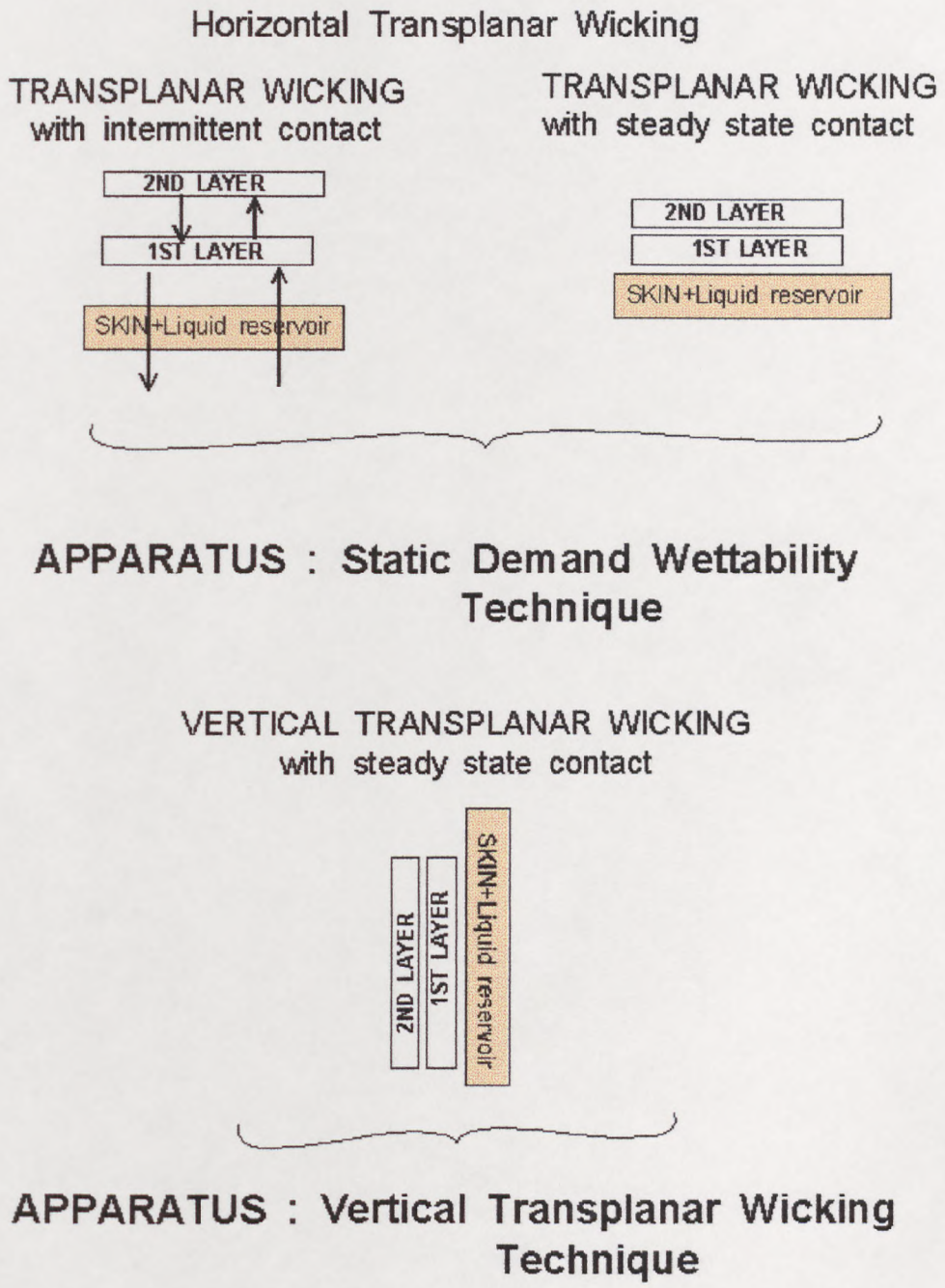
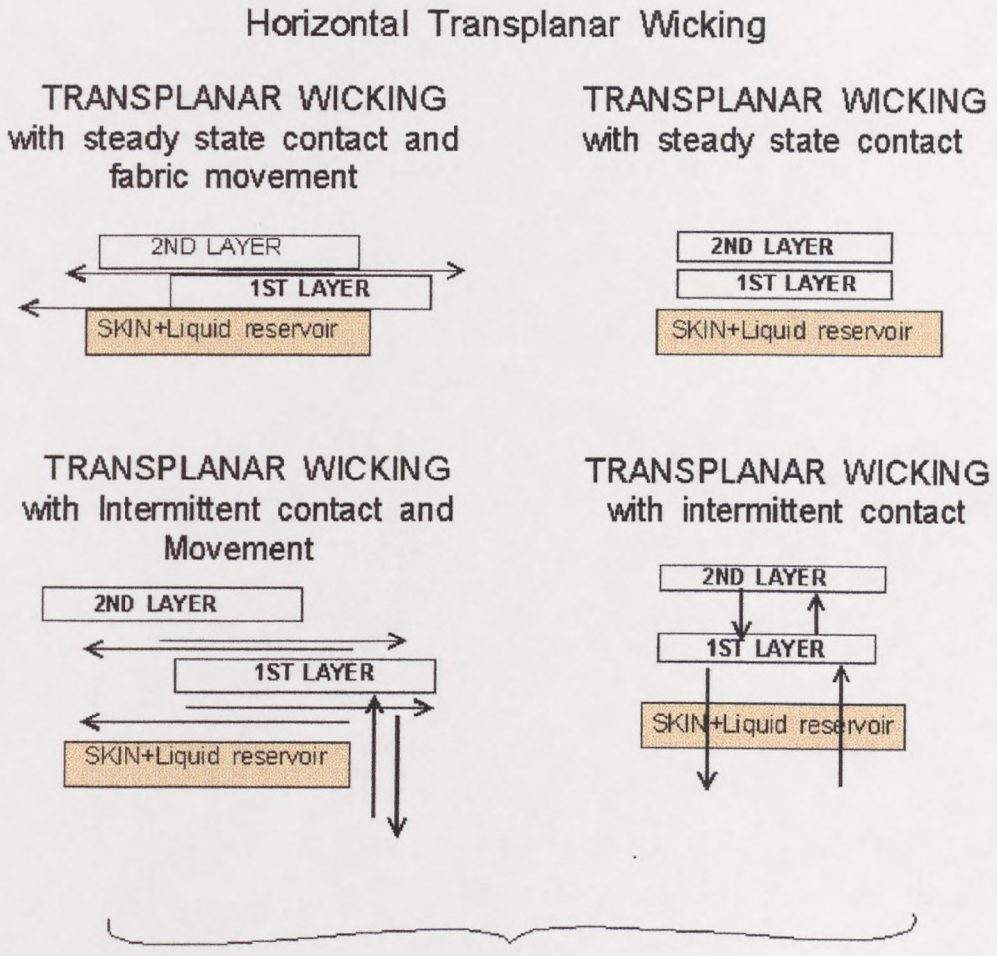


Fig. 32 A representation of the various wicking processes which may occur within a clothing system and the apparatus developed to simulate the processes – the Dynamic Demand Wettability Apparatus



In order to investigate the liquid transport system within clothing, all these factors had to be taken into consideration. With this in mind three pieces of equipment were developed with a view to simulating as many of these processes as possible in order to give an overall view of the liquid transport mechanism occurring within a clothing assembly, see Figures 31 and 32.

The first piece of equipment, the **Horizontal static demand wettability** apparatus (see Fig. 31 and Fig. 39) would incorporate and simulate as near as possible transplanar wicking in the horizontal static state as well as incorporating the various types of contact which may take place within the clothing environment. Using a variety of experimental time intervals the duration of multi-layer fabric contacts could be investigated. This technique could also combine the use of different pressures on the fabric layers during the wicking process, and its effects.

The second piece of equipment – the **Horizontal Dynamic demand wettability** apparatus (see Fig. 32 and 48) simulates the introduction of movement within fabric layers and with the skin. However this piece of apparatus could not incorporate all types of movement that may occur within a clothing system. Both these types of apparatus were developed with different forms of liquid reservoir; therefore the liquid introduction may be slightly different to that occurring under static conditions. This would also mimic the different areas around the human body where different amounts of sweat may be released.

The final piece of equipment incorporates the vertical state – **the Vertical transplanar wicking** apparatus (see Fig. 31 and Fig. 53), this state is expected to occur over most of a clothing system. This state was the most difficult to simulate, and meant that other aspects investigated in the other pieces of apparatus could not be duplicated on this piece of apparatus. However this vertical transplanar wicking apparatus also required another type of liquid reservoir and another type of liquid introduction into the system.

With the combination of these three pieces of apparatus it is hoped that a clearer overall understanding of the liquid transport system within a clothing assembly may be achieved.

3.1 EQUIPMENT DEVELOPMENT

3.1.1 BACKGROUND

A sensitive gravimetric technique was devised by Miller and Tyomkin[16] in 1984, which was capable of measuring the rate and total uptake of liquid in the fabric transplanar direction (perpendicular to the fabric plane) under known negative pressure gradients (see Fig. 33). Their technique was based on the "Porous plate method" [35], and, in turn, the technique used in this experimental work is loosely based on both these methods with adaptations.

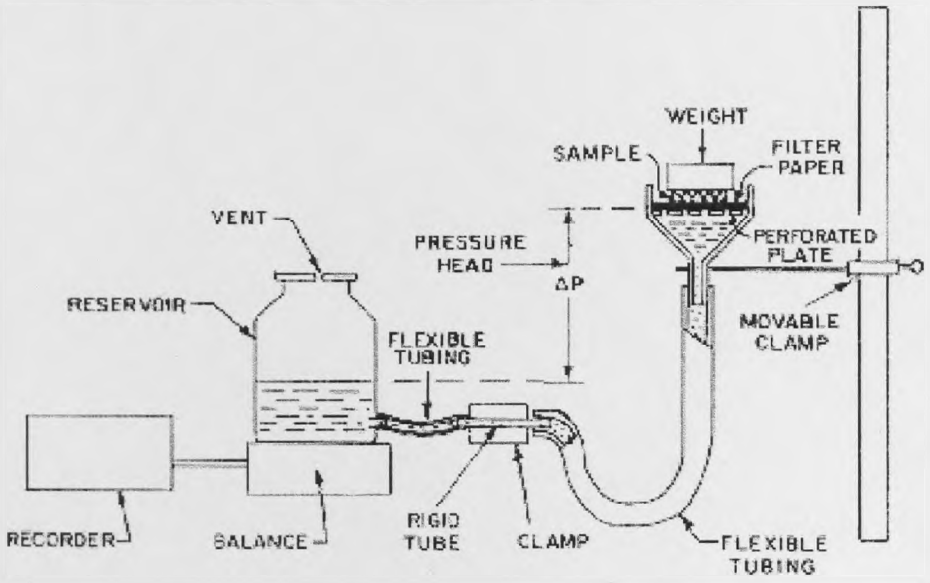


Fig. 33 Instrumentation for studying demand wettability under negative pressure gradients.[16]

3.2 HORIZONTAL STATIC DEMAND WETTABILITY TECHNIQUE

The Static Demand wettability equipment developed consists of a Buchner funnel, which acts as a wetting chamber attached to a water reservoir via two flexible tubes separated by a rigid glass tube. The wetting chamber and the water reservoir are suspended between two stands, and initially raised to identical heights. The water reservoir is then set to a permanent height for the whole of the test period.

Placed in the funnel is a layer of Whatman ® filter paper No.90, then a skin simulant (a white woven cotton fabric ; ref.: Cotton.L) , and the test sample or sample assemblies are placed on top. The specification for the white woven cotton.L fabric is described in Table 22.

A compression disc and a series of weights were devised to enable testing to be conducted under different compression states (see Fig. 42).

- The water reservoir is filled with distilled water to about half its capacity, filling the various tubes and partially filling the wetting chamber.
- One of the main features of this piece of equipment is its ability to establish a known negative pressure gradient, which ensures that the skin simulant is wet, yet not flooded.
- The water level is held just below the filter paper and this ensures the test area is not flooded.
- The negative pressure gradient is established before testing takes place.

Originally the piece of equipment used by Miller and Tyomkin [16] was designed to take continuous liquid uptake measurements during testing via weight loss from the reservoir indicated by a top-loading recording balance (see Fig.33). However this method could not be used to measure liquid uptake from individual layers within an assembly.

To overcome this problem the test sample layers had to be measured individually, and at set time periods. Various time periods, and measuring methods, were explored.

3.2.1 COMPONENT DEVELOPMENT

This technique consisted of various components, these can be seen in Fig.39;

- ◊ Wetting chamber - Buchner funnel
- ◊ Liquid reservoir - Inverted bottle
- ◊ Filter paper - Filter paper 'Whatman' No. 90
- ◊ Skin simulant - Woven cotton fabric (ref. no: cotton.L) (washed)
- ◊ Compression system - Perspex disc and weighted bags
- ◊ Sample removal system - Tweezers (no human contact)
- ◊ Weighing system - Dedicated Top-loading balance (to ± 0.000g)
- ◊ Timing System - Digital Timer
- ◊ Liquid Indicator - Food Dye

Initial static demand wettability tests were carried out on the woven cotton.L chosen to be the skin simulant. It was during this initial testing that various components of the equipment, such as the weight/compression system and the sample weighing methodology were devised and developed.

Several samples of 'cotton L' were tested on the demand wettability tester, with both the filter paper and skin simulant in place, and with only filter paper beneath the test sample . Less variable results were obtained when the cotton was present as the skin simulant, see Table 3 and Figures 34 and 35.

This experiment was also performed over various time intervals, and gave a good indication of liquid uptake per min. and per 30 sec. of the woven 'Cotton.L' fabric. Results from these short experiments can be seen in Tables 4 and 5, and Figures 36-38. From the results it was determined that with the skin simulant in place experimental variability was greatly reduced, giving more reproducible results.

Table 3

HORIZONTAL DEMAND WETTABILITY TESTS
COMPARISON EXPERIMENTS

ASSEMBLY ORDER = SAMPLE - COTTON.L = TOP
SKIN SIMULANT = MIDDLE
FILTER PAPER = BOTTOM

A

COTTON

REF.No.	-V P/H	WT. g/cm^2	ABSORPTION RATE/MIN									
			1	2	3	4	5	6	7	8	9	10
1	1cm	0.0g/cm^2	1.9	1.9	1.8	1.8	1.9	1.8	1.8	1.8	1.8	1.9
1	1cm	0.66g/cm^2	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.7	1.8
4	2cm	0.0g/cm^2	1.5	1.6	1.6	1.7	1.7	1.7	1.6	1.7	1.6	1.7
4	2cm	0.66g/cm^2	1.6	1.6	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
6	3cm	0.0g/cm^2	0.3	0.9	1.2	1.3	1.3	1.3	1.3	1.4	1.4	1.4
7	3cm	0.66g/cm^2	1.3	1.4	1.4	1.5	1.5	1.5	1.5	1.6	1.5	1.5

ASSEMBLY ORDER = SAMPLE - COTTON.L = TOP
FILTER PAPER = BOTTOM

B

COTTON

REF.No.	-V P/H	WT. g/cm^2	ABSORPTION RATE/MIN									
			1	2	3	4	5	6	7	8	9	10
3	1cm	0.0g/cm^2	1.9	1.9	1.8	1.8	1.9	1.8	1.8	1.8	1.8	1.9
3	1cm	0.66g/cm^2	1.9	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.9	1.9
5	2cm	0.0g/cm^2	1.6	1.7	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
5	2cm	0.66g/cm^2	1.6	1.6	1.6	1.6	1.7	1.7	1.7	1.7	1.7	1.7
6	3cm	0.0g/cm^2	1.3	1.5	1.5	1.6	1.6	1.6	1.6	1.6	1.6	1.6
7	3cm	0.66g/cm^2	1.6	1.6	1.7	1.6	1.7	1.6	1.6	1.6	1.6	1.6

Fig. 34. **COMPARISON OF WICKING AT 2 DIFFERENT COMPRESSION WEIGHTS AND 3 DIFFERENT NEGATIVE HEADS**

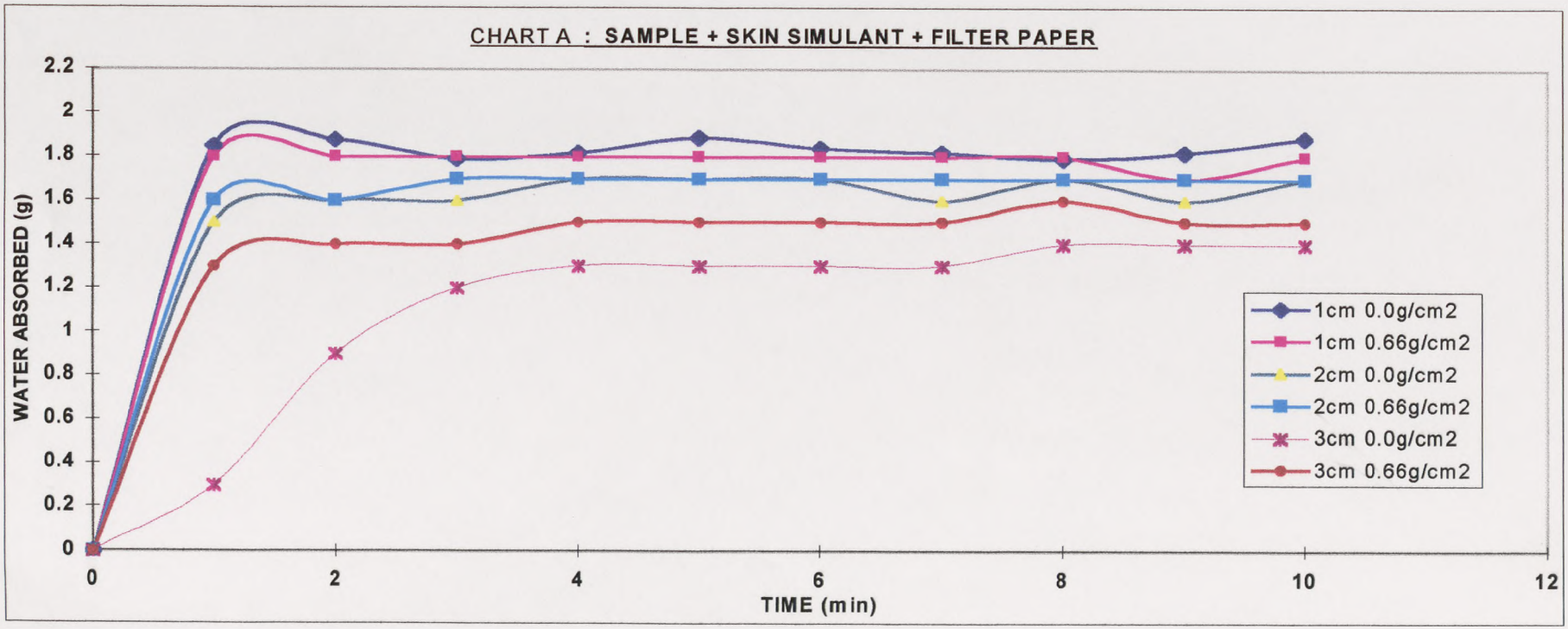


Fig. 35

COMPARISON OF WICKING AT 2 DIFFERENT COMPRESSION WEIGHTS AND 3 DIFFERENT NEGATIVE HEADS

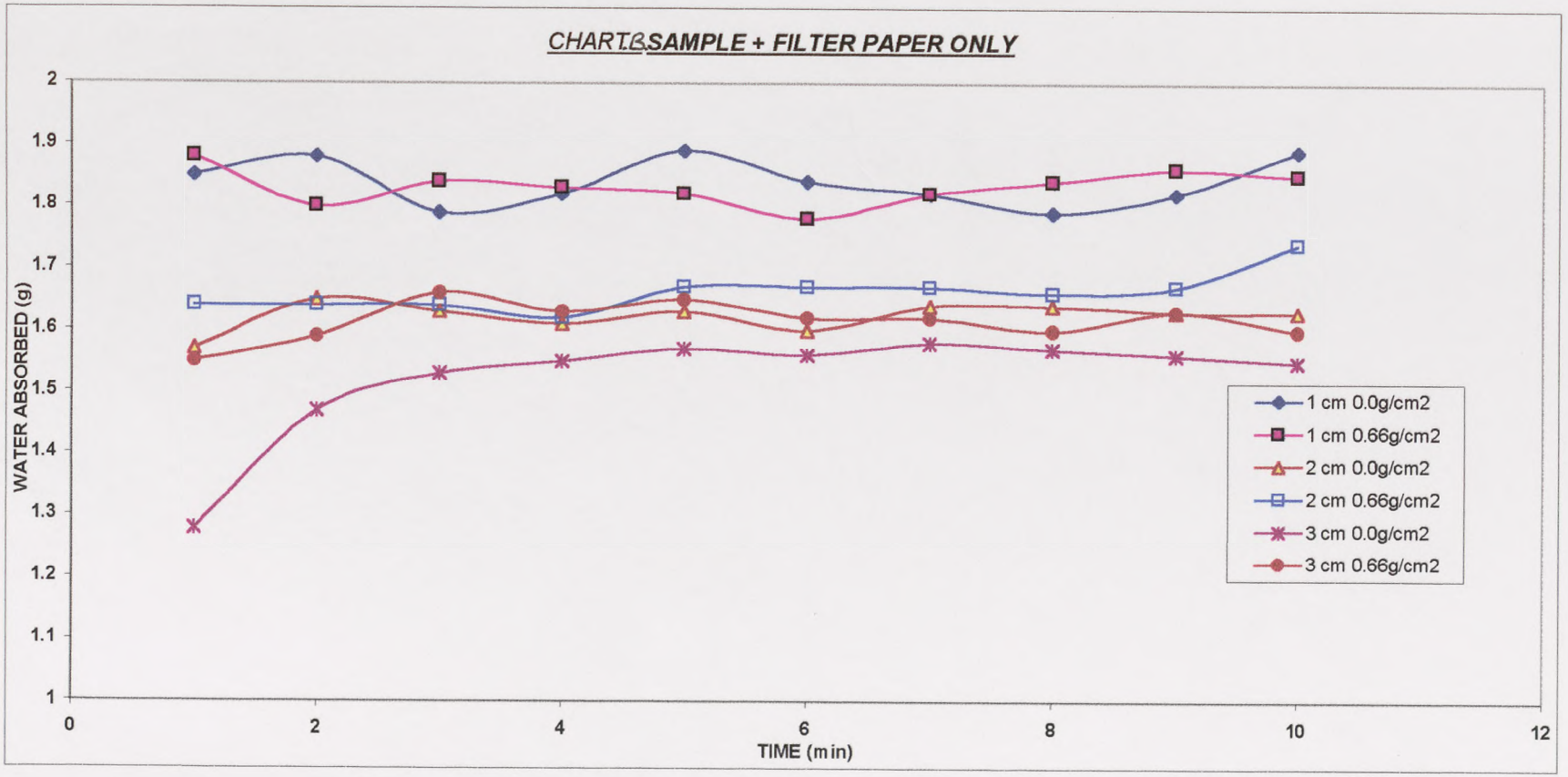


Table 4.

HORIZONTAL DEMAND WETTABILITY TEST
Multi-Layer Tests

-VE PRESSURE HEAD = 2.0cm
COMPRESSION WEIGHT = 1.30g/cm^2

(Top)	MEAN WATER CONTENT (%)										
TIME (min)	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
COTTON.L	0	1.0	1.4	1.7	2.0	2.1	2.2	2.2	2.4	2.4	2.5
ACRYLIC	0	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3
POLYPROP	0	0.6	1.6	2.7	4.6	6.1	8.2	11.6	14.7	17.7	21.3
(Bottom)											

	MEAN WATER CONTENT (%)										
TIME (min)	0	1	2	3	4	5	6	7	8	9	10
COTTON.L	0	2.0	4.1	4.7	6.0	6.1	7.8	18.9	22.7	29.2	46.2
ACRYLIC	0	0.8	7.0	8.4	14.2	18.1	24.9	35.5	42.9	52.8	70.7
POLYPROP	0	5.0	13.5	24.5	36.7	52.2	69.2	84.9	102.0	117.5	131.0

Table 5.

DEMAND WETTABILITY TESTS
MULTI-LAYER TESTS

..-VE PRESSURE HEAD = 2 cm
COMPRESSION WEIGHT = 1.30 g/cm^2

	MEAN (%) WATER CONTENT										
(Top)	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
COTTON.L.(0.5)	0	1.00	1.41	1.74	1.98	2.06	2.17	2.20	2.39	2.40	2.46
COTTON.L.(1.0)	0		2.0		4.1		4.7		6.0		6.1
ACRYLIC-(0.5)	0	0.07	0.15	0.16	0.21	0.22	0.22	0.21	0.21	0.23	0.26
ACRYLIC -(1.0)	0		0.8		7.0		8.4		14.2		18.1
POLYPROP- (0.5)	0	0.55	1.57	2.74	4.60	6.13	8.18	11.60	14.73	17.66	21.30
POLYPROP- (1.0)	0		5.0		13.5		24.5		36.7		52.2
(Bottom)											

Fig. 36

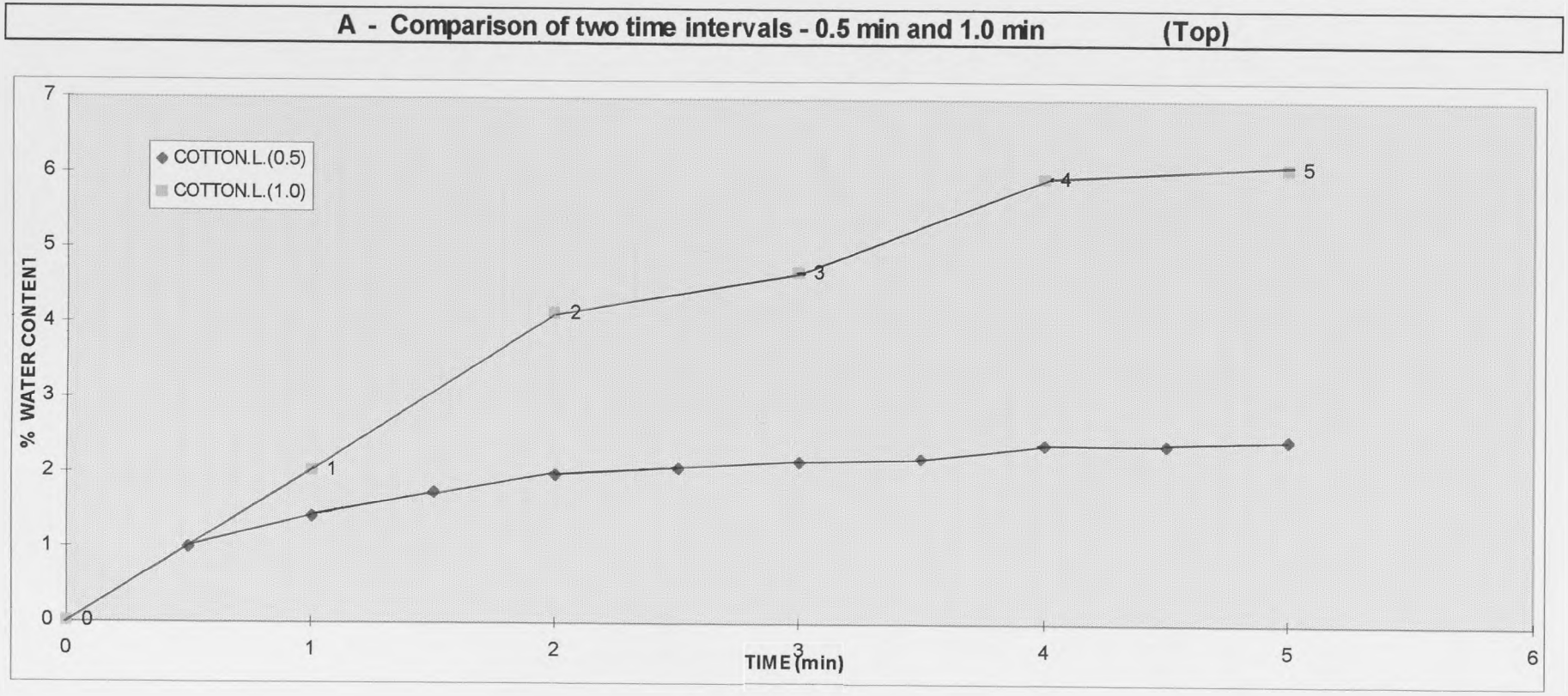

A - Comparison of two time intervals - 0.5 min and 1.0 min (Top)
COTTON.L.(0.5)
COTTON.L.(1.0)
% WATER CONTENT
TIME (min)
0
1
2
3
4
5
6
7
0
1
2
3
4
5

Fig. 37

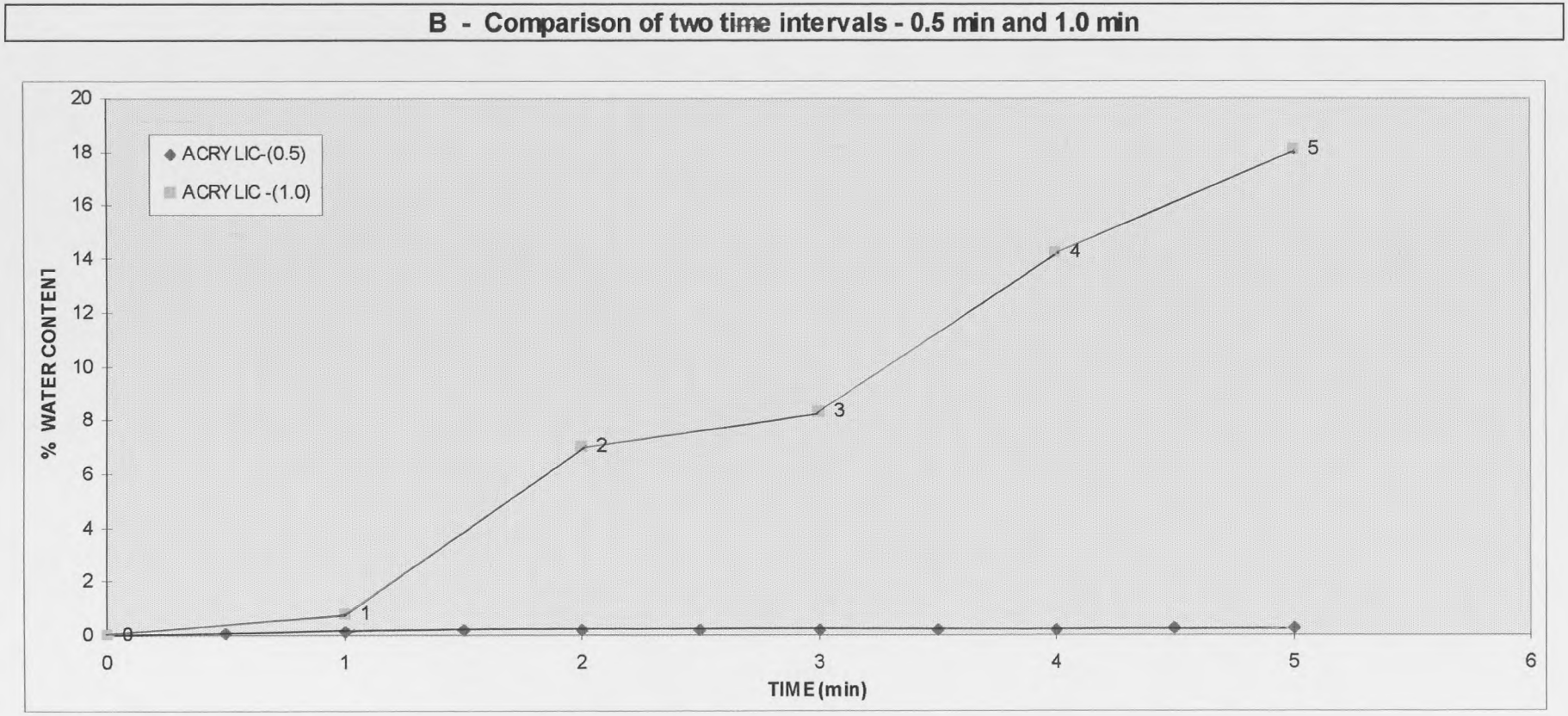
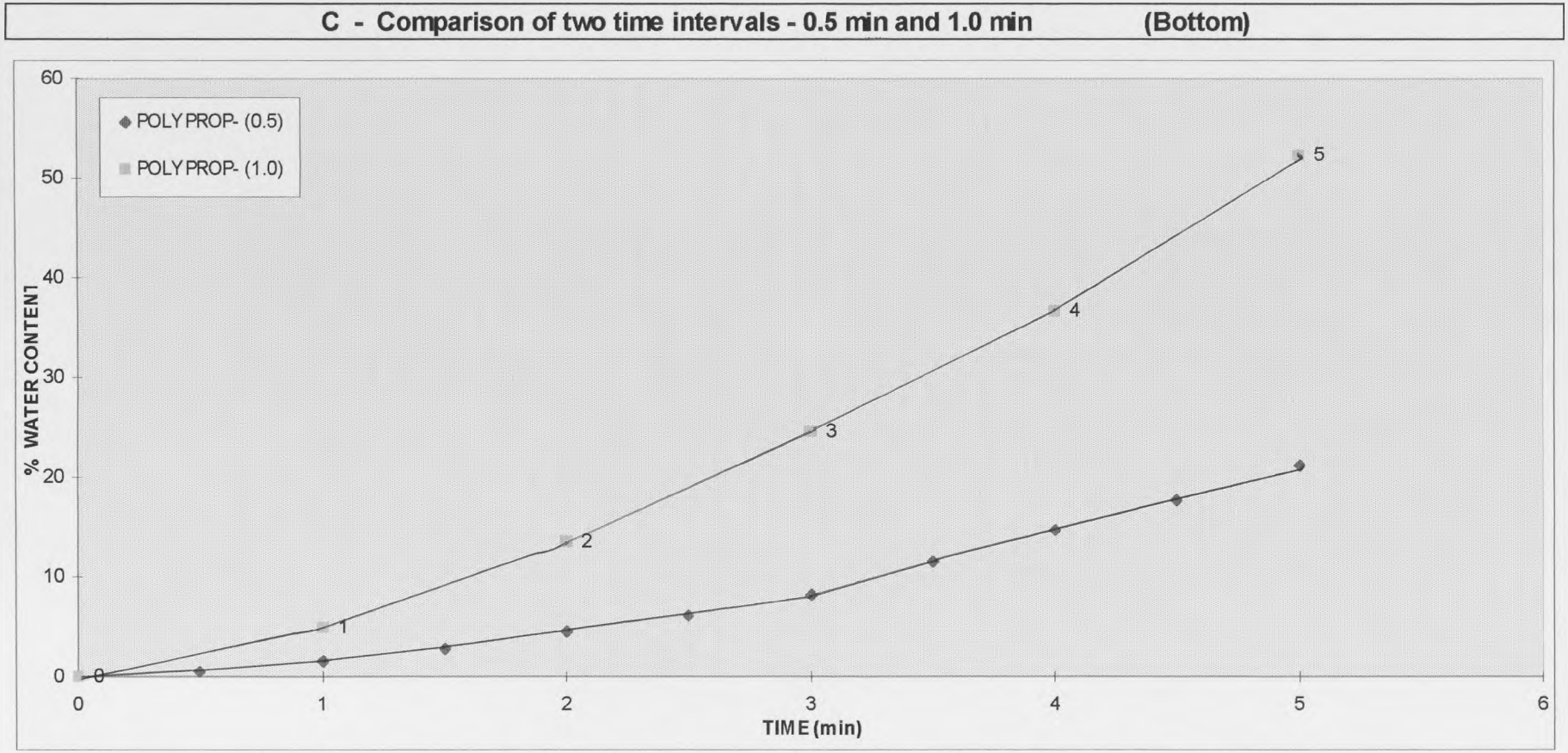

B - Comparison of two time intervals - 0.5 min and 1.0 min
ACRYLIC-(0.5)
ACRYLIC -(1.0)
% WATER CONTENT
TIME (min)
0
1
2
3
4
5
6
0
2
4
6
8
10
12
14
16
18
20

Fig. 38


C - Comparison of two time intervals - 0.5 min and 1.0 min (Bottom)
POLY PROP- (0.5)
POLY PROP- (1.0)
% WATER CONTENT
TIME (min)
0
10
20
30
40
50
60
0
1
2
3
4
5
6
0
1
2
3
4
5

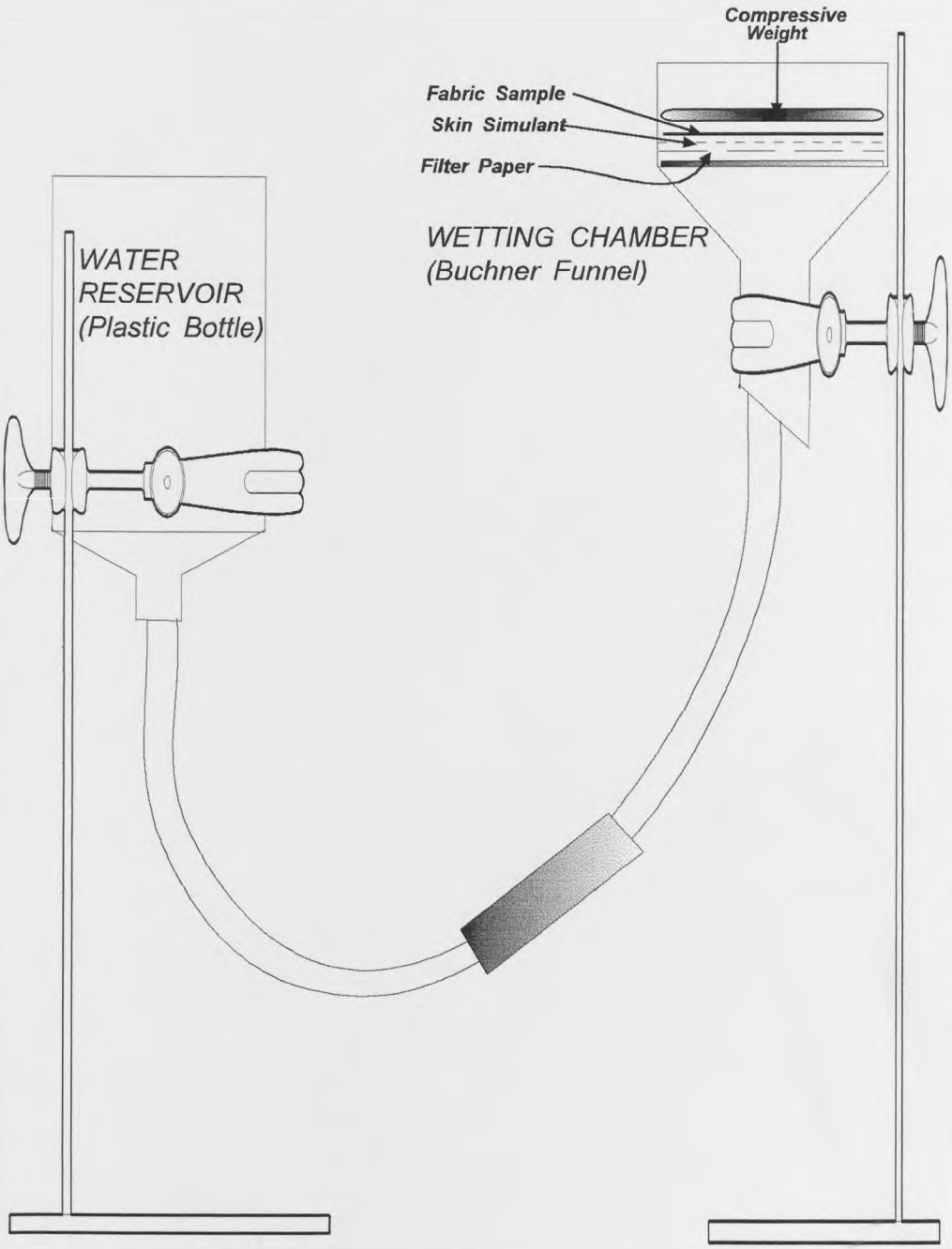


Fig. 39 Diagrammatic representation of Static Demand Wettability Test Equipment.

3.2.1.1 Compression Weight Development

Although these tests bear no real resemblance to the real life situation, there was a need to make these tests follow parameters as close to life as practically possible. Therefore with this in mind, compression of the test fabrics both singly and in assembly were taken into account. The fact that clothing assemblies are rarely in practice in the horizontal state could not be taken into account at this stage, as wicking in the transplanar direction could not be tested in a vertical state on this piece of apparatus.

The compression load was constructed in the form of a disc with interchangeable weights being added on top of the disc. The flat circular disc was constructed of a Perspex transparent disc of 5.5mm thick, 92mm in diameter and a mass of 43.8g to fit the Buchner funnel, and to completely cover the test samples. Perspex was chosen for its lightness, transparency, flatness, and ease of removal during tests.

The development of the additional weights took the form initially of a soft plastic dish-shaped structure with high sides which was thought to aid the ease of removal. Standard weights were ruled out as the required compression weights could not be established to the exact g/cm^2. It was therefore decided to use a dish structure and add the desired weight in the form of lead pellets or glass beads, (and in some cases sand). This enabled the weight of the perspex disc to be accounted for in the calculations of the compression weight required. This proved satisfactory initially, but due to the speed and lack of ease of removal, it was not thought to be a permanent solution.

A second idea was tried, roughly at first to determine whether the general principle would work. This was based on an idea used for the dynamic demand wettability equipment, in which small weighted bags were filled with either lead pellets, glass beads or sand to the required weight. This idea was transferred to the static demand wettability tester, in which small rounded plastic bags were manufactured and filled with the required weight in either lead pellets, glass beads or sand.

The initial results were quite good as it gave a good rounded weighted bag which would lie flat on top of the perspex disc covering the entire surface area of the disc. Once the initial prototype bag was satisfactory, various weighted bags were constructed of the required weights calculated as follows:-

COMPRESSION DEVICE = Perspex Disc (i) + Extra weight (Weighted Bag) (ii)

(i) **PERSPEX DISC ① Wt.** = 43.8 g

DIAMETER = 9.2 cm

THICKNESS = 0.55cm

AREA (πr^2) = 66.48cm^2

$\therefore$ COMPRESSION Wt (g/cm^2) = $\frac{43.8}{66.48}$ = **0.66 g/cm^2**

(ii) **WEIGHTED BAG**

(Sealed plastic bag wt.) = 0.85 g

CHOSEN WEIGHTS -

Table 6 **CALCULATION TABLE**

REQ'D WT (g/cm^2)	TOTAL WT(g) (Disc + Bag)	BAG WT.(g) (Bag + Pellets)	PELLET/BEAD WT.(g)
1.0	66.48	22.68	21.83
2.0	132.96	89.16	88.31
3.0	199.44	155.64	154.79
4.0	265.92	222.12	221.27

3.2.1.2 Liquid/Water Type

Small experiments were also carried out to determine whether the effect of different types of water, had any effect on the results. This was needed to determine whether water could be used , as in effect, the transmission of sweat was being tested. Earlier the constituents of sweat were listed, in section 1.2.3.3, however the very nature of liquid sweat makes it a difficult commodity to collect and test in this way, and due to its many components it tends to go stale after a few hours. A few of the chemical composites have been used to reproduce an 'artificial liquid perspiration' (see BS.1006:1989, E04) the standard for Colourfastness to Perspiration. However this also had a very short shelf-life, and with this in mind the following experiments were carried out ;

(i) due to the fact that artificial perspiration and water appeared to be of similar consistency , tests were carried out to determine the surface tension of human sweat,

(ii) the surface tension of water and artificial perspiration were also examined and compared.

Tests carried out at B.T.T.G [86] concluded that as the nearest substance to human perspiration, artificial perspiration had a surface tension closer to water than human perspiration and differed only in chemical content, water could be used in the tests. Next further tests were carried out to determine if the type of water used had a significant effect. The water types tested were Distilled water ; Carbonated water ; Deaerated water [24].

3.2.1.3 Vertical Planar Wicking Tests using Different Water Types.

Small experiments were carried out on two fabrics, woven cotton (cotton.L.) and knitted cotton using three different types of water. This determined whether the use of distilled water, as opposed to another type, would greatly influence the results of wicking. Three types of water were chosen to test, distilled, carbonated (spring water), and deaerated water. The latter was prepared as described by Denton [24]. Each water type was tested using a vertical planar wicking test.

Samples were cut into strips of 3 x 8cm. These were attached to a glass plate with a series of 'teeth' running down each side of the plate. The fabrics were laid on top of the plate , and the edges of the fabric pressed on to the teeth. The underside of the plate was marked out in graduations of millimetres, with a starting point of zero. Once attached the sample and plate were lowered into a receptacle of the test liquid, which was filled to the correct height. The plate was held upright in the middle with the water level touching the zero mark on the plate. Once the sample was lowered into the water a timer was set in motion, and recordings of the time taken for the water to reach a series of heights in steps of 10mm were registered. The experiment was repeated for all three types of water. The results can be seen in Tables 7 and 8, and Figures 40 and 41.

Table 7. Test sample woven Cotton.L (Skin simulant)

WATER TYPE	WICKING RATE (mm/sec)					
	10	**20**	**30**	**40**	**50**	**60**
CARBONATED	2.92	1.33	0.69	0.47	0.32	0.30
DEAERATED	4.17	2.67	0.85	0.65	0.55	0.29
DISTILLED	1.00	0.83	0.68	0.43	0.29	0.22

Table 8. Test sample Cotton.L (knitted Blue)

WATER TYPE	WICKING RATE (mm/sec)					
	10	**20**	**30**	**40**	**50**	**60**
CARBONATED	4.17	4.17	3.30	2.10	1.35	0.99
DEAERATED	5.00	5.00	3.17	2.11	1.56	1.09
DISTILLED	4.17	4.00	3.00	2.02	1.45	1.10

Fig. 40 **Vertical Planar Wicking Test - Water Comparison (Test sample woven Cotton.L Skin simulant)**

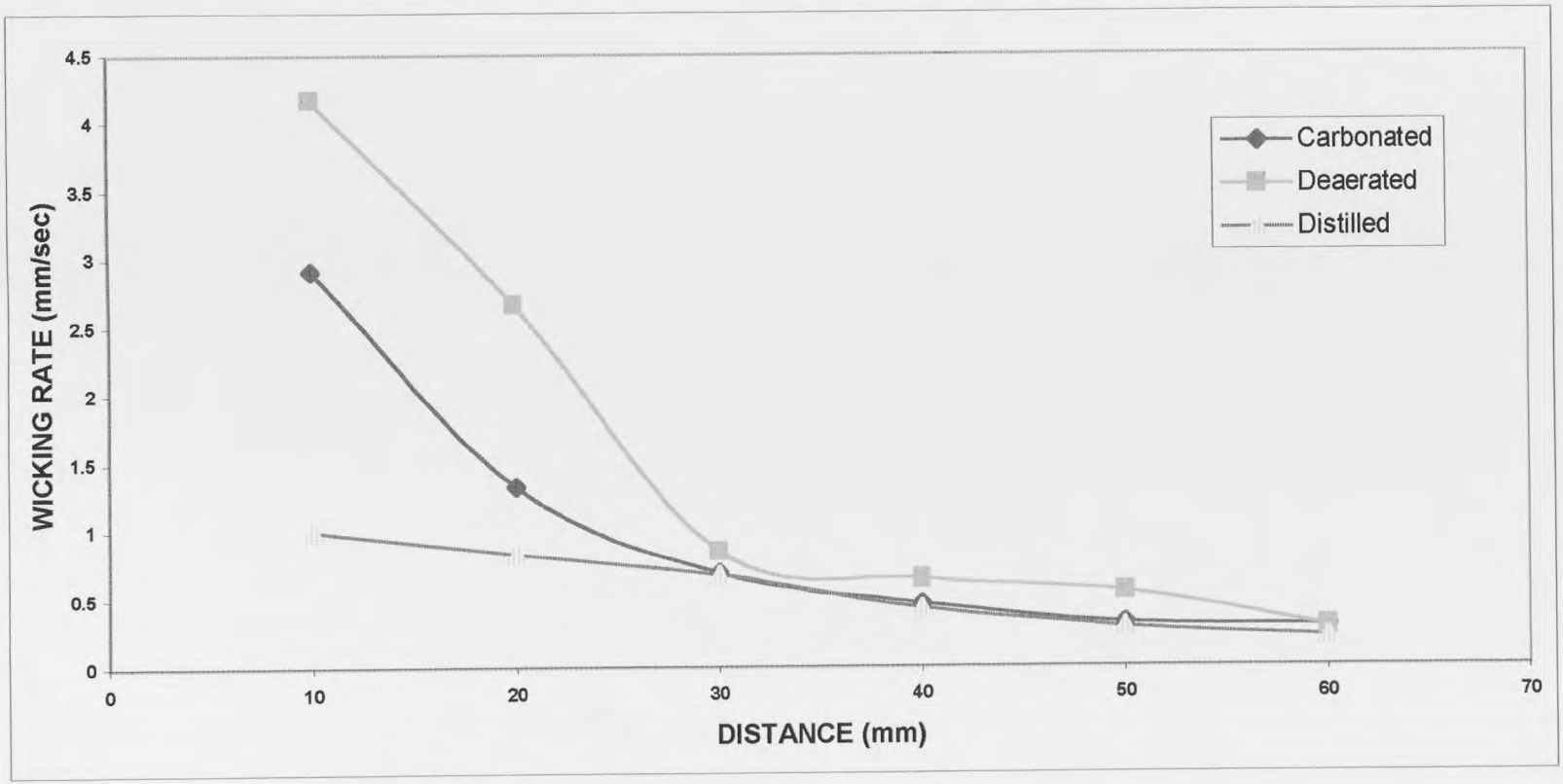
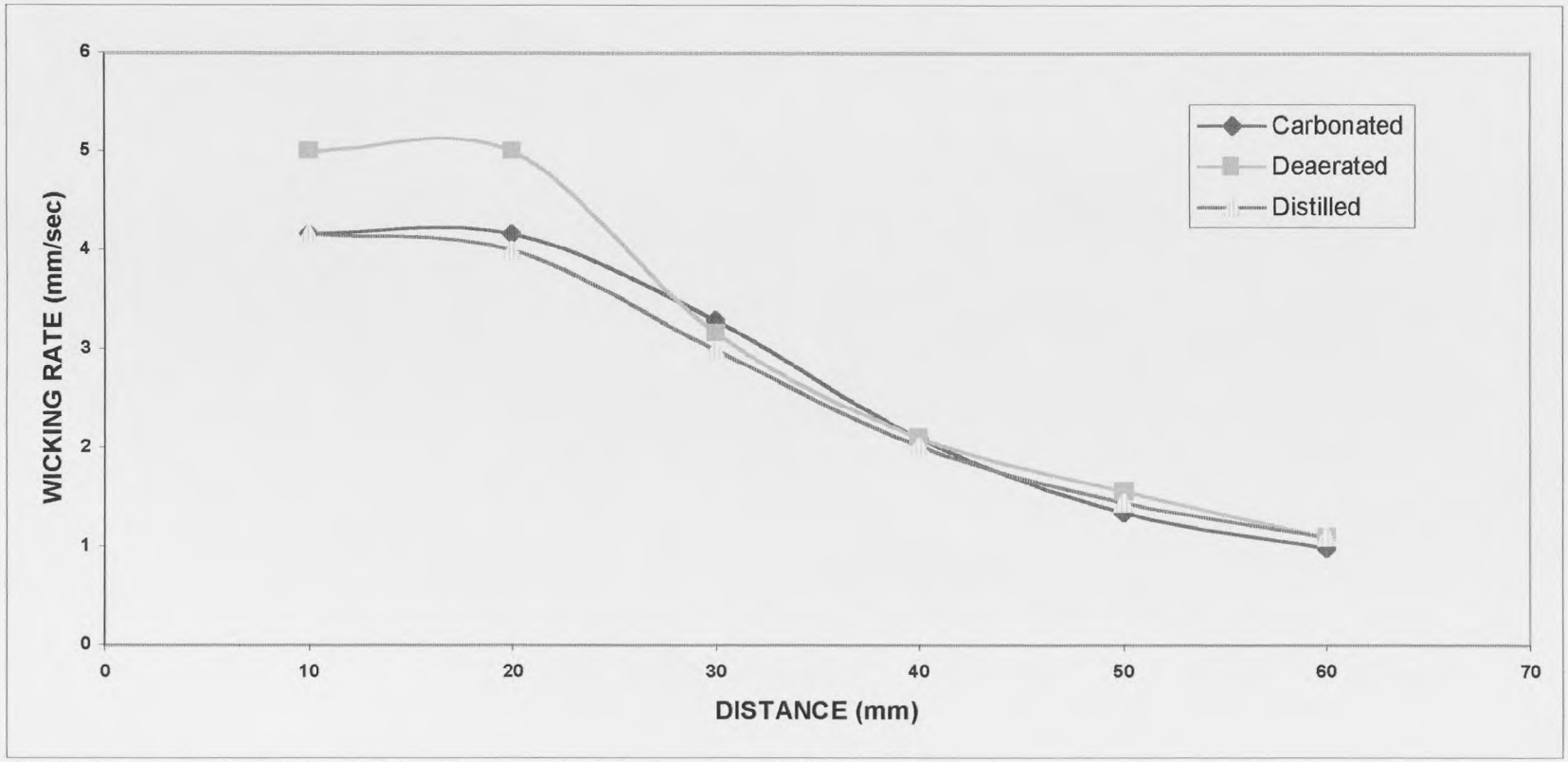


Fig. 41 **Vertical Planar Wicking Test - Water Comparison (Test sample knitted blue Cotton.L.)**



3.2.1.3.1 Results and Discussion

Experiments carried out by Denton [24] on the wetting out of yarn packages in preparation for package-dyeing discovered that air could be trapped within the inter-fibre spaces when large inter-yarn spaces were rapidly filled with water. Continued penetration within the packages was then opposed by the pressure of the entrapped air.

Further experimentation using 'dissolved air water'[24] revealed that an unusually rapid wetting time could be achieved. This was due to the entrapped air in the yarn being dissolved by the relatively airless recently boiled water (dissolved air water), creates a partial vacuum in the yarn, which in turn assisted with penetration. Denton states that some tests are more affected by dissolved air than others , mainly those involving the test samples being totally immersed in water.[24]

The experiments carried out in this investigation also determined that in both fabric samples (Cotton.– blue weft knitted fabric sample, and Cotton.L – white woven skin simulant) dissolved air water (deaerated water) produced a higher wicking rate initially than the other water types. However beyond the 30mm range the deaerated water appears to perform similarly to that of the other water types.

It would seem that once the partial vacuum created by the deaerated water has achieved penetration within these inter-fibre spaces the deaerated water begins to act approximately at the same rate as the other water types such as distilled water, or carbonated water. This can be seen in tables 7 and 8, and Figures 40 and 41, during the second half of the experiments all three water types performed at similar rates.

Although deaerated water produces an initial rapid water uptake, this would be unrepresentative of the normal conditions found in perspiration on the skin surface, or within fabric layers within a clothing system.

With this in mind it was decided to continue to use distilled water as the experimental liquid for this investigation.

3.2.1.4 Liquid Indicator

Once the type of water to be used i.e. distilled water was established, a colour indicator was necessary. Tests carried out on dyed fabric samples gave a good indication when a test sample was wet or when initial wicking had begun. However in the case of the undyed test samples initial wetting could not be observed easily. So some sort of colour indicator or tracer was necessary.

The use of a food dye in the distilled water was thought appropriate as it was easily rinsed out of the test samples and was easily dissolved in water. This subsequently proved satisfactory for all tests where observation of the end-point was necessary.

The dye ingredients were as follows:

Concentrated Gel food colouring -

Glucose syrup

Sugar

Water

Edible Starch

Citric Acid

Stabiliser : Sodium Benzoate

Colour : (Red) E110; E123

Liquid Food Colouring -

Water

Glycerol

Citric Acid

Preservative : Sodium Benzoate

Colour : Carmoisine (E122) – [C.I. Food Red 3]

3.2.2 WEIGHING TECHNIQUE

As described earlier the individual fabric layers need to be measured separately. Using tweezers each test sample was removed after the required wicking period, separated and placed on the weigh pan. However another problem was discovered during initial testing. Once the samples had started to take up water, water would be left on the weighing pan during the weighing process. So in order to avoid this a small wire frame was manufactured and placed on the weigh pan. The sample was weighed on the frame which meant there was minimum contact with the sample and no water was lost during each weighing period. Several methods of weighing the samples were evaluated ;

I. WEIGHING BOTTLES

Originally each sample was transferred (after the required period of wicking) to a top-loading balance for weighing via a small weighing bottle. However during initial wettability tests on the assemblies, it was observed that although some fabrics picked up water/moisture on one side, it may not soak through to the other side of the fabric immediately due to the nature of the fabric. However on removal for weighing and being placed in weighing bottles, the samples had to be squeezed and folded. This caused agitation to the fabric surface, aiding moisture/water transport, and increasing the speed and distribution of liquid uptake rate through the fabric samples, thus adding another variable to the test. It was decided that samples should be weighed flat to eliminate as much agitation as possible, so sealable plastic bags were tried.

II. PLASTIC BAGS

Drying rate tests were carried out on fabric samples using sealable numbered plastic bags. This enabled the samples to be removed and placed in a fairly flat state in these bags for weighing. However, this slowed down testing considerably, and involved the use of a considerable number of bags, depending on the time interval between each weighing, and the number of fabric layers in a test assembly.

III. DEDICATED BALANCE

This final method of measuring the liquid uptake of each fabric layer proved to be the most satisfactory. This involved measuring the samples immediately, by removing the samples from the wetting chamber and weighing them on a balance within a chamber, within a few seconds, and replacing the sample in the wicking chamber for the next time period of wicking.

Tests were carried out to determine the drying time of the samples in the atmosphere, and in the weighing chamber, and the time taken to measure the samples, from removal from the wetting chamber to measuring on the balance, to replacing in the chamber. The loss of water by evaporation during the few seconds required for the weighing proved satisfactorily low, and in general negligible.

3.2.3 METHODOLOGY DEVELOPMENT

It was deemed easier to have the reservoir set to a permanent height for all the tests, and use the wetting chamber to adjust the negative pressure head height. This was carried out at the beginning of all tests.

Initially small experiments were carried out on different negative pressure heights to determine the appropriate starting point, using the woven cotton as the test sample as this was a high wicking fabric.

- Firstly the reservoir is set to a permanent height for all the tests.
- The Buchner funnel or wetting chamber is lowered below the water level in the reservoir until the level in the chamber is raised well above the filter paper , saturating it completely.
- Once the filter paper is completely wet, the wetting chamber is raised above the water level in the reservoir ; at this stage the water level in the chamber will recede, however when the chamber is raised further the water level in the chamber will remain at a level just below the filter paper.
- This will give a negative hydrostatic head to the required pressure gradient height. When the water levels are equal there is zero pressure gradient.

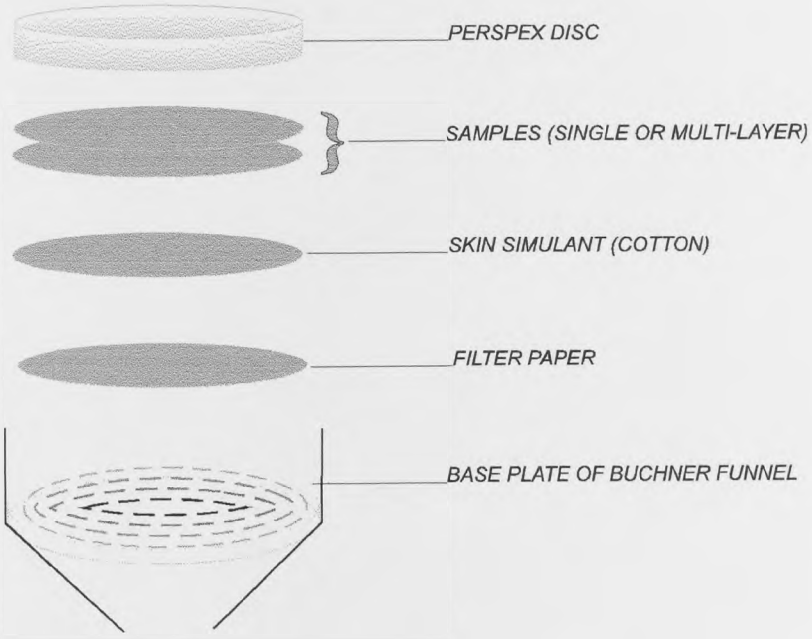


Fig. 42 Component sequence for Static demand wettability test.

3.2.4 REPRODUCIBILITY

Due to the nature of the investigation and the new technique being developed, the reproducibility had to be taken into consideration.

Experimentation was carried out to determine if the experimental reproducibility was achievable after a series of tests carried out to test the methodology produced large coefficient of variation percentages (CV%) using 1 minute intervals.

Initially fabric samples chosen for these experiments were associated with heat and flame protective clothing. A number of tests were carried out and the CV% was calculated for these fabrics as part of the methodology. The following results were obtained from these fabrics see Table 9 and 10 ; Figures 43 and 44.

Table 9.

DEMAND WETTABILITY TEST
Static test Comparison

TEST SAMPLE - PVC
Knitted PVC - typical underwear fabric
-VE P/H = 2.0 cm
WEIGHT = 0.66/cm

						PERCENTAGE WATER ABSORBED %										
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
PVC - 1	0	10.36	30.35	50.17	69.82	85.82	100.25	111.69	121.31	128.36	135.49	141.79	148.92	153.90	159.70	164.59
PVC - 2	0	15.22	34.66	55.75	77.92	96.94	111.41	122.83	133.42	140.86	148.72	155.33	162.03	168.32	177.25	184.95
PVC - 3	0	45.09	94.82	144.48	194.05	241.86	288.91	334.52	379.25	422.73	466.26	509.38	552.90	595.38	638.27	680.71
PVC - 4	0	35.79	76.14	116.99	158.14	197.04	233.92	268.81	302.82	334.95	367.24	398.84	430.75	461.81	494.01	525.51
mean		26.61	58.99	91.85	124.98	155.42	183.63	209.46	234.20	256.72	279.42	301.34	323.65	344.85	367.31	388.94
Stdev		16.53	31.57	46.34	60.91	76.31	92.70	109.89	127.34	145.58	163.73	182.17	200.56	219.14	237.13	255.42
CV%		**62.1**	**53.5**	**50.5**	**48.7**	**49.1**	**50.5**	**52.5**	**54.4**	**56.7**	**58.6**	**60.5**	**62.0**	**63.5**	**64.6**	**65.7**

Table 10.

DEMAND WETTABILITY TEST
Static Test Comparison

TEST SAMPLE - ACRYLIC
Knitted Acrylic - typical underwear fabric
-VE P/H = 2.0 cm
WEIGHT = 0.66g/cm

						PERCENTAGE WATER CONTENT (%)										
TESTS	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
ACRYLIC-1	0	63.07	97.07	115.31	125.40	136.97	145.04	154.22	161.84	171.06	177.49	181.65	187.41	194.31	197.16	204.08
ACRYLIC-2	0	20.93	49.92	74.77	94.34	104.04	113.20	119.71	127.50	133.84	142.74	151.41	160.69	168.13	173.21	179.59
ACRYLIC-3	0	131.73	183.01	208.21	220.90	230.33	240.08	251.22	256.80	262.75	274.59	280.11	285.15	290.12	297.21	305.50
mean		71.91	110.00	132.76	146.88	157.12	166.11	175.05	182.05	189.22	198.27	204.39	211.09	217.52	222.53	229.72
Stdev		55.93	67.48	68.41	65.96	65.51	66.01	68.18	66.97	66.35	68.34	67.30	65.52	64.22	65.77	66.76
CV%		**77.8**	**61.3**	**51.5**	**44.9**	**41.7**	**39.7**	**39.0**	**36.8**	**35.1**	**34.5**	**32.9**	**31.0**	**29.5**	**29.6**	**29.1**

Fig. 43 **HORIZONTAL DEMAND WETTABILITY TEST**
Static Test Comparison

TEST SAMPLE – PVC
-VE P/H = 2.0CM
WEIGHT = 0.66g/cm^2

PERCENTAGE WATER CONTENT v TIME (min)

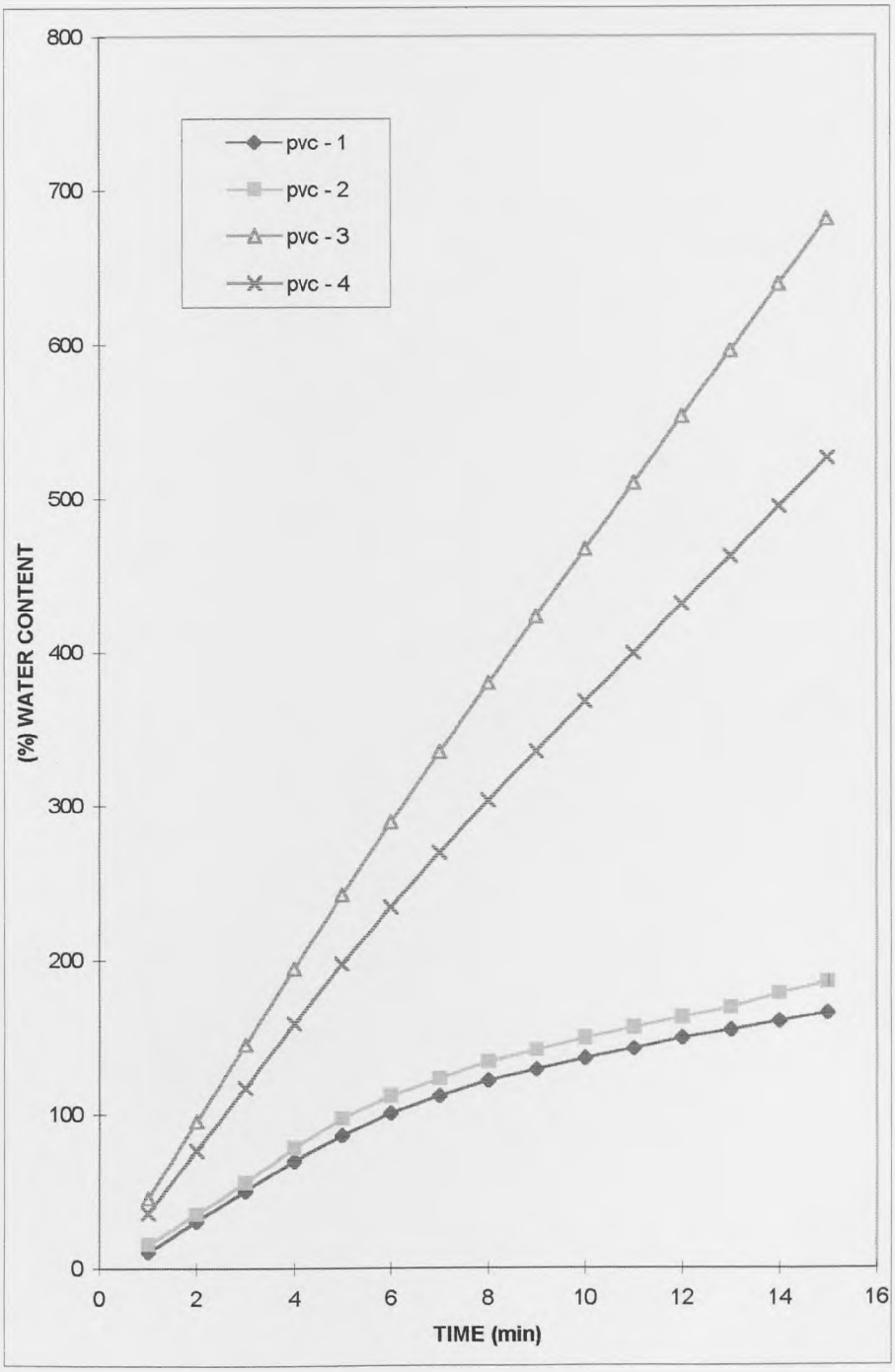
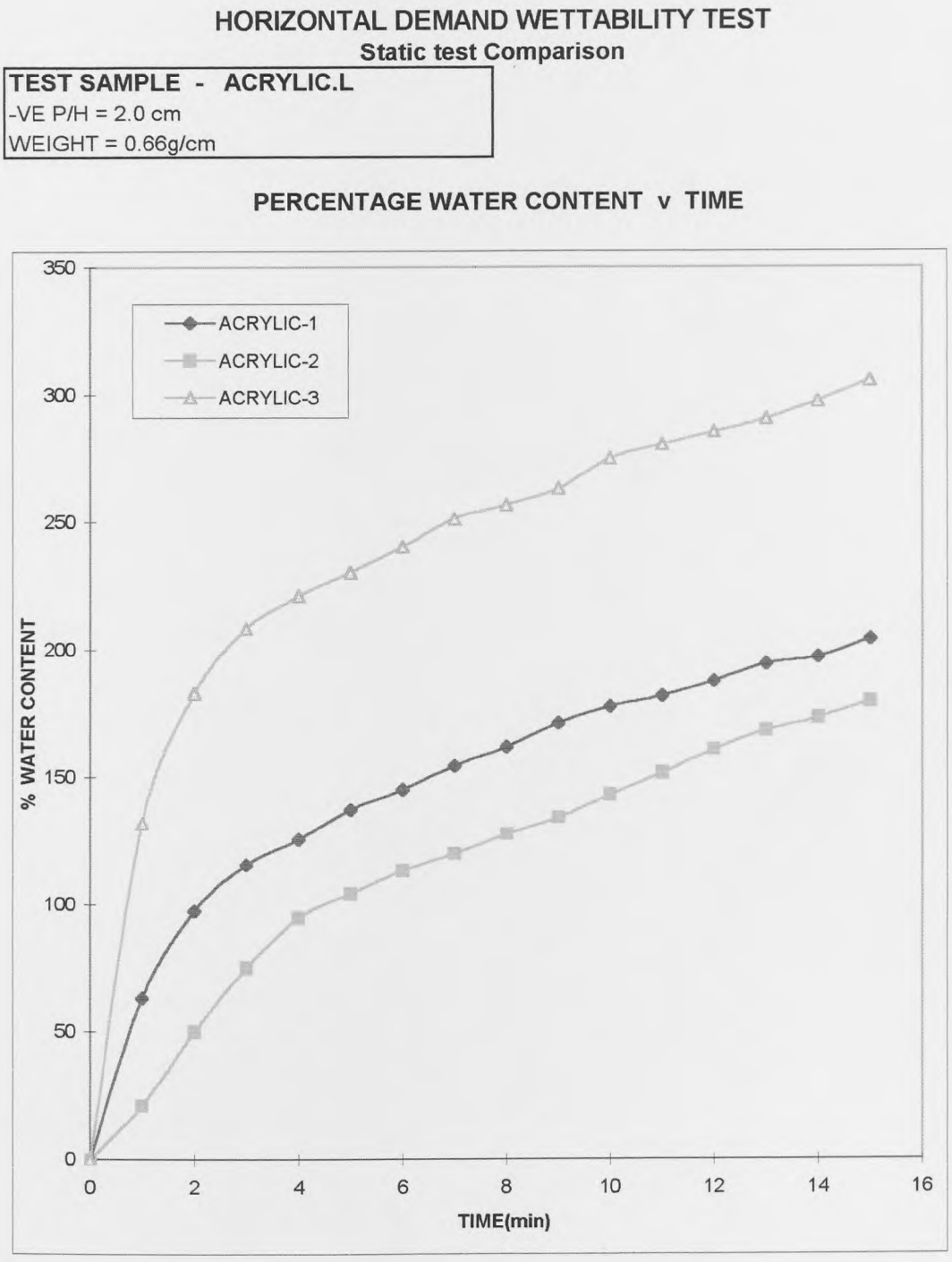


Fig. 44


HORIZONTAL DEMAND WETTABILITY TEST
Static test Comparison
TEST SAMPLE - ACRYLIC.L
-VE P/H = 2.0 cm
WEIGHT = 0.66g/cm
PERCENTAGE WATER CONTENT v TIME
ACRYLIC-1
ACRYLIC-2
ACRYLIC-3
% WATER CONTENT
TIME(min)
0
50
100
150
200
250
300
350
0
2
4
6
8
10
12
14
16

The large CV% values produced by these experiments were considered to be too large and needed to be investigated to determine whether this was a fault in the methodology, the equipment, or an inherent factor in the testing of these fabric.

In order to reduce the variability inherent in these fabric in general, the samples used were a smooth - surfaced woven Nylon 6.6 bolting cloth provided by Leeds University. These nylon fabric samples were prepared in the same way as previous samples.

A modification of the test method was also thought to be needed , not only to reduce variability but to show up any differences in the time intervals used.

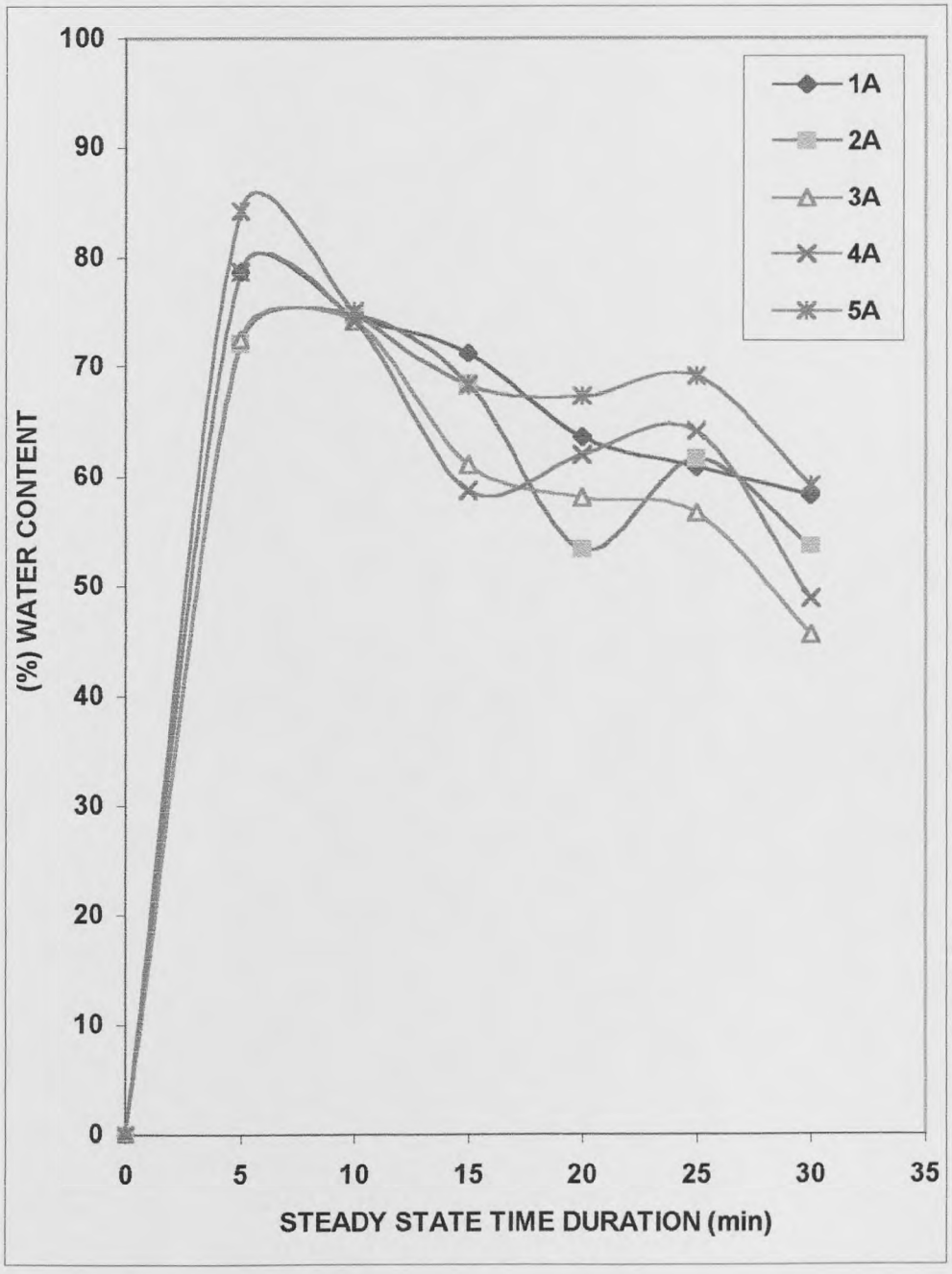
Therefore experiments were carried out on the nylon samples using a steady state time interval. As mentioned in section 3.0 wicking can occur intermittently or continuously and this should be reflected. The nylon samples were tested in the continuous state for the following time periods ; 5; 10 ; 15 ; 20 ; 25 ; and 30 minutes. The results can be seen in table 11 and figure 45. It can be seen by the CV% obtained from these experiments that these are much lower than results obtained from earlier tests carried out on the PVC and Acrylic fabric samples, see tables 9 and 10.

However the types of contact occurring in any clothing system can be both intermittent and continuous, so a change in the wicking time intervals from 1 minute intervals to 1,3,7 and 10 minute intervals was evaluated, and a minimum compression weight applied. This proved to be much more satisfactory. This time interval was also a combination of intermittent and continuous wicking duration, starting off intermittent and extending the duration to simulate a more continuous time period. The results can be seen in tables 12 – 17.

Table 11

(min) WICKING DURATION	(%) Water Content for Nylon test samples							
	1A	2A	3A	4A	5A	Mean	SD	CV%
0	0.0	0.0	0.0	0.0	0.0	0		
5	78.7	72.1	72.5	78.7	84.3	77.2	5.1	6.5
10	74.6	74.8	74.2	74.2	75.1	74.6	0.4	0.5
15	71.3	68.5	61.1	58.8	68.4	65.6	5.4	8.2
20	63.6	53.4	58.1	61.9	67.3	60.9	5.3	8.8
25	60.8	61.6	56.7	64.0	69.1	62.5	4.6	7.3
30	58.3	53.7	45.6	48.9	59.2	53.1	5.9	11.1

Fig. 45 **Mean Percentage Water content of woven Nylon continuous filament fabric samples for steady state tests**



From figure 45 the results from the nylon samples revealed a marked reduction in liquid uptake after the first time interval (5 minutes), with a steady decline thereafter. It would seem that at longer wicking times the amount of liquid retained by the samples decreased over time. This may be influenced by the nature of the fibre surface in these test sample (i.e. Nylon). The cross-section of this fibre was circular therefore the surface of the fibre would be smooth and unable to create more interfibre channels in which to retain the liquid first wicked into the nylon from the cotton. The marked decrease in liquid uptake in the nylon fabric cannot be due to evaporation because of the design of the apparatus. However over longer periods of time gravity would be able to exert an effect on the capillary transport of liquid in the nylon occurring in the transplanar direction rather than in the horizontal planar direction because gravity has an almost negligible effect in this latter direction. The skin simulant which is a cotton fabric would be continually wicking throughout the test, but over longer time periods it is considered that the fabric would seek the easiest source of liquid. This would come from the wet nylon sample through back wetting into the cotton. Because the nylon is less efficient in retaining liquid it is clear that the cotton would begin to take back liquid from the nylon and this back wicking effect would then decrease the amount of liquid that the nylon samples would retain after longer time periods.

The test method was then carried out in the following stages:

1. The liquid reservoir was set to a permanent height.
2. The wetting chamber was lowered and raised, and locked at its required height of 0cm, the height at which the water levels in both the wetting chamber and the reservoir are equal. This procedure initiates the wetting of the filter paper, and traps the water at the required level just below the filter paper.
3. The wetting chamber was then raised to the required pressure head height of 2.0cm.
4. The skin simulant was then laid on top of the filter paper and left for a while, complete saturation of the simulant took a few minutes.

5. Fabric sample or samples which had been conditioned for 23 hours in 65% RH at 20°C were then ready to be weighed on a top-loading balance.
6. The sample(s) was then laid on top of the simulant and timed for 1 min, and removed and re-weighed.
7. The sample was replaced on the simulant for another 2 min, removed, re-weighed and replaced in the wetting chamber.
8. The sample(s) was then left to wick for a further 7 and 10 minutes respectively, the weights were recorded for these time intervals
9. The results were calculated along with the CV% for all these samples.

This test method was the methodology finally chosen for the horizontal static demand wettability technique.

Table 12 Nylon 1A-Percentage Water content at 1,3,10 and 20 minute intervals

NYLON 1A % WATER CONTENT/TIME PERIOD(min)					
TEST Nos.	**0**	**1**	**3**	**10**	**20**
1	0	13.28	39.55	64.97	70.90
2	0	51.41	62.15	68.93	70.34
3	0	10.99	30.70	69.86	75.49
4	0	18.03	52.11	67.89	70.70
5	0	12.39	59.72	68.17	69.58
Mean		21.22	48.85	67.96	71.40
SD		17.08	13.43	1.84	2.34
CV%		**80.5**	**27.5**	**2.7**	**3.3**

Table 13 Nylon 2A-Percentage Water content at 1,3,10 and 20 minute intervals

NYLON 2A % WATER CONTENT/TIME PERIOD(min)					
TEST Nos.	**0**	**1**	**3**	**10**	**20**
1	0	23.94	53.52	65.35	68.45
2	0	20.85	55.21	73.52	74.37
3	0	20.56	58.59	68.73	72.11
4	0	28.73	58.87	62.54	64.79
5	0	38.03	52.68	60.56	65.92
Mean		26.42	55.77	66.14	69.13
SD		7.27	2.85	5.15	4.06
CV%		**27.5**	**5.1**	**7.8**	**5.9**

Table14. Nylon 3A-Percentage Water content at 1,3,10 and 20 minute intervals

NYLON 3A % WATER CONTENT/TIME PERIOD(min)					
TEST Nos.	**0**	**1**	**3**	**10**	**20**
1	0	22.10	61.47	66.01	71.67
2	0	36.26	59.77	67.71	75.07
3	0	13.60	59.49	66.29	67.71
4	0	16.71	54.67	69.12	70.25
5	0	38.14	57.06	66.38	70.34
Mean		25.36	60.62	66.86	73.37
SD		11.24	2.65	1.31	2.69
CV%		**44.3**	**4.4**	**2.0**	**3.7**

Table15. Nylon 4A-Percentage Water content at 1,3,10 and 20 minute intervals

NYLON 4A % WATER CONTENT/TIME PERIOD(min)					
TEST Nos.	**0**	**1**	**3**	**10**	**20**
1	0	23.16	64012	64.69	70.62
2	0	16.34	52.11	56.06	68.73
3	0	19.66	54.21	63.48	67.70
4	0	13.76	44.38	68.82	73.31
5	0	26.69	60.11	62.64	67.42
Mean		19.92	54.99	63.14	69.56
SD		5.17	7.60	4.62	2.45
CV%		**26.0**	**13.8**	**7.3**	**3.5**

Table16. Nylon 5A-Percentage Water content at 1,3,10 and 20 minute intervals

NYLON 5A % WATER CONTENT/TIME PERIOD(min)					
TEST Nos.	**0**	**1**	**3**	**10**	**20**
1	0	24.86	65.25	67.51	69.49
2	0	20.06	61.02	69.77	72.32
3	0	25.71	59.04	61.30	68.64
4	0	38.98	68.36	75.14	76.27
5	0	33.62	62.15	66.95	70.06
Mean		28.64	63.16	68.14	71.36
SD		7.56	3.68	5.01	3.07
CV%		**26.4**	**5.8**	**7.3**	**4.3**

Table 17. Mean Test Results for Nylon samples Nos. 1A-5A

% WATER CONTENT/TIME PERIOD(min)					
TIME (min)	**0**	**1**	**3**	**10**	**20**
NYLON - 1A	0	21.22	48.85	67.96	71.40
NYLON - 2A	0	26.42	55.77	66.14	69.13
NYLON - 3A	0	25.36	60.62	66.86	73.37
NYLON - 4A	0	19.92	54.99	63.14	69.56
NYLON - 5A	0	28.64	63.16	68.14	71.36
Mean		24.31	56.68	66.45	70.96
SD		3.65	5.54	2.02	1.70
CV%		**15.0**	**9.8**	**3.0**	**2.4**

From these results it can be seen that the CV% has been greatly decreased, but variation can not be eliminated (see Tables 12-17). This was to be expected due to the nature of the test, the property being investigated and the inherent nature of the substrates being tested.

The test method was vindicated as the sole cause of variation produced between tests because it was shown that once the substrate variability was reduced (i.e. by using woven Nylon) the CV% decreased considerably. However the pattern of variability was greatest at the beginning of the test, particularly during the first few minutes, and this appears to be so throughout all testing. It was also noted that there was continued reduction in CV% throughout the subsequent time intervals in all tests.

The increase in the duration of the wicking time intervals also appears to have helped in the reduction of variability between tests.

Mean test results from each test sample also produced a lower CV% and this can be seen in Table 17, confirming a satisfactory methodology for this stage of the investigation.

Further testing was carried out using Nomex and Acrylic fabric samples using the altered wicking time intervals of 1,3,10 and 20 minutes, producing the results seen in Tables 18 and 19 and Figures 46 and 47.

Table 18.

MEAN DEMAND WETTABILTY TEST RESULTS

NOMEX SAMPLE
(non-drying tests)
COMPRESSION WEIGHT = 0.66g/cm
-VE P/H = 2.0 cm

SAMPLES	WATER CONTENT/MIN (%)				
	0	1	3	10	20
NOMEX -1	0	6.64	14.79	31.80	45.53
NOMEX -2	0	2.62	6.36	22.31	35.94
NOMEX -N1	0	4.14	9.41	19.02	28.72
NOMEX -N2	0	3.17	6.81	15.50	28.44
NOMEX -N3	0	4.59	10.72	22.64	31.42
Average =	0	4.23	9.62	22.25	34.01
stdev =		1.56	3.41	6.07	7.11
cv% =		**36.8**	**35.4**	**27.3**	**20.9**

Table 19.

MEAN DEMAND WETTABILTY TEST RESULTS

ACRYLIC SAMPLE
(non-drying tests) water pH = 7.0
COMPRESSION WEIGHT = 0.66g/cm
-VE P/H = 2.0 cm

SAMPLE	WATER CONTENT/MIN (%)				
	0	1	3	10	20
ACRYLIC -1	0	11.05	58.30	177.22	243.38
ACRYLIC -2	0	10.17	39.05	144.23	196.01
ACRYLIC -3	0	5.93	45.32	141.76	204.18
ACRYLIC -4	0	2.87	14.67	119.66	173.78
Average =		7.5	39.3	145.7	204.3
stdev =		3.81	18.29	23.73	29.03
cv% =		**50.8**	**46.5**	**16.3**	**14.2**

Fig. 46

MEAN HORIZONTAL DEMAND WETTABILITY TEST RESULTS
NOMEX SAMPLE
(non-drying tests)
COMPRESSION WEIGHT = 0.66g/cm
-VE P/H = 2.0 cm

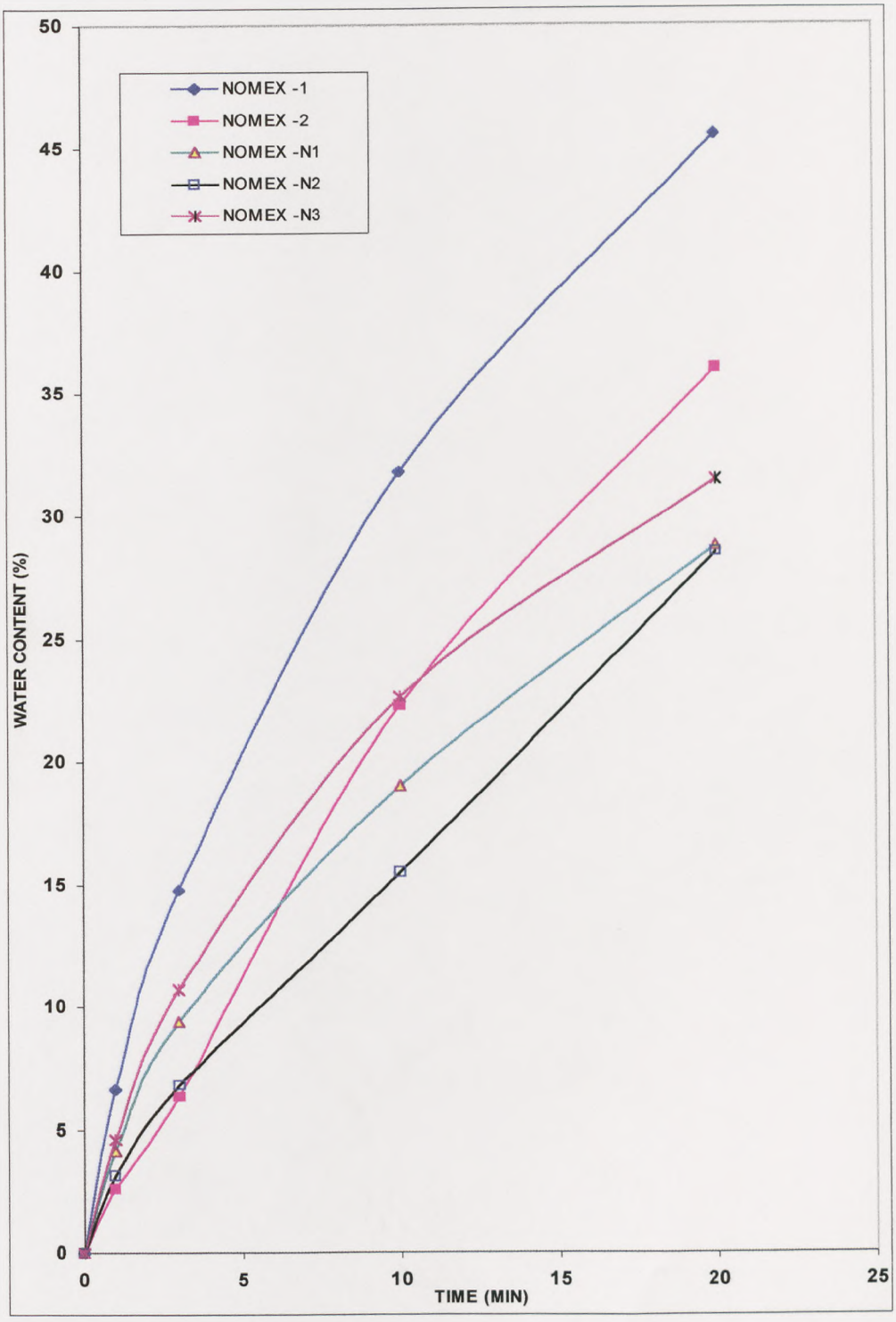
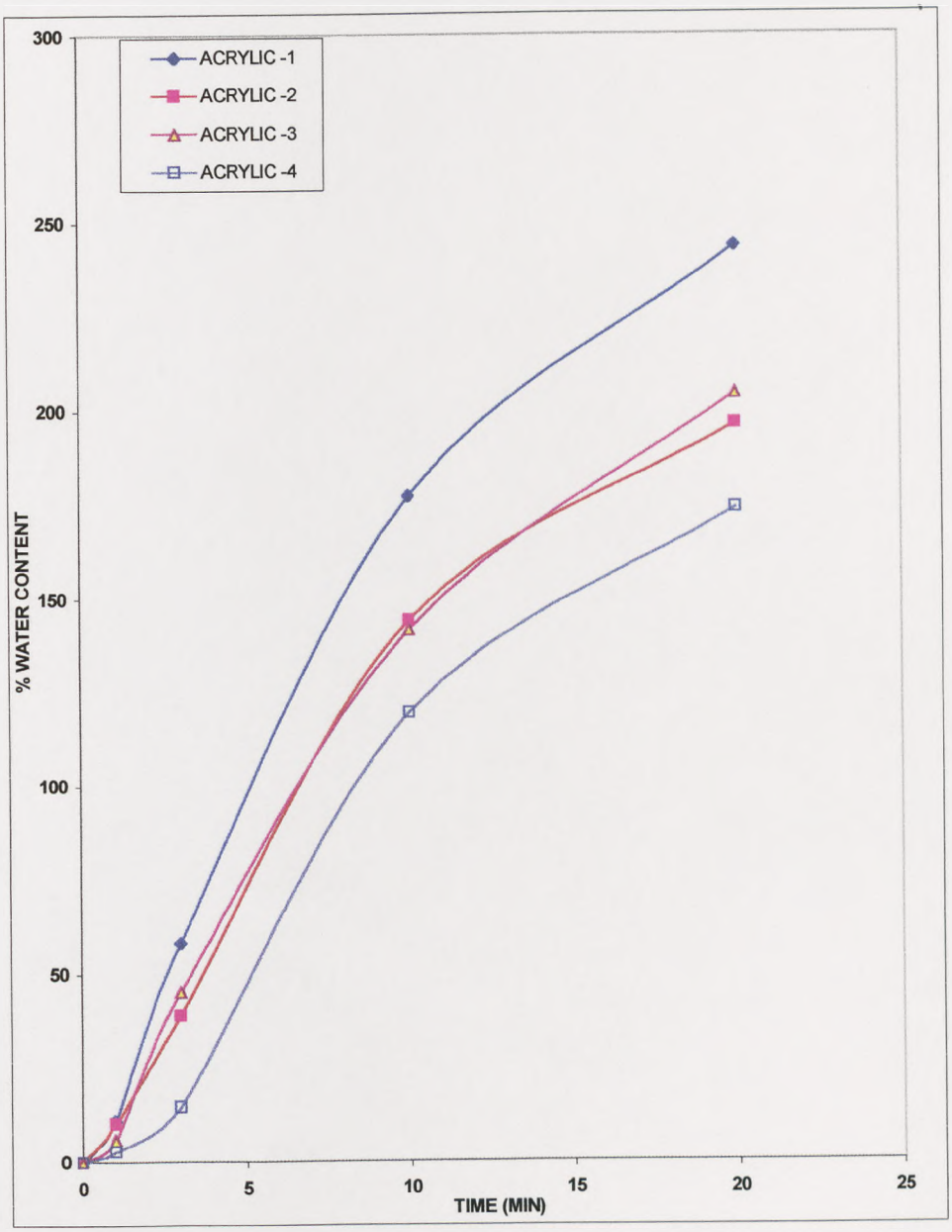


Fig. 47

MEAN HORIZONTAL DEMAND WETTABILITY TEST RESULTS

ACRYLIC SAMPLE

(non-drying tests)
COMPRESSION WEIGHT = 0.66g/cm
-VE P/H = 2.0 cm



3.3 HORIZONTAL DYNAMIC DEMAND WETTABILITY TECHNIQUE

Wicking during general wear would rarely take place just in the static state, because as a person moves so must the clothing move. Invariably there is constant movement taking place within a clothing assembly, during everyday wear ; between the skin and the first fabric layer, and between the first layer and the second fabric layer. Therefore movement may also have an effect on wicking, see section 3.0. As there appeared to be little or no work available on substrate movement and wicking, another piece of equipment needed to be developed to investigate this aspect of wicking

3.3.1 THE EQUIPMENT

This piece of equipment was designed to test the effect of the relative motion of two fabrics in close planar contact on the rate of transplanar wicking between these fabrics, in a "demand wettability" type apparatus. It was obvious that the apparatus described in (Section 3.2) could not be adapted to this purpose, and therefore another apparatus was constructed.

Using an initial basic construction first devised by BTTG, the original skeletal construction was redesigned and this apparatus was developed. The apparatus consists of a metal plate constructed on wheels, which could run backwards and forwards by means of an electric motor on a small track, , with the speed of movement being variable.

Clamped to the plate is a medium to hold the liquid, in this case a sponge, approximately 1.5 cm thick, and placed on top of this is the skin simulant. Above the running plate is a second plate which is held stationary. In the centre of this plate is an opening to hold and locate the test sample. This plate may be raised and lowered to set heights above the liquid holding medium, ensuring nothing touches the sponge during testing except the test sample.

The test samples are attached to a Perspex plate which fits inside the opening on the top plate and lies on the sponge. In order to allow free movement of the sample within the plate opening different sizes of Perspex plate were used, dependent on the number of sample layers being tested, (see Figs. 48 and 49).

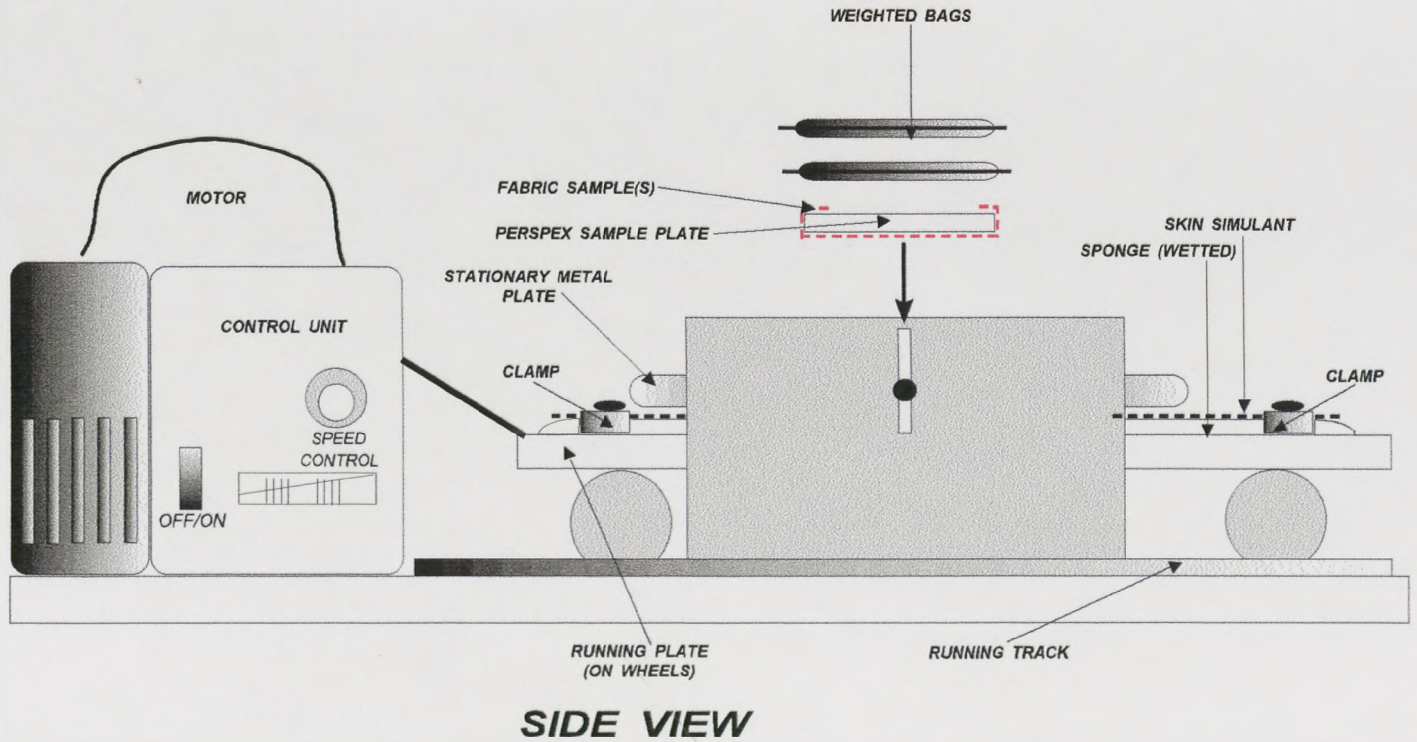


Fig. 48 Diagrammatic representation of the Horizontal Dynamic Demand Wettability Apparatus

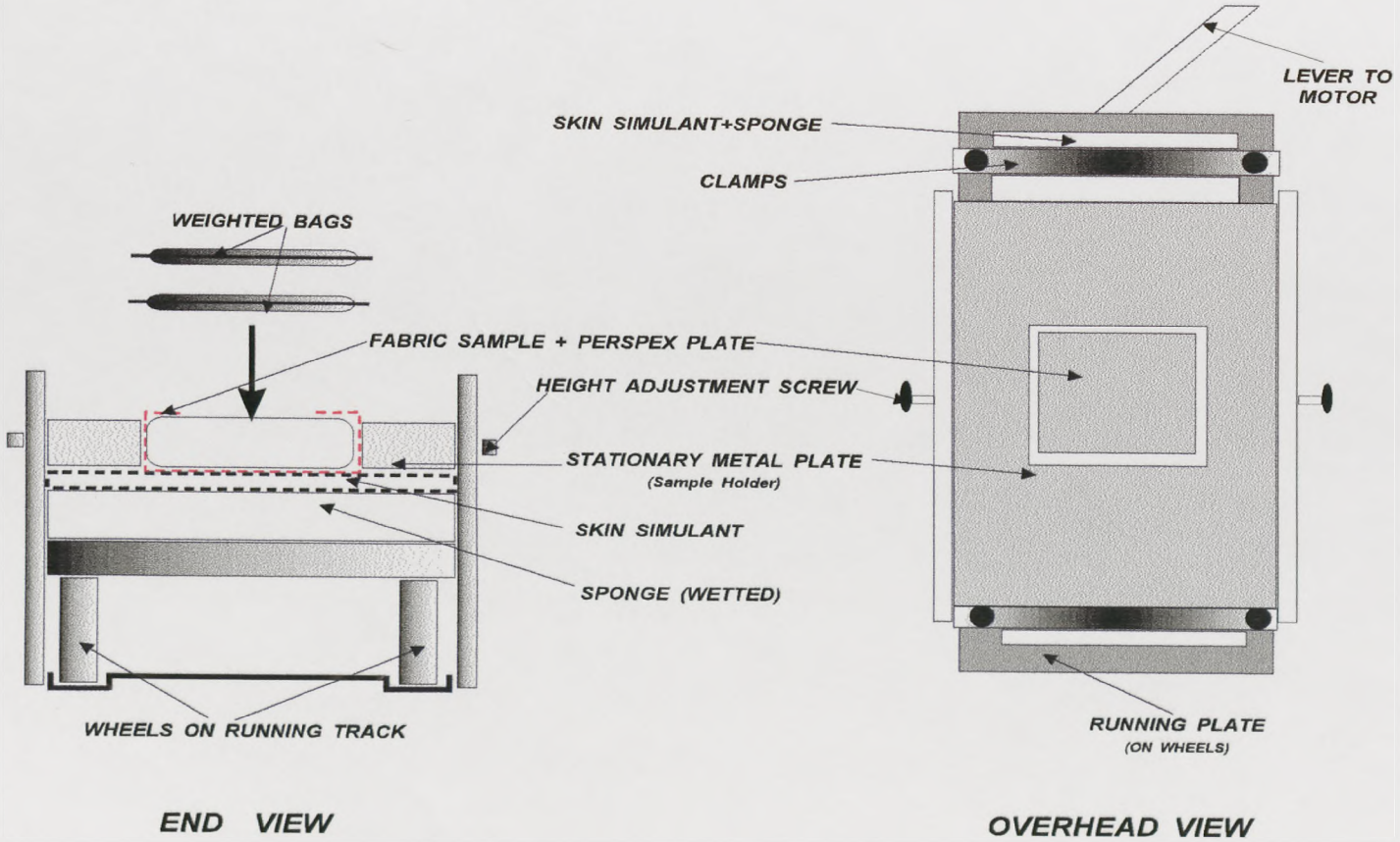


Fig. 49 **Diagrammatic representation of the Horizontal Dynamic Demand Wettability Apparatus, Moving section.**

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3.3.2 COMPONENT DEVELOPMENT

The Demand Wettability technique consists of the following components :

- ◊ Liquid Medium - Sponge (Wetted)
- ◊ Skin Simulant - Woven cotton fabric (ref: Cotton.L)
- ◊ Sample Holder - Perspex plate and acetate band
- ◊ Compression system - Perspex plate and weighted bags
- ◊ Weighing system - Top-loading Balance
- ◊ Timing system - Digital Timer
- ◊ Sample Removal system - Tweezers

3.3.2.1 Compression Weight Development

As with the static demand wettability test equipment a compression weight was also needed, and this took a similar form to the weights used in the static equipment.

Plastic weighted bags were manufactured to the same sizes as the Perspex sample plates, and weights were calculated in the same way as before. Weights equivalent to 1 g/cm^2, 2g/cm^2, 3g/cm^2, and 4g/cm^2 were made for each Perspex plate.

3.3.2.2 Sample Attachment

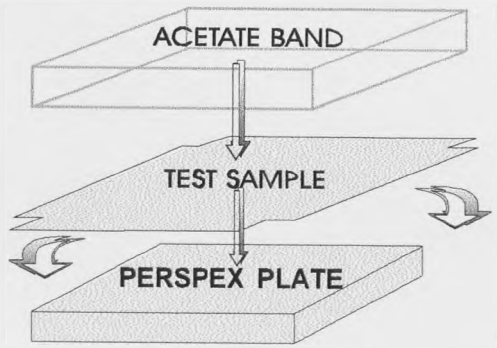
After some experimentation several methods of sample attachments were tested, as follows :

i. The use of double-sided sellotape was initially utilised, and had favourable results in the beginning. It was particularly useful during the multi-layer tests as it enables the final layer only to be attached to the plate. However with certain fabrics taking up large amounts of water, this failed during movement and the sellotape would detach from the plate.

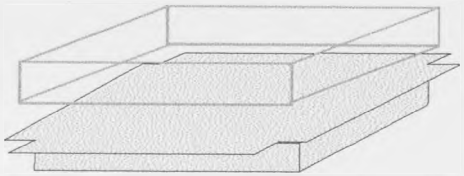
ii. Secondly " Blutack'' was tried, using the same general method as the double-sided tape and attaching only the final layer.

However once again during high liquid take up and movement, detachment from the Perspex plate occurred.

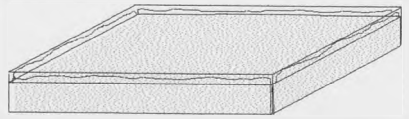
A method whereby the presence of liquid in the sample had no affect on the attachment method was found. The manufacture of an acetate band and the incorporation of miniature 'bulldog' clips produced a method which worked perfectly during movement . The samples were placed on the Perspex plate and the belt was pushed on to the plate to fit around the plate/sample edges. The sample or samples were then attached to the belt by the mini bulldog clips, (see Fig. 50) on all four sides.



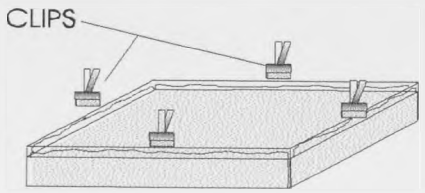
1. COMPONENTS



2. SAMPLE(S) ATTACHMENT TO SAMPLE PLATE



3. SAMPLE(S) PRESSED TO PLATE BY ACETATE BAND



4. SAMPLE(S) ATTACHED TO BAND BY MINIATURE 'BULLDOG' CLIPS

Fig. 50 **Horizontal Dynamic demand wettability test - components and sample attachment method**

3.3.2.3 Liquid Medium / Skin Simulant

This came in the form of a sponge of approximately 1.5 cm in thickness and 5 x 12 cm in dimensions with small pores. A variety of experiments were carried out to determine the ideal water content of the sponge in order to prevent significant drying out during testing.

Other aspects were tested to determine the following ;

(i.) During movement was water expelled from the sides of the sponge ?

(ii.) Does the sponge 'ride-up' during movement ?

(iii.) What was the drying rate of the sponge, was there a significant effect ?

(iv.) What was the best water content for the sponge ?

All the above questions were investigated with the following conclusions;

- During movement there was no water loss from the sponge, both at the slowest and fastest speed for the time period of 5 minutes. This test was repeated several times giving satisfactory results.
- Riding-up of the sponge during movement did not occur, however riding-up did occur early on in some of the test samples. This problem was solved with the production of a satisfactory sample attachment. (see section 3.3.2.2).
- The drying rate of the sponge was less than 0.01g over a 60 minute time period and had no significant effect.
- In order to gain a test period for as long as possible and not over saturate the skin simulant , a test weight for the sponge was established at 100.4 g $\pm$ 0.3g, (the dry weight of the sponge = 6.3g)

The skin simulant was made from a woven undyed bleached cotton, the same fabric previously used for the static demand wettability technique. Cut to the same size as the sponge, it lay on the top of the sponge and immediately took up water. This created a continuously moistened layer to perform the tests. Once again various aspects were tested these being ;

(i.) Does the sample move freely on the skin simulant ?

(ii.) Was the fabric a good continuous wicker ?

- Initially most samples moved freely on the skin simulant , although one or two once wet resisted during movement and began dragging on the skin simulant. However this problem was solved (see section 3.3.2.2).
- A woven cotton fabric was used as the skin simulant. Cotton is a known good wicking fibre and was an obvious choice. In addition this woven fabric had a closer surface appearance to the skin than a knitted fabric.

3.3.3 METHODOLOGY DEVELOPMENT

On top of the sponge lies a second layer; this is the 'skin simulant'. The simulant was represented by the same fabric used in the static tests, namely the cotton L. woven fabric.

The tests were runs as follows;

1. The sponge is soaked in distilled water and then squeezed out until it holds a predetermined amount of water, this being 100.4g ± 0.3g (recorded weight).
2. The sponge is then clamped on to the plate with the skin simulant lying on top smooth and flat.
3. Each test sample layer is cut to a set size and shape, and then weighed before it is attached to the plate.
4. The Perspex plate, the belt and the clips are weighed together and recorded.
5. The test sample(s) are weighed and the results recorded.
6. The test sample or samples are attached to the Perspex plate with the clips and belt, and placed in the sample opening, with the sample facing the skin simulant.
7. Compression weights may be placed on top of the sample plate at this point as required.
8. The speed setting is set, (In all tests the slowest speed setting was used) *
9. The plate is set in motion for a set time period.

At the end of the time period, (**Multi-layer tests**) - the plate is removed and each sample is removed and weighed on a top-loading balance and the weight recorded. The samples are then re-attached to the plate and the cycle is repeated for a further period of time.

(**Single layer tests**) - the plate is removed with the sample and together these are weighed on a top-loading balance and the weight recorded. The sample and plate are then replaced in the opening and the cycle is repeated for a further period of time.

* Machine speed is measured thus, 1 = one backward and forward movement ←→, therefore speed is calculated as, slowest = 40/min. ; fastest = 90/min.

3.4 VERTICAL TRANSPLANAR WICKING TECHNIQUE

As mentioned before although these newly developed pieces of equipment and tests are able to give a reasonable indication of what is happening during the wicking process, this so far has been only with the fabric in the horizontal state. To give an indication of what could be happening under 'real life' conditions, wicking in the vertical state was also investigated.

Factors against testing in this state were firstly, the extreme difficulty in developing a test which works in the vertical direction and secondly, comparison with other wicking tests in the horizontal state are not easily achieved.

However a simple piece of equipment was developed which allowed vertical transplanar wicking to be carried out.

3.4.1 COMPONENT DEVELOPMENT

Initially fabric was suspended from a stand , weighted at one end to keep it taut, and then water was introduced to the centre of the fabric. Small amounts of water were then squeezed on to the surface of the fabric at interval to see if liquid uptake could be achieved. Initial experiments were successful on the knitted (blue) cotton. However there was a tendency in the beginning to lose water by water droplets falling from the surface of the samples because of the effect of gravity. The whole component structure was then revised and refined as other difficulties were discovered. This included difficulty in maintaining the surface contact between layers.

The basic method worked, but component development continued along the following lines ;

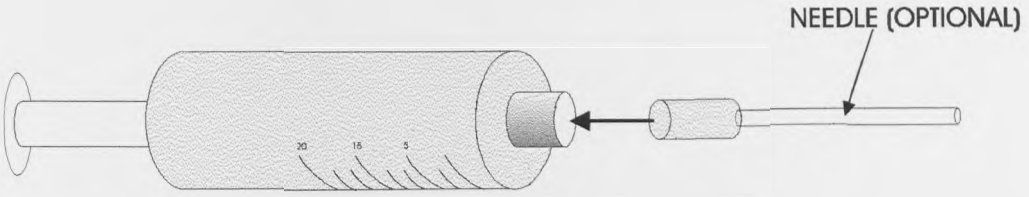
(i.) An experiment was carried out using a burette as a reservoir , as then the amount of water introduced to the fabric surface could possibly be monitored and controlled. However the introduction of the water to the fabric proved extremely difficult to control and this method was abandoned. The use of a syringe proved more successful, as the reservoir of water could be suspended horizontally from the start, and the amount of water introduced to the vertical fabric could still be monitored and controlled.

(ii.) The samples had been originally suspended from stands by large 'bulldog clips' on both ends of the sample; however this proved unsatisfactory as the weight of the clips tended to stretch the samples, and in multi-layer tests the layers would not stay together. The use of plates was introduced to reduce this phenomenon. Two Perspex plates were designed and manufactured for this purpose, (See Fig.51)

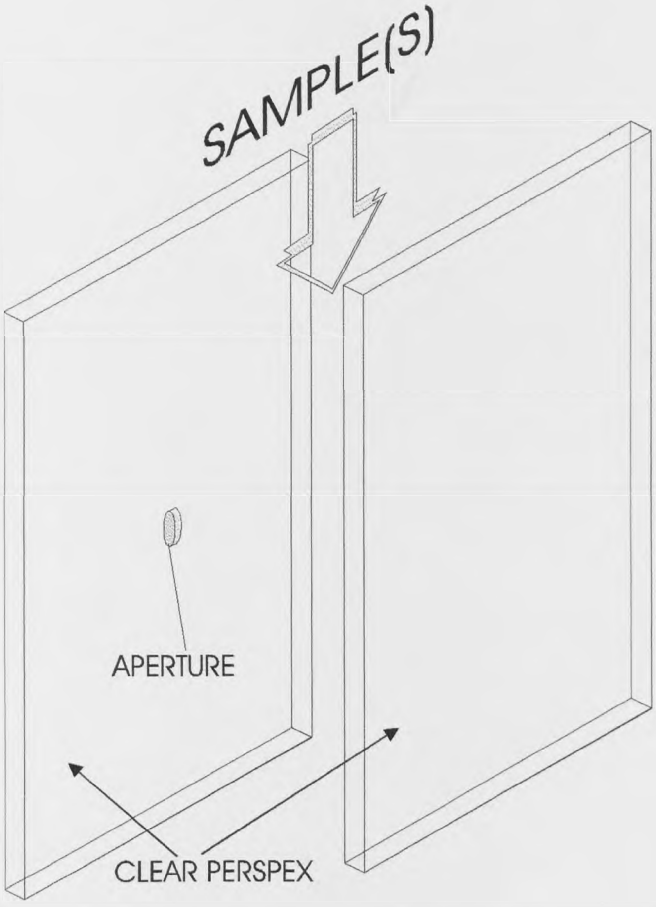
a) Plate 1. was 7 x 14cm and ;

b) Plate 2. was 7 x 14cm with a hole drilled centrally in it (approximately 2mm in diameter) in order to house the tip of the syringe (see Fig. 52). The fabric samples would be sandwiched between the plates and suspended by the clips from the top of the stands. This enabled multi-layer assemblies to be tested, and no direct weight was exerted on the samples.

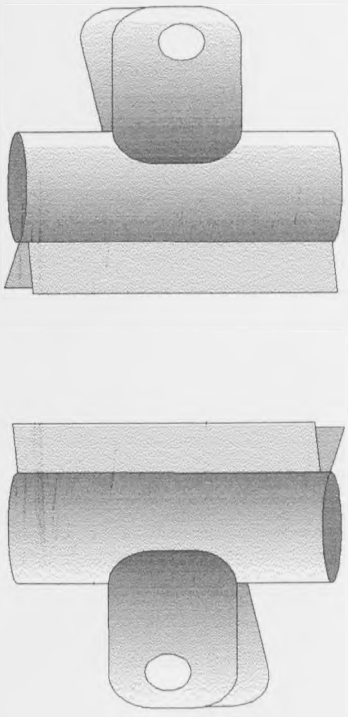
(iii.) The liquid used for these tests was distilled water originally, and this worked satisfactory on the dyed blue knitted cotton. However this was not sufficient for the other test fabrics , and as these were white samples the water had to be coloured to aid visual assessment of these test fabrics. Once again the food colouring dyes were employed for this purpose (see section 3.2.1.4).



1. WATER RESERVOIR - SYRINGE



2. SAMPLE HOLDER PLATES



3. SAMPLE PLATE CLIPS

Fig. 51 Components for Vertical transplanar wicking technique.

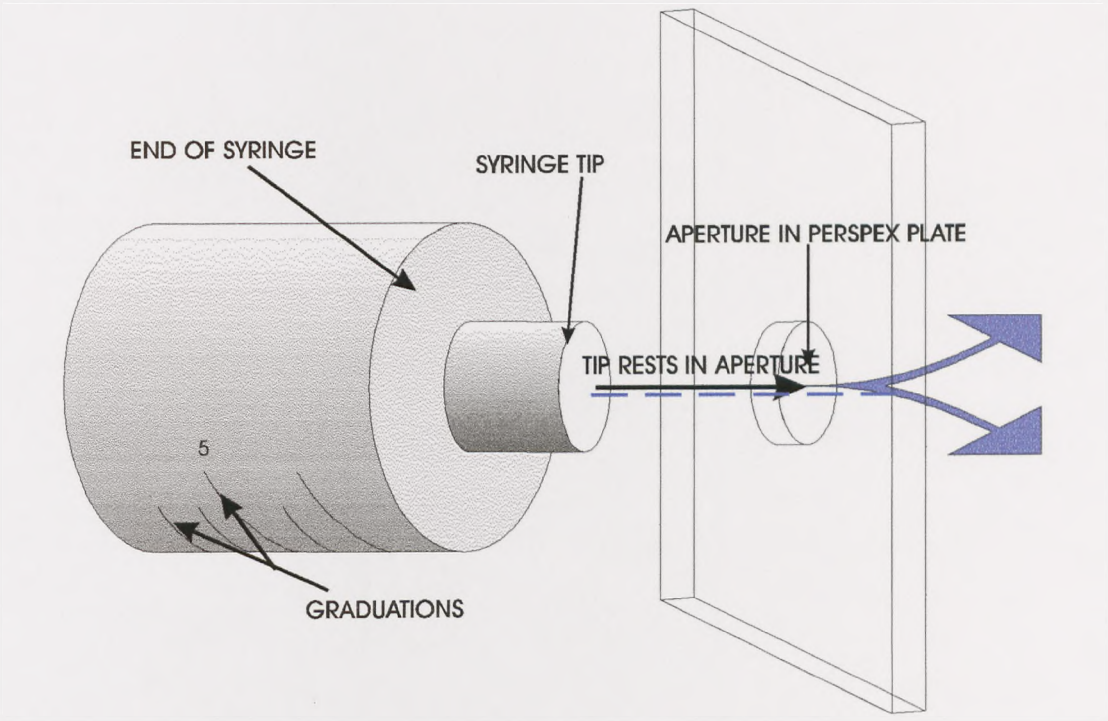


Fig.52 Syringe tip fits into aperture in Perspex sample plate.

The first basic experiments were carried out on the dyed knitted cotton fabric which was a high wicking fabric and these proved successful, so small tests were carried out on the other test samples, Acrylic.L. , Nomex, and Polypropylene. This proved successful for the acrylic and Nomex fabrics, but due to the hydrophobic nature of polypropylene, once the water was introduced to the fabric surface it remained there for a long period of time without being wicked within the fabric or subsequent layers.

Experiments were conducted with a needle attached to the syringe when testing polypropylene fabrics, to determine whether this would improve wettability.

The use of a syringe when testing the polypropylene fabric improved wettability only slightly, and was of no significant use. The use of the polypropylene samples was therefore abandoned in the vertical transplanar wicking tests.

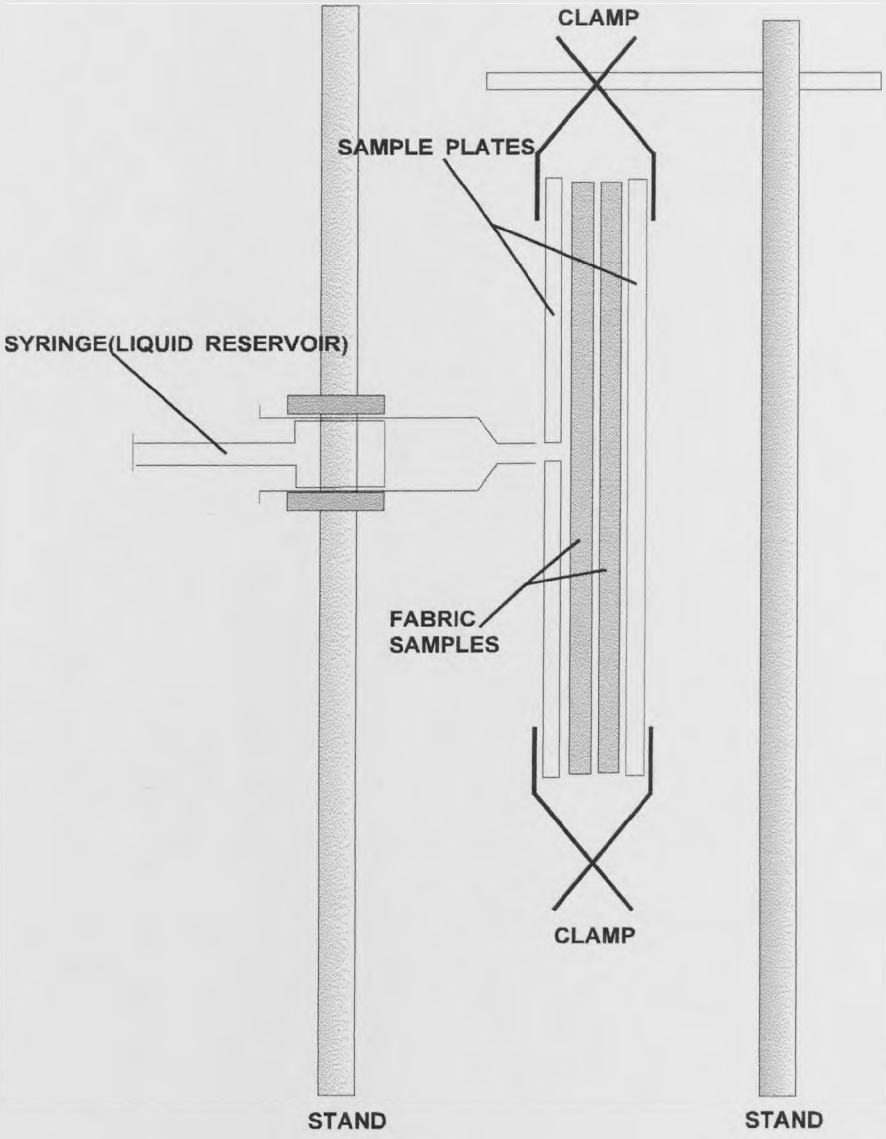


Fig. 53 Transplanar Vertical wicking Test Equipment

3.4.2 METHODOLOGY DEVELOPMENT

The vertical transplanar wicking test is set up with the following components (see Fig.51) ;

◊ Liquid reservoir - Syringe
◊ Sample holder - Two clear Perspex plates with aperture
◊ Compression clamps - Two large Bulldog clips
◊ Sample removal system - Tweezers
◊ Weighing system - Top-loading balance
◊ Saturation recording system - Marker pen

With a few changes during development the methodology developed for the first stage of the test was as follows :

- the sample layers were weighed and the results recorded ;
- the samples were sandwiched between the Perspex plates and clamped at one end, and into the stand at the other ;
- the syringe was filled with coloured distilled water and fixed into its stand, and levelled at the aperture in the sample plate.

Initial experiments were performed with the test samples cut to a much smaller size (3 x 5cm) ; however this method produced uneven pressures on the samples, caused by bending of the plates around the samples.

The samples were then cut to the same size as the Perspex plates (7 x 14cm) to eliminate this problem.

The second stage of the tests was also revised, to introducing the liquid to the fabric surface through the aperture, until breakthrough occurred on the outer surface of the second layer of test fabric. The samples were then removed and weighed individually. The percentage water content was calculated at breakthrough for each fabric layer.

However this determined the percentage water content of the whole fabric sample, and not the percentage content of the wet area.

The second stage method was then changed to the following ;

1. Sample layers 1 and 2 were laid flat and aligned with the warp running down both fabrics, on plate 1 and sandwiched with plate 2 on top.
2. The plates were clamped both ends and into the first stand .
3. The syringe was filled with coloured distilled water and fixed into its stand, and levelled at the aperture in the sample plate.
4. The plunger of the syringe was depressed until a drop of liquid adhered to the tip of the syringe, the tip was then pushed up against the aperture so that the liquid travelled through the aperture.
5. The plunger was depressed again just enough to allow the liquid to touch the surface of the fabric.
6. If the fabric sample exhibited rapid wicking the liquid would almost instantly migrate into the fabric. Once this happened more liquid was introduced to the surface in minute amounts, until liquid appeared on the other side of the second fabric layer.
7. Once breakthrough had occurred, an outline of the wet areas on both fabric layers was drawn on the perspex plates in marker pen.
8. The whole assembly was then detached from the stand and the sample layers removed and weighed.
9. The outlines on each plate were then traced on to paper for later measurements, the outlines can then be removed for retesting.

Once the test is over the shapes of the wet areas are traced on to the dry test fabrics, and cut out and weighed.

Using this method the percentage water content in the wet area only could be determined.

3.5 SECONDARY EXPERIMENTATION

3.5.1 CONTACT POINTS

Through observing the sequence of events occurring during testing using the dynamic demand wettability technique and static demand wettability technique, one of the factors which appears to influence the variability of results is contact between one fabric layer and the next.

This in itself is influenced by the fabric geometry, the compression of the fabric layers, the orientation of fabric layers to each other and finally by the fabric surface appearance.

Due to the uneven absorption sequence which appeared to occur in any multi-layer wicking test ; a small experiment was set up. This was used to determine the pattern of contact points possible under various conditions, as well as the regularity of any that could be produced, and the experimental reproducibility of the test.

Components

◊ Liquid Medium	-	Sponge (diameter = 9.0 cm)
◊ Medium Holder	-	Perspex dish
◊ Liquid	-	Coloured water (dye : red)
◊ Skin simulant	-	Woven Cotton (Ref. Cotton.L) dia. = 9.0cm
◊ Compression Weight	-	Perspex dish and Weighted bags

3.5.1.1 Experiment - 1

Tests were carried out on test samples to determine the pattern sequence of contact points. The methodology commenced as follows :

- The sponge was soaked completely in a dye solution, completely saturating the sponge.
- This then rested in the Perspex dish. A layer of the skin simulant was placed on top of the liquid medium and left to absorb the coloured liquid.
- Once ready the test sample was placed on the skin simulant until colour appeared on the top side of the test sample.

3.5.1.2 Experiment - 2

The second experiment was a repetition of the first, but with the addition of the compression weight (the Perspex disc). Once again this was left until the colour appeared visible on the top side of the test sample. The sample was then removed and the contact pattern recorded (see figure 54).

These experiments were repeated for knitted and woven fabrics and the various fibre types.

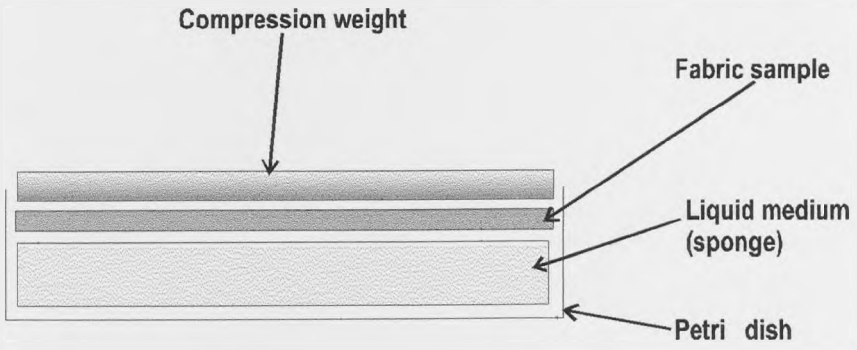


Fig. 54 Contact Points Experimentation equipment

It was also repeated on multi-layer fabric assemblies to register the possible contact points between two different fabric layers and the possible contact patterns.

Although some fabrics produced regular patterns , others did not, and these patterns were not on the whole repeatable with subsequent testing.

Although a large series of contact points could be produced, not all of these produced viable liquid transfer points from one layer to another. Also the spread was not an even pattern over a test sample ; which produced variability both within individual test samples and within subsequent tests.

3.6 TEST SAMPLE DATA

There were four main test fabrics used for the main body of the research, picked from a larger group of fabrics used in initial testing, equipment and technique development, and these were carefully characterised. Other fabric samples were not characterised in depth.

The first group of fabrics Group [A] were characterised in general, full analysis was carried out on Group [B] fabrics. The groups were as follows :

GROUP [A] FABRICS – Weft Knitted fabrics

Acrylic
PVC (Polyvinyl chloride)
Acrylic.L
Cotton.L
Nylon 6.6
Coolmax (Polyester)

GROUP [B] FABRICS - used as main research fabrics.

Cotton.L (knitted - blue)
Acrylic.L
Nomex
Polypropylene
Cotton.L. (woven - white) [acting as Skin Simulant]

3.6.1 SAMPLE FABRIC DATA

Table 20.
WOVEN FABRIC SAMPLES

REF.NO.	SAMPLE	STRUCTURE	SAMPLE TYPE
C (L)	COTTON.L (White)	Plain weave	SKIN SIMULANT
N (U)	NYLON (White)	Plain weave	TEST SAMPLE

Table 21.
KNITTED FABRIC SAMPLES

REF.NO.	SAMPLE	STRUCTURE	SAMPLE TYPE
C	COTTON.L (Blue)	Interlock	TEST SAMPLE
P	POLYPROPYLENE	1x1 Rib	TEST SAMPLE
N	NOMEX (Ecru)	1x1 Rib	TEST SAMPLE
A	ACRYLIC.L (White)	Interlock	TEST SAMPLE
PV	PVC (White)	1x1 Rib	TEST SAMPLE
CM	COOLMAX (Green)	1x1 Rib	TEST SAMPLE

Sample Fabric Characteristics.

KEY
wpc = wales/cm cpc = courses/cm s = stitch density/ (cm^2)
ℓ = stitch length(cm) k = Tightness factor ($tex^{½}\ell^{-1}$)

Table 22. Fabric Characteristics - Mean values

REF.No.	KNITTED SAMPLES	Wpc	Cpc	S	ℓ	k
C	COTTON.L (Blue)	29.9	15.0	448.5	0.16	32.2
P	POLYPROPYLENE	21.3	16.9	360.0	0.29	15.0
N	NOMEX (Ecru)	20.0	17.7	354.0	0.28	13.3
A	ACRYLIC.L (White)	23.6	11.8	278.5	0.20	33.9
PV	PVC (White)	25.2	11.0	277.2	0.19	24.5
CM	COOLMAX (Green)	17.7	15.9	281.4	0.29	16.9
REF.No.	**WOVEN SAMPLES**	**Ends/ cm**	**picks/ cm**			
C(L)	COTTON.L (White)	28.3	28.3			
N(U)	NYLON (White)	40	40			

Table 23. Sample Fabric Properties - Mean values

REF.No.	SAMPLE	MASS g/m^2	THICKNESS (mm)	AIR PERM-EABILITY (mm/sec)
C(L)	COTTON.L (White)	157	0.711	132
N(U)	NYLON (White)	59	0.147	5787
C	COTTON.L (Blue)	193	1.579	654
P	POLYPROPYLENE	205	1.676	855
N	NOMEX (Ecru)	147	0.906	1412
A	ACRYLIC.L (White)	258	1.936	1399

Table 24. Yarn Characteristics - Mean values

Key - C/F = Continuous Filament Yarn count – (Tex)

REF.No.	SAMPLE Woven	YARN COUNT Warp	Weft	C/F or STAPLE
C(L)	COTTON.L (White)	63.7	23.5	Staple
N(U)	NYLON (White)	6.3	9.9	C/F
Knitted Samples				
C	COTTON.L (Blue)		26.6	Staple
P	POLYPROPYLENE		18.9	Staple
N	NOMEX (Ecru)		13.9	Staple
A	ACRYLIC.L (White)		45.9	Staple
PV	PVC (White)		21.6	Staple
CM	COOLMAX (Green)		23.9	Staple

3.6.1.1 Fabric Sample Data - (Experiment 3)

Each fabric used in this research was characterised in general, for each fabric type. However some sub-tests were carried out on a small number of the fabric samples tested.

A few samples were picked out and cpc ; wpc ; ℓ and k measurements were collected from each sample before testing commenced and repeated after testing was completed. The results were compiled as follows :

Table 25. Fabric Geometry properties before and after testing for the weft knitted fabric samples.

Ref. No.	Sample Type	Before wpc	After wpc	Before cpc	After cpc	Before ℓ	After ℓ	Before k	After k
Main knitted test samples									
C	Cotton	29.9	29.1	15.0	12.2	0.16	0.14	32.2	36.8
A	Acrylic	23.6	23.6	11.8	11.8	0.20	0.20	33.9	33.9
P	Polyprop	21.3	21.3	16.9	16.9	0.29	0.29	15.0	15.0
N	Nomex	20.0	19.7	17.7	17.7	0.28	0.28	13.3	13.3
Supplementary knitted samples									
CM	Coolmax	17.7	18.9	15.9	16.3	0.29	0.27	16.9	18.1
PV	PVC.	25.2	25.2	11.0	11.0	0.19	0.19	24.5	24.5

These weft knitted fabric test samples were constructed of two different fabric structures, interlock and 1x1 rib, see figures 55 and 56.

The blue knitted Cotton and Acrylic fabric were constructed of interlock, and the Polypropylene and Nomex fabrics were produced in 1x1 rib.

Fig. 55 **1 x 1 RIB**[79]

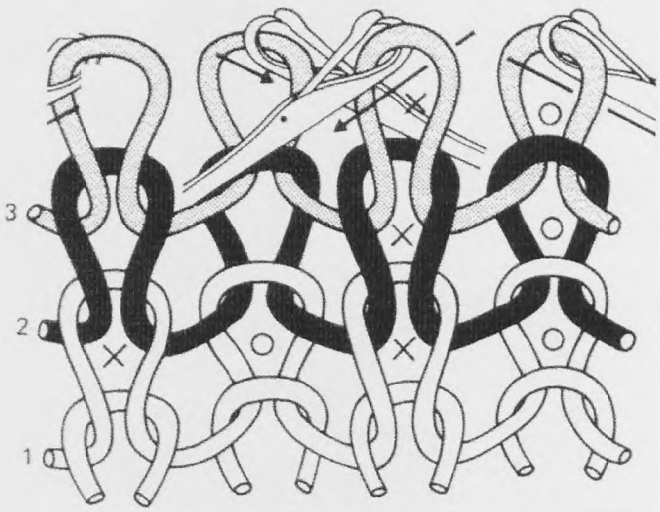
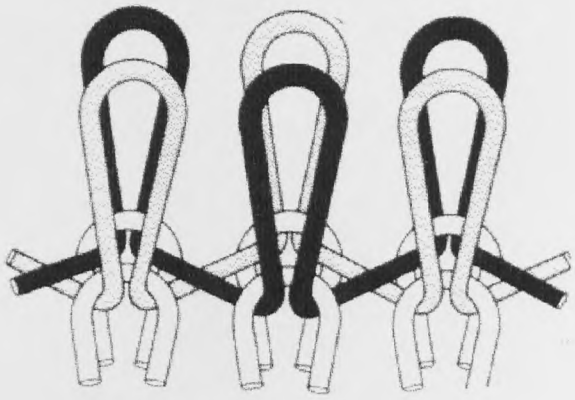


Fig. 56 **INTERLOCK** [79]



CHAPTER 4

4.0 DATA FROM INITIAL EXPERIMENTAL WORK

During the initial experimentation and development of the horizontal static demand wettability technique, various aspects of the wicking process were observed. These were investigated further.

4.0.1 ABSORPTION/WICKING DISTRIBUTION PATTERN

It was noted during the testing of single layer samples observed using the Static wicking equipment, that initial wicking took place in patches, and never over the whole fabric at once. It was first thought that this may be due to some aspect of the test method. Other factors such as, unevenness in the perspex plate, air bubbles beneath the filter paper and skin simulant, or air pockets between the perspex disc and the test sample were also investigated. All these factors were checked as follows:

- The first of these factors, the thickness of the disc was measured over its whole area using a micrometer. This determined that the perspex disk had a very even surface.
- All air bubbles if they were present (so far as they could be observed) were removed from beneath the filter paper and skin simulant.
- Various methods were employed to eliminate the possibility of air pockets between the disc and sample, and reduce the possible effects of any slight variations in the thickness of the perspex disc and fabric samples, which could cause variations in multi-layer pressures.

These were:

(i) Use of a very high loft and open nonwoven fabric as an interface between the top fabric layer and the perspex disc, (this interface allowed trapped air to be diffused out sideways). Wicking tests were carried out, observed and compared with earlier tests.

(ii) Use of a light rubber sheet placed between the perspex disc and top fabric layer. Wicking tests were carried out again and compared.

However both these methods made no real difference to the presence of patches in the test samples, and consequently it was thought that air pockets were unlikely to be a cause of the patchiness in transplanar wicking.

Further analysis was carried out on the production of these patches observed during earlier tests.

Single and multi-layer samples were tested on the static demand wettability equipment and the sequences of absorption patterns observed were recorded ; test conditions used were under different compressional weights of ; $0.66g/cm^2$; $1.0g/cm^2$; and $2.0g/cm^2$, and at a pressure head height of 2.0cm.

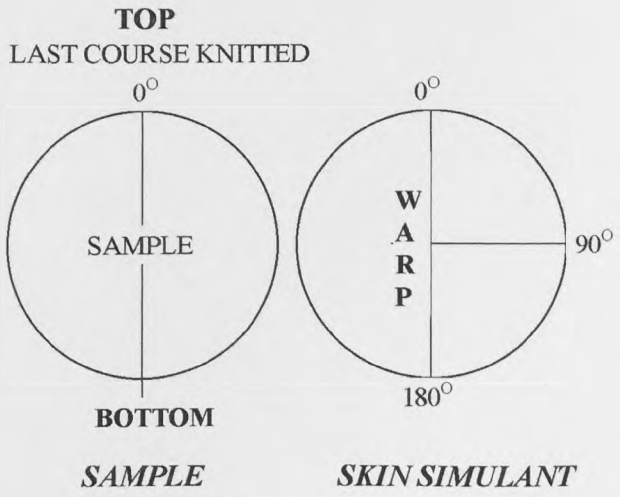
In the multi-layer tests the warps of each sample were aligned with the warp of the skin simulant, and were changed from 0° (aligned : warp to warp ; top to top ; bottom to bottom) to 90° or 180°.

The test method for analysis of the pattern sequence of absorption was as follows :-

- In the multi-layer tests , assemblies of blue weft knitted cotton, were used.
  [A fabric dyed blue was used to aid visual observation of the wicking process; the fabric had been washed prior to the tests to remove all finishes from the fabric.]

Assemblies were collated so that all layers were aligned to 0° with the skin simulant. Figure 57 illustrates how the samples were aligned with the skin simulant. Aligning the top of the sample with the top of the skin simulant which represents 0°.

Fig. 57



- The assembly was then put on the skin simulant with the Perspex disc placed on top with additional weights when necessary for a time period of 1minute.
- The samples were then removed and the pattern of absorption on each layer was recorded on a diagram.
- This was repeated several times under different weights with the samples aligned to different angles.

4.0.2 EXPERIMENTS ON MULTI-LAYER ASSEMBLIES

A second set of experiments was carried out as above using 2-layer assemblies. These results were also recorded as diagrams , see Figures 61 and 62.

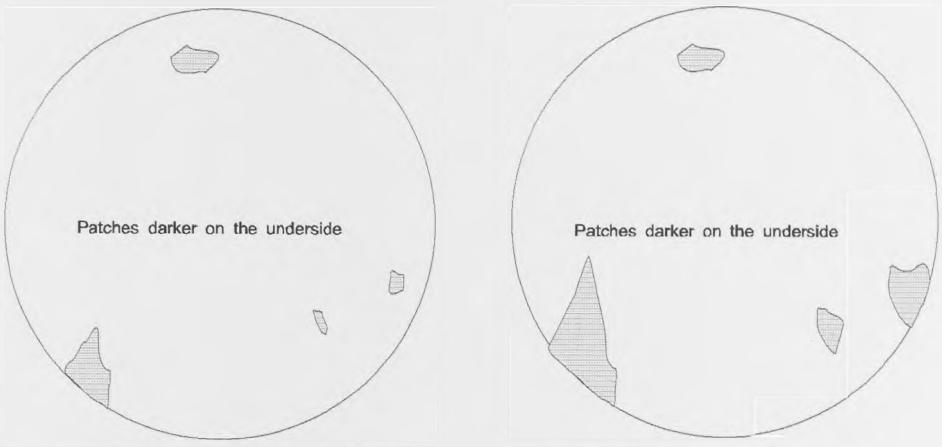
From the analysis of the diagrams it became clear almost immediately that in the multi-layer assemblies wicking from the first layer to subsequent layers took place before the first layer was completely wetted. Initial wetting took place in small patches and expanded horizontally outwards, and this happened in every case.

Figures 58 to 62 represent approximate time-lapse representations of the liquid distribution within the test samples, in single and double layer assemblies under different compression weights.

Fig. 58 **Horizontal Static transplanar wicking test**

SINGLE LAYERS

Compressional weight applied = 0.0g/cm²



APPEARANCE AFTER 15 SECONDS

APPEARANCE AFTER 30 SECONDS

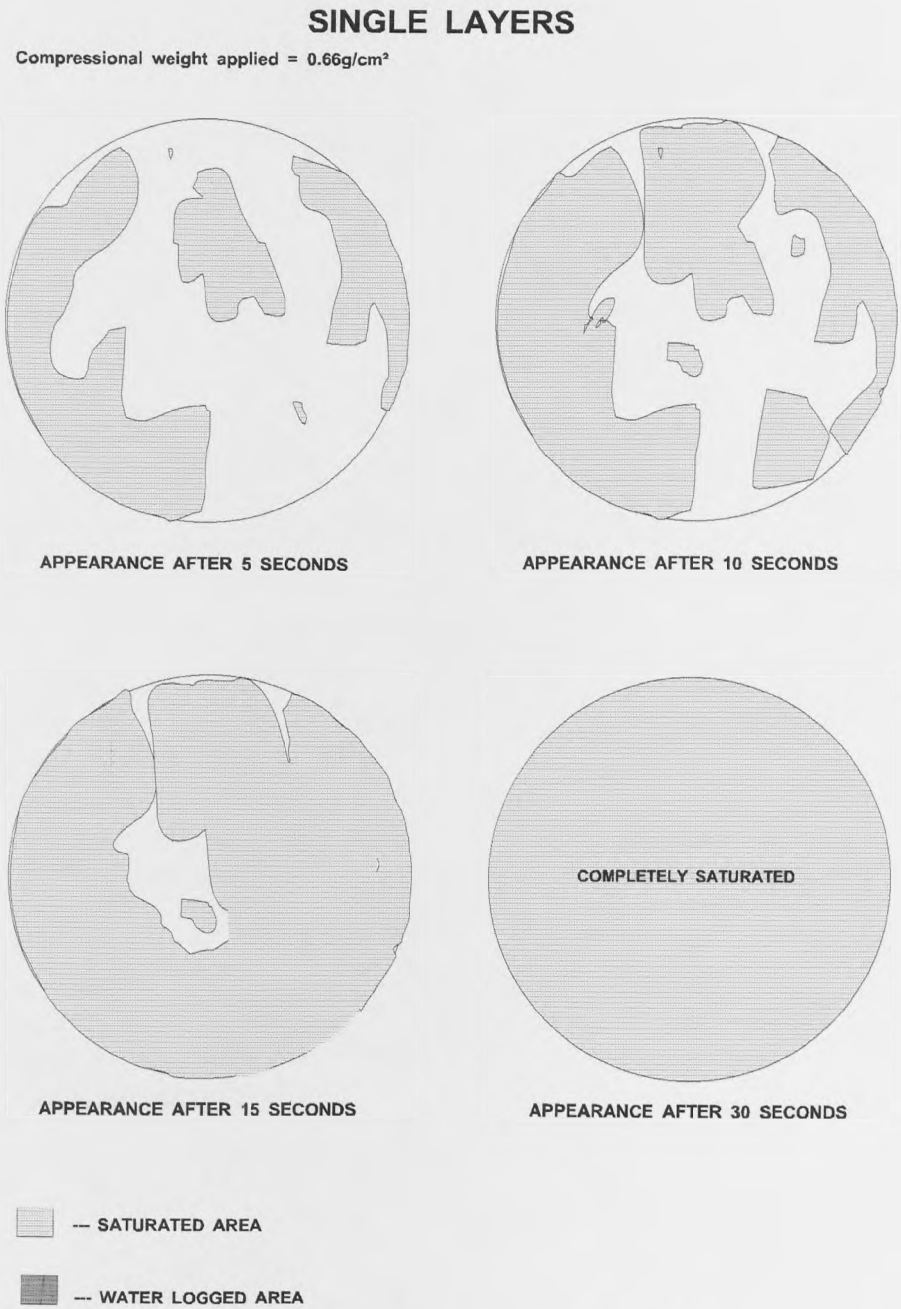
--- SATURATED AREA

--- WATER LOGGED AREA

Test samples - blue weft knitted Cotton fabric.

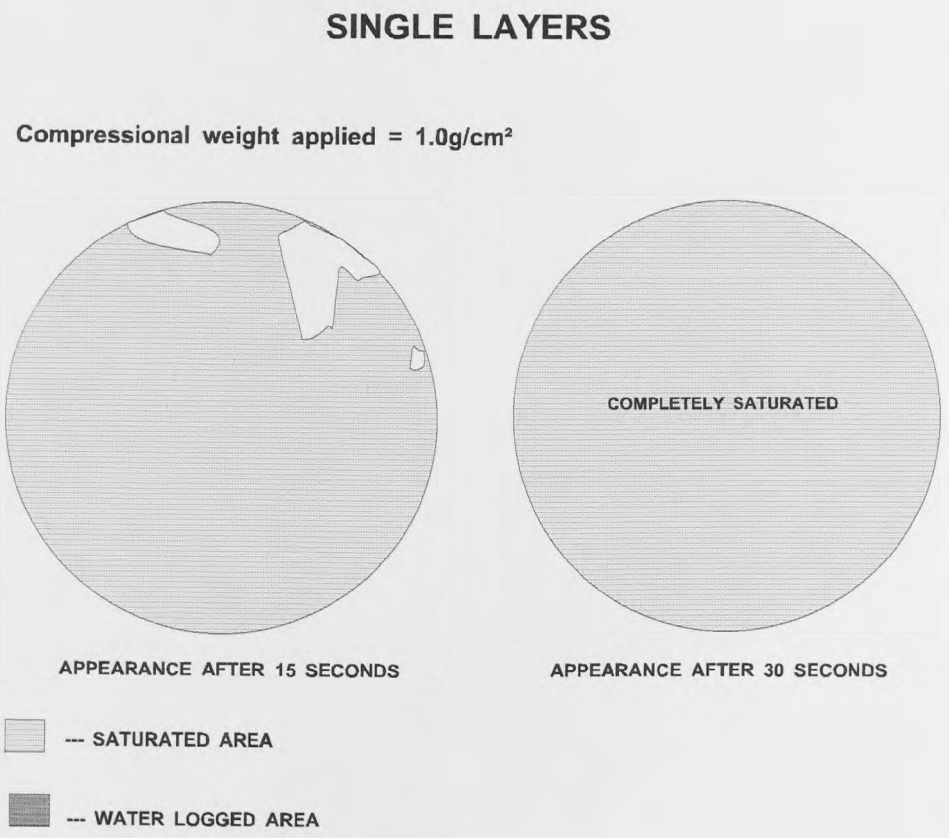
Figure 59 represents a single layer sample broken down into smaller time segments under a compressional weight of 0.66g/cm^2.

Fig. 59 Horizontal Static transplanar wicking test – absorption patterns



Test samples - blue weft knitted Cotton fabric.

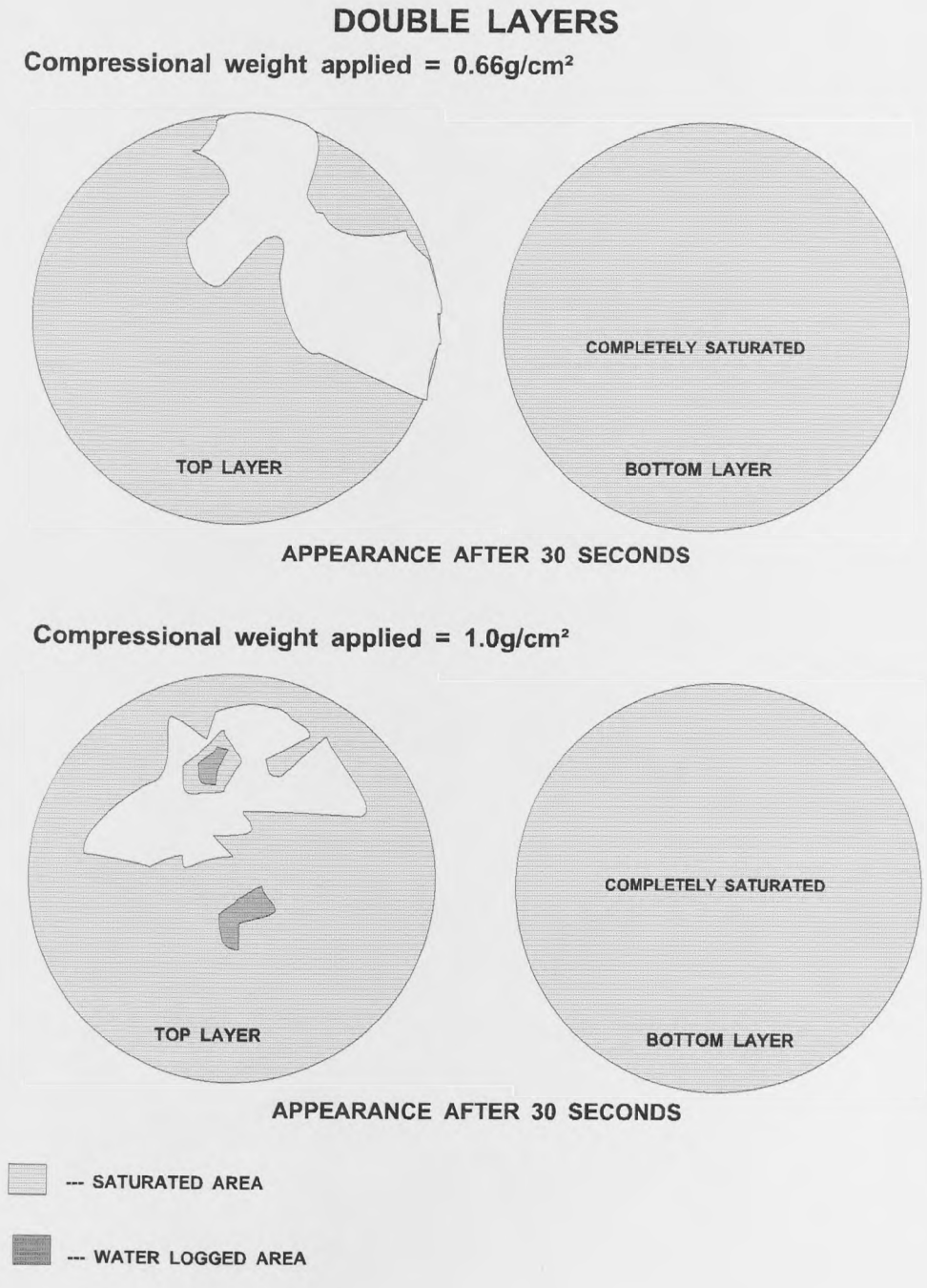
Fig. 60 Horizontal Static transplanar wicking test – absorption patterns



Test samples - blue weft knitted Cotton fabric.

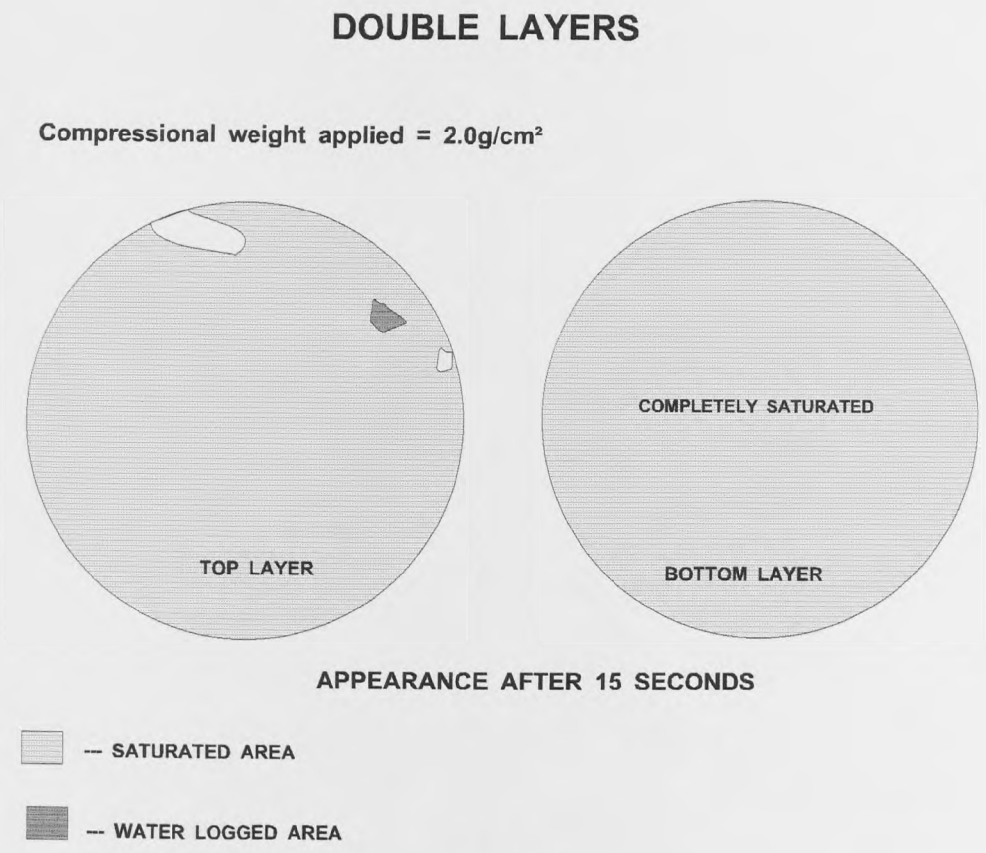
The following figures represent results from the double layer experiments.

Fig. 61 Horizontal Static transplanar wicking test – absorption patterns



Test samples - blue weft knitted Cotton fabric.

Fig. 62 Horizontal Static transplanar wicking test – absorption patterns



Test samples - blue weft knitted Cotton fabric.

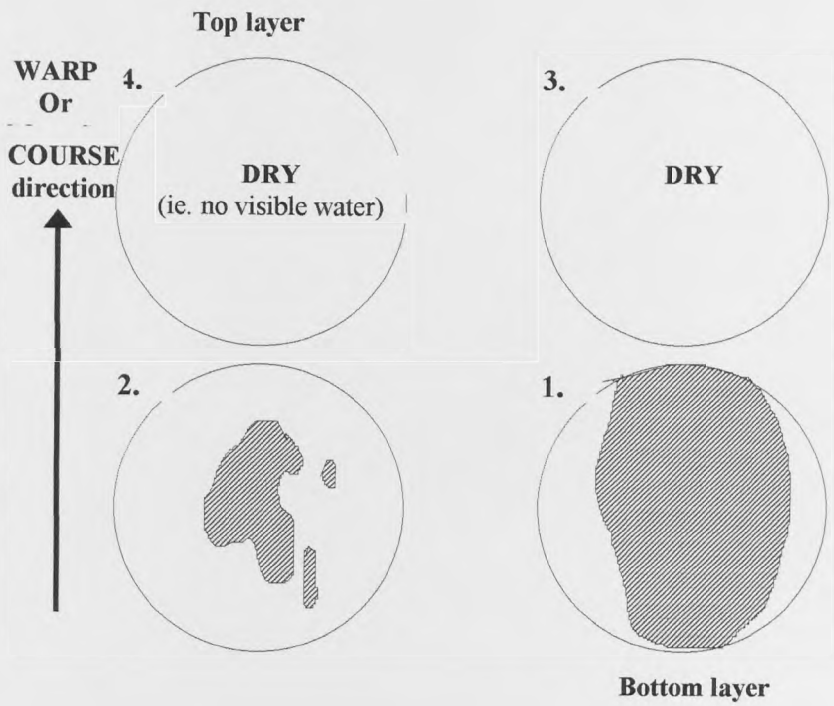
As a means of determining whether wicking is dominant in any particular direction, experiments were carried out as above with the addition of a film of plastic as an interface, placed between the skin simulant and the first layer of the test assembly.

The interface was a plastic sheet cut to the same size as the test samples with a hole of 3cm in diameter cut in the centre. This would allow the contact area to be reduced to one small area of the test sample and slow down the overall absorption rate. The direction of the planar wicking in the fabrics could be easily observed, and transplanar wicking would be concentrated at one point. Tests were carried out using 4-layer assemblies.

Typical results were as follows.

Fig. 63 **Horizontal Static transplanar wicking test – absorption patterns in multi-layer assemblies for test samples - blue weft knitted Cotton fabric.**

		(Top - Bottom)
Test sample Nos.	=	4 - 1
Weight applied	=	0.66 g/cm^2
Pressure head /H	=	2.0cm
N.B	=	Test using plastic film interface (A)
Alignment	=	0°
Time	=	1 min



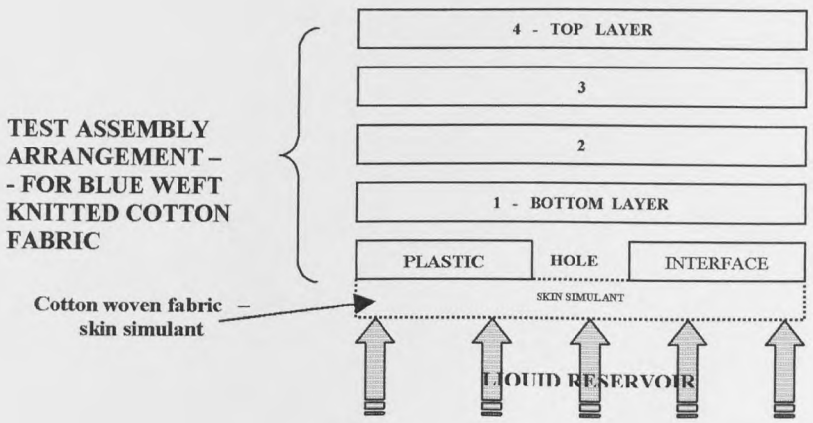
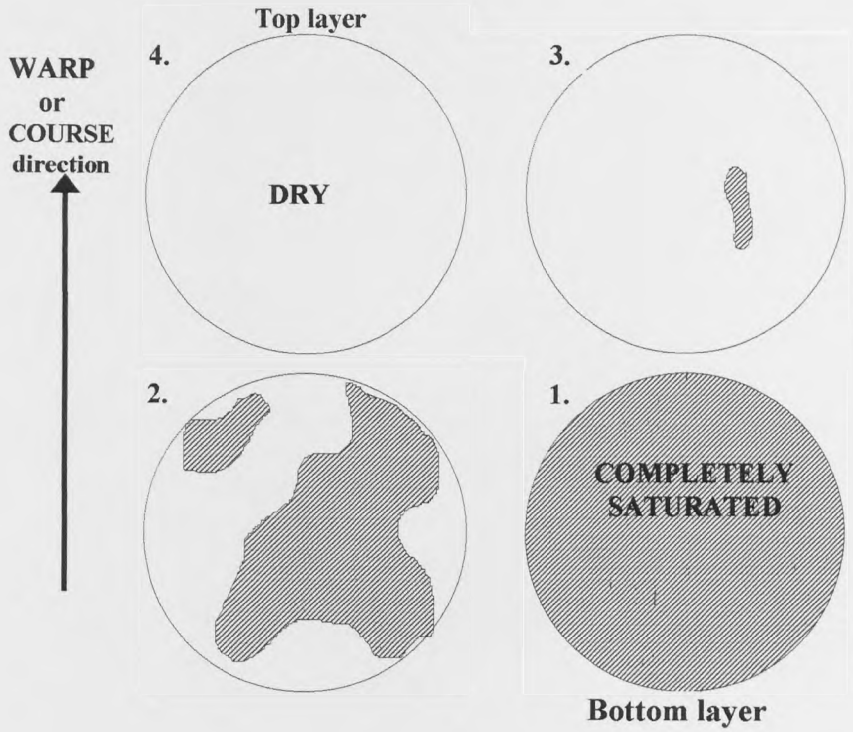


Fig. 64 **Horizontal Static transplanar wicking test – absorption patterns in multi-layer assemblies for test samples - blue weft knitted Cotton fabric.**

		(Top - Bottom)	
Test sample Nos.	=	4 - 1	
Weight applied	=	0.66 g/cm^2	
Pressure head/H	=	2.0cm	
N.B	=	No interface	**Alignment = 0°**
Time	=	1 min	



In all cases the planar wicking rate was quicker in the course direction than in the wale direction , no matter how small the wet patch. Once again layers 2 and 3 began wicking to the next layers before themselves becoming completely wetted. It was thought that the reason for the dominant direction of wicking in these last tests was due mainly to fabric structure, (this is supported by previous work on wicking carried out at BTTG on a research project)[87]. It was also noted that by decreasing the area available for transplanar wicking, the wicking process was almost totally controlled by planar wicking, the rate of which hardly appeared to be reduced.

Changes in the initial alignment of different fabric layers in the test produced slight differences in the wicking rate but these were extremely small for any specific fabric combination.

As described in section 4.0.1, the first visible appearance of water in the test layers took place in several small patches scattered around the test sample , and with progression of time these spread in area and more patches appeared. Taking into account these observations another set of experiments were carried out. Using the same technique (static demand wettability) as before , single layers were left to wick for a time period of 15 minutes with no perspex disc on top in the first set of experiments, and with the perspex disc in the second set of experiments.
This produced samples containing patches of visible moisture. The samples were then removed and the areas of wet patches and visibly dry patches were cut from the sample and weighed.
The wet and dry patches were then left to dry for 24 hours and re-weighed. The dry patches in most cases were obtained from areas as close to wet patches as possible, and in some cases almost adjacent to a wet patch. This procedure was repeated for the 2-layer assemblies. These experiments were carried out on the blue weft knitted cotton only. The results obtained are illustrated in Tables 26 to 29.

The results showed that in general the wet areas(patches) contained large amounts of water, and the dry patches remained in general dry, or liquid water-free, even in areas almost adjacent to a wet patch. This indicated that the wicking process in these wet patches occurred by transplanar wicking, spreading side-ways by planar wicking through the fabric system. Wicking was therefore not occurring universally over the whole sample area, transporting liquid upwards towards the top of the sample.
Further horizontal transplanar wicking tests were carried out on single layers using additional time intervals of 10 ; 20 ; 25 ; 30 ; and 35 minutes, either applying $0.66g/cm^2$ weight or applying no weight. Examination of the wet and dry areas occurring during the horizontal wicking tests was carried out. Horizontal wicking was allowed to occur for the various set time periods and the samples are removed. A wet patch or area was cut from the sample, and the dry area immediately next to it was also removed and the weights recorded.

The liquid content for both sub-samples at the time of removal from the horizontal wicking apparatus was then calculated.

The same experiment was conducted on double layer samples, and these gave similar results to that of the single layer tests, in that there were small areas or patches of high water content next to dry or almost dry areas, (see tables 28 and 29). This would determine the liquid content at the time of removal for these isolated pockets of saturation.

Single Layers

Table 26 Horizontal static demand wettability test – Water content in wet areas only after 15 minutes.

Weft Knitted Blue COTTON Fabric Samples

Single - Layer Assemblies

-VE P/H = 2cm

Weight applied = 0.66g/cm²

Alignment = 0°

TEST TIME = 15min

SAMPLE No.4	CONDITION	WT. AT TIME (g)	DRY WT.	% H_2O
PIECES - A	WET	0.235	0.097	142.3
PIECES – B	WET	0.235	0.097	142.3
PIECES – C	DRY	0.061	0.060	1.7
PIECES – D	DRY	0.110	0.110	0.0
SAMPLE No.3	**CONDITION**	**WT. AT TIME (g)**	**DRY WT.**	**% H_2O**
PIECES - A	WET	0.960	0.307	212.7
PIECES - B	MED.WET	0.270	0.111	143.2
PIECES - C	DRY	0.150	0.150	0.0
SAMPLE No.5	**CONDITION**	**WT. AT TIME (g)**	**DRY WT.**	**% H_2O**
PIECES - A	WET	0.420	0.121	247.1
PIECES - B	WET	0.362	0.106	241.5
PIECES - C	DRY	0.054	0.054	0.0

Table 27 Horizontal static demand wettability test – Water content in wet areas only after 35 minutes

Weft Knitted Blue COTTON Fabric Samples

Single - Layer Assemblies

-VE P/H = 2cm

Weight applied = 0.00g/cm²

Alignment = 0°

TEST TIME =35min

SAMPLE No.1	CONDITION	WT. AT TIME (g)	DRY WT.	% H_2O
PIECES - A	WET	0.160	0.090	77.8
PIECES - B	DRY	0.192	0.192	0.0
SAMPLE No.2	**CONDITION**	**WT. AT TIME (g)**	**DRY WT.**	**% H_2O**
PIECES - A	WET	0.067	0.033	103.0
PIECES - B	WET	0.030	0.017	76.5
PIECES - C	DRY	0.116	0.115	0.9
PIECES - D	DRY	0.095	0.095	0.0
PIECES - C	DRY	0.054	0.054	0.0

Double Layers

Table 28 Horizontal static demand wettability test – Water content in wet areas only

Weft Knitted Blue COTTON Fabric Samples

Double – Layer Assemblies

-VE P/H = 2cm

Weight applied = 0.66g/cm²

Alignment = 0°

C/S = Complete saturation

TEST TIME = 15 min				
SAMPLE No. 20	**CONDITION**	**WT. AT TIME (g)**	**DRY WT.**	**% H_2O**
PIECE - A	C/S	4.015	1.247	***222.0***
SAMPLE No.19				
PIECE - A	WET	0.047	0.023	***104.3***
PIECE - B	DRY	0.060	0.060	***0.0***
TEST TIME = 10 min				
SAMPLE No. 9	**CONDITION**	**WT. AT TIME (g)**	**DRY WT.**	**% H_2O**
PIECE - A	C/S	4.712	1.194	***294.6***
SAMPLE No. 10				
PIECE - A	WET	1.213	0.435	***178.9***
PIECE - B	WET	1.391	0.490	***183.9***
PIECE - C	DRY	0.051	0.050	***2.0***

Table 29 Horizontal static demand wettability test – Water content in wet areas only

Weft Knitted Blue COTTON Fabric Samples

Double - Layer Assemblies

-VE P/H = 2cm

Weight applied = 0.66g/cm²

Alignment = 0°

C/S = Complete saturation

TEST TIME = 30 min				
SAMPLE No.14	**CONDITION**	**WT. AT TIME (g)**	**DRY WT.**	**% H_2O**
PIECE - A	C/S	5.495	1.195	***359.8***
SAMPLE No.13				
PIECE - A	WET	0.197	0.089	***121.3***
PIECE - B	WET	0.172	0.084	***104.8***
PIECE - C	DRY	0.095	0.095	***0.0***
PIECE - D	DRY	0.068	0.068	***0.0***
TEST TIME = 25 min				
SAMPLE No.6	**CONDITION**	**WT. AT TIME**	**DRY WT.**	**% H_2O**
PIECE - A	C/S	5.43	1.175	***362.1***
SAMPLE No.8				
PIECE -A	WET	0.929	0.293	***217.1***
PIECE - B	WET	0.828	0.244	***239.3***
PIECE - C	DRY	0.089	0.089	***0.0***

TEST TIME = 20 min				
SAMPLE No. 12	**CONDITION**	**WT. AT TIME**	**DRY WT.**	**% H_2O**
PIECE - A	C/S	5.462	1.247	***338.0***
SAMPLE No.11				
PIECE - A	WET	0.395	0.149	***165.1***
PIECE - B	WET	0.07	0.034	***105.9***
PIECE - C	DRY	0.147	0.147	***0.0***
PIECE - D	DRY	0.137	0.137	***0.0***

4.0.3 HORIZONTAL TRANSPLANAR WICKING POINTS (CONTACT POINTS)

Analysis of these experiments gave rise to the hypothesis that horizontal transplanar wicking initially only took place at specific contact points on a fabric sample. If transplanar wicking occurs through the 'Contact points' between fabric layers it would follow that the nature and number of interfabric contact points may differ according to the individual fabric structures, the relative orientation of the fabrics, and the localised contact pressures.

The next series of experiments established that each fabric layer consisted of a series of possible contact points on both sides of a sample. However horizontal transplanar wicking would only take place at these contact points, provided that these approached saturation with liquid i.e. 'water-logged' and were therefore ready and able to transfer some of the saturation liquid to the layer above, thus facilitating the transfer of the liquid from one layer to the next.

A small experiment was devised to capture and record the possible contact points on a fabric sample between the sample and the skin simulant; this is described in section 3.4.

Repeats of these tests on fabric samples proved that the exact reproduction of interfabric contact points in subsequent tests was not always possible. Each test produced a new set of interfabric contact points, and hence a new set of horizontal transplanar wicking points was observed.

It is clear that the greater the number of initial interfabric contact points (and hence transplanar wicking points) in the test the quicker a fabric sample would absorb and transfer liquid to subsequent layers by horizontal transplanar wicking.

If there are no interfabric contact points initially, it is considered that no horizontal transplanar wicking would take place until the whole of the initial fabric layer is saturated with liquid. At that point horizontal transplanar wicking should probably occur more simultaneously across the whole of the test specimen. Thus horizontal transplanar wicking would take place from fabric to fabric only if :

(a) suitable interfabric contact points exist initially, and

(b) enough water is present in the first fabric (inter-yarn water, i.e. contact points are waterlogged) to effect horizontal transplanar wicking.

A variation in the number and position of these interfabric contact points is considered to be the main reason for the experimental variations in the wicking rates observed in the initial demand wettability tests. Because these variations are extremely difficult to eliminate in all but the most uniform and regular of fabric structures, variation in the wicking rate in horizontal wicking tests are an inherent factor affecting the transplanar wicking rate.

Many factors may influence the presence and variety of contact points between fabrics, some of which can be related to the factors which also influence abrasion and wear resistance in a fabric.

It therefore follows that factors that alter the nature of the fabric structure, in particular the surface nature of the fabrics should demonstrate marked changes in horizontal transplanar wicking rates because of the changes in the nature of interfabric contact points

Some of the factors which may influence the presence of contact points are :

(1) Local pressures or stress concentrations developing on specific yarn points or areas (i.e., the true area of contact)

(2) Geometric area of contact between fabric and fabric

(3) Threads per cm / courses/cm and wales/cm

(4) Crown height (i.e. The extent of deformations out of the plane of the fabric resulting from the intersection of warp and weft yarns)

(5) Yarn linear density

(6) Yarn crimp

(7) Float length / stitch length

(8) Yarn cohesiveness

(9) Fabric tightness / stitch density

(10)Cover factor / tightness factor

These factors have been discussed fully by Backer and Tanenhaus[58] and Kaswell[75] in relation to abrasion and wear resistance in woven fabrics,. But with some minor changes also apply to knitted fabrics.

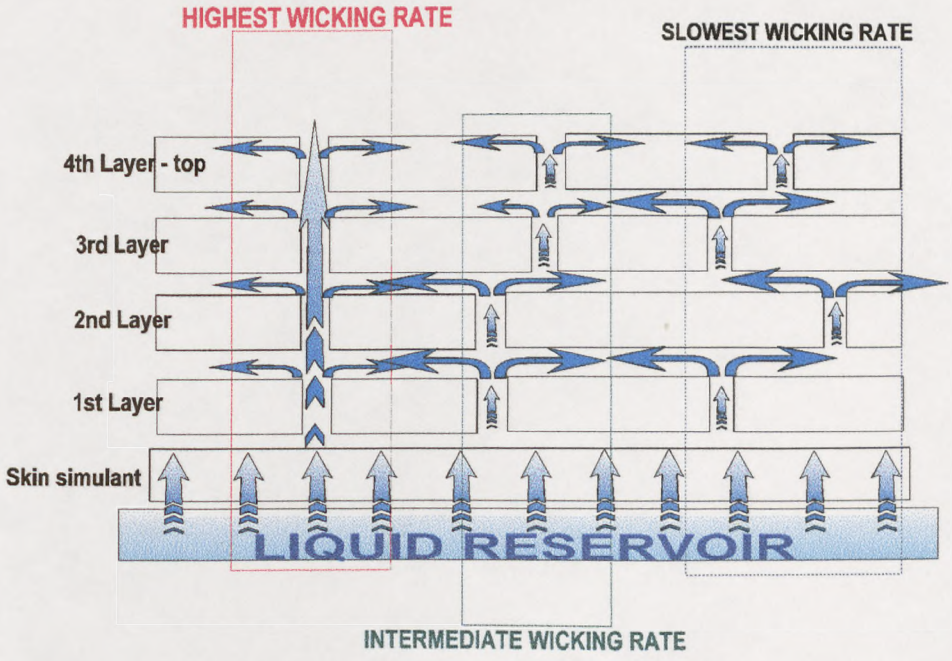
4.0.4 WICKING THEORY

The presence of numerous prominent areas i.e. the crowns of a woven fabric and the heads of the loops in a knitted fabric would be the most likely type of contact point to facilitate horizontal transplanar wicking.

The bottom layer once completely saturated holds water in all areas including all the contact points on the upper surface of the saturated sample. Once these come in contact with the next layer, creating the correct type of capillary channels, water can be transferred to the next fabric layer. Planar wicking will take place next, and the contact points on the lower side of the next layer also take on water upwards and sideways (planar). This process continues through each layer.

The speed at which horizontal transplanar wicking through various fabric layers will occur will depends on a series of three general levels of interfabric contact points. The speed at which transplanar wicking will occur through a multi-layer assembly will depend on the amount of horizontal planar wicking that needs to occur before coming in contact with another good interfabric contact with the next layer. An illustration of this process can be seen in figure 65.

Fig. 65 Representation of the three levels of inter-fabric contact sequences



The highest possible wicking rate shows the best possible sequence of contiguous interfabric contact points necessary for the highest level of liquid transport through multi-layer fabric systems. This level of transmission is mainly controlled by horizontal transplanar wicking.

The medium wicking rates will be made up of a series of good and not so good, or good and bad inter-fabric contacts, relying on both horizontal planar and transplanar wicking, but with transplanar wicking as the predominant process.

The lowest wicking rates are controlled mainly by horizontal planar wicking with transmission to subsequent layers only occurring at good interfabric contact points. This may result in the preceding lower fabric layers becoming almost completely saturated before transferring liquid to the next fabric layer.

The liquid transmission sequence through a multi-layer fabric system will be made up of a complex combination of these three types of inter-fabric contact points.

4.1 RESULTS FROM EQUIPMENT AND METHODOLOGY DEVELOPMENT

4.1.1 STATIC DEMAND WETTABILITY METHOD

It was during initial development of the methodology that testing was carried out on the reproducibility of the technique. Tests were carried out on Acrylic, Nomex and Polypropylene fabric samples.

Tables 30 – 32 and Figures 66 – 68 illustrates results obtained from reproducibility tests performed on these 3 fabric samples. Repeat tests on these fabrics produced coefficient of variation percentages (cv%) which were still high, although lower than the results from early testing. However a repeating pattern was observed, a high initial cv% in the first minute decreasing at each time interval. The variability could not be eliminated, as explained in section 4.0.3, although the amount of variation produced seemed to depend on the fabric/fibre type. Therefore the cv% for the acrylic, Nomex and polypropylene samples were fairly high but as expected on the basis of previous experiments, with the polypropylene fabric producing extremely high cv%. As illustrated by figure 67 the Acrylic sample produced the lowest variation at the end of the tests giving an end cv% of 7.2%.

Table 30

MEAN DEMAND WETTABILITY TEST RESULTS

NOMEX SAMPLE - 1x1 Rib fabric
(non-drying tests)
COMPRESSION WEIGHT = 0.66g/cm
-VE P/H = 2.0 cm

SAMPLES	WATER CONTENT/MIN (%)				
	0	1	3	10	20
NOMEX -1	0	5.70	13.68	27.14	42.19
NOMEX -2	0	6.61	16.06	31.21	46.70
NOMEX -N1	0	6.38	14.81	30.30	44.76
NOMEX -N2	0	7.87	14.60	38.54	48.46
Mean =	0	6.64	14.79	31.80	45.53
stdev =		0.91	0.98	4.82	2.69
cv% =		**13.6**	**6.6**	**15.2**	**5.9**

Table 31

MEAN DEMAND WETTABILITY TEST RESULTS

ACRYLIC SAMPLE - Interlock fabric
(non-drying tests) water pH = 7.0
COMPRESSION WEIGHT = 0.66g/cm
-VE P/H = 2.0 cm

SAMPLE	WATER CONTENT/MIN (%)				
	0	1	3	10	20
ACRYLIC -1	0	12.04	45.03	142.80	199.44
ACRYLIC -2	0	7.50	39.34	145.72	204.34
ACRYLIC -3	0	22.32	71.15	152.79	203.94
ACRYLIC -4	0	23.07	55.86	168.14	231.72
ACRYLIC -5	0	27.28	66.69	140.56	192.59
Mean =		18.44	55.61	150.00	206.41
stdev =		8.295	13.612	11.135	14.919
cv% =		44.98	24.48	7.42	7.23

Table 32

MEAN DEMAND WETTABILITY TEST RESULTS

POLYPROPYLENE SAMPLE - 1x1 Rib fabric
(non-drying tests) water pH = 7.0
COMPRESSION WEIGHT = 0.66g/cm^2
-VE P/H = 2.0 cm

SAMPLES	WATER CONTENT/MIN (%)				
	0	1	3	10	20
POLYPROP - 1	0	1.24	3.58	12.61	28.53
POLYPROP - 2	0	1.97	6.38	24.30	55.50
POLYPROP - 3	0	0.63	1.76	4.78	9.28
POLYPROP - 4	0	0.38	0.88	7.32	27.40
POLYPROP - 5	0	0.20	0.41	0.76	1.32
Mean		0.88	2.6	9.96	24.41
Std		0.72	2.43	9.10	20.95
CV%		**81.7**	**93.6**	**91.4**	**85.8**

Fig. 66

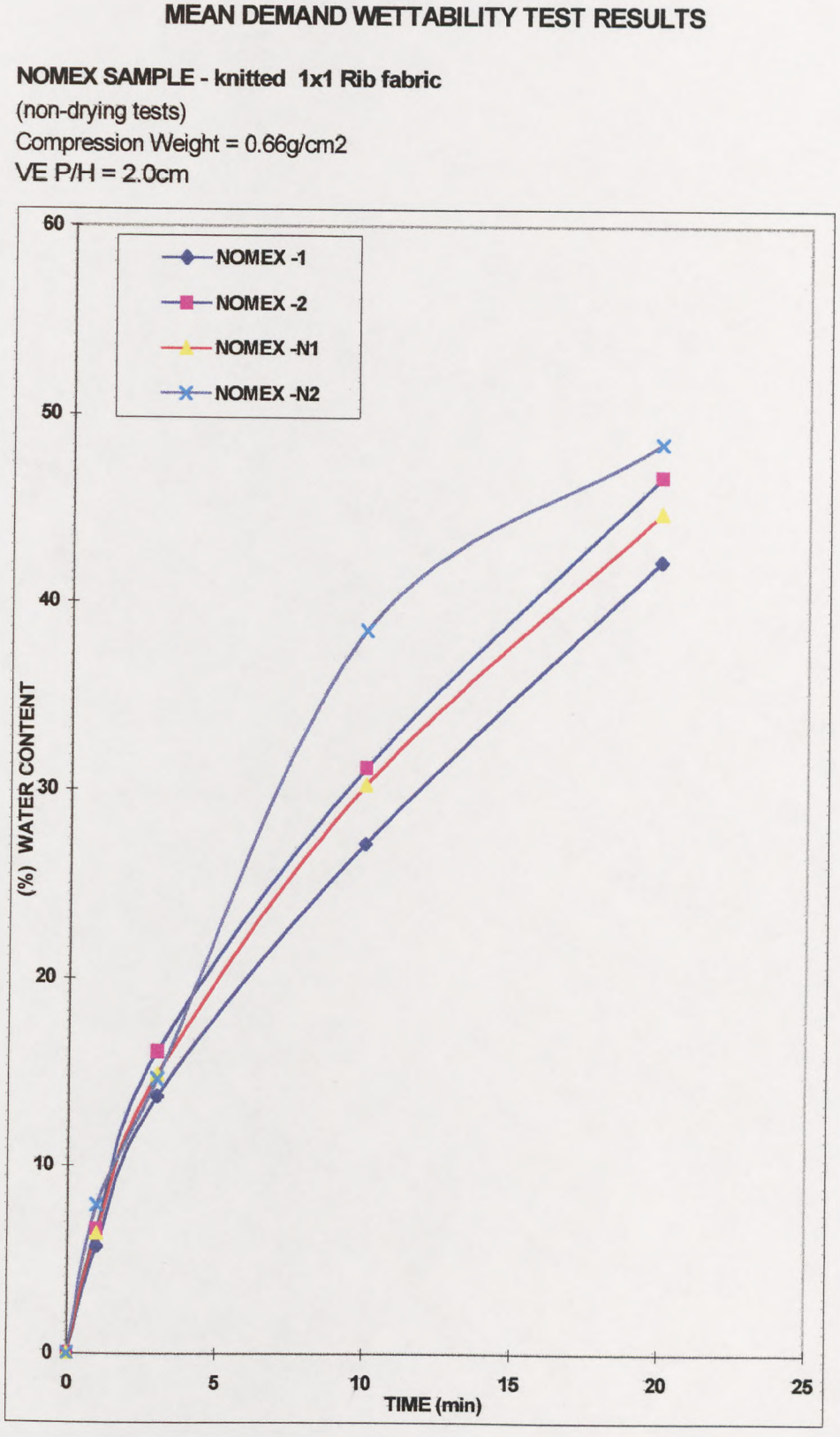

MEAN DEMAND WETTABILITY TEST RESULTS
NOMEX SAMPLE - knitted 1x1 Rib fabric
(non-drying tests)
Compression Weight = 0.66g/cm2
VE P/H = 2.0cm
NOMEX -1
NOMEX -2
NOMEX -N1
NOMEX -N2
(%) WATER CONTENT
TIME (min)
0
10
20
30
40
50
60
0
5
10
15
20
25

Fig. 67

MEAN DEMAND WETTABILITY TEST RESULTS

ACRYLIC SAMPLE - knitted Interlock fabric
(non-drying tests)
Compression Weight = 0.66g/cm^2
VE P/H = 2.0cm

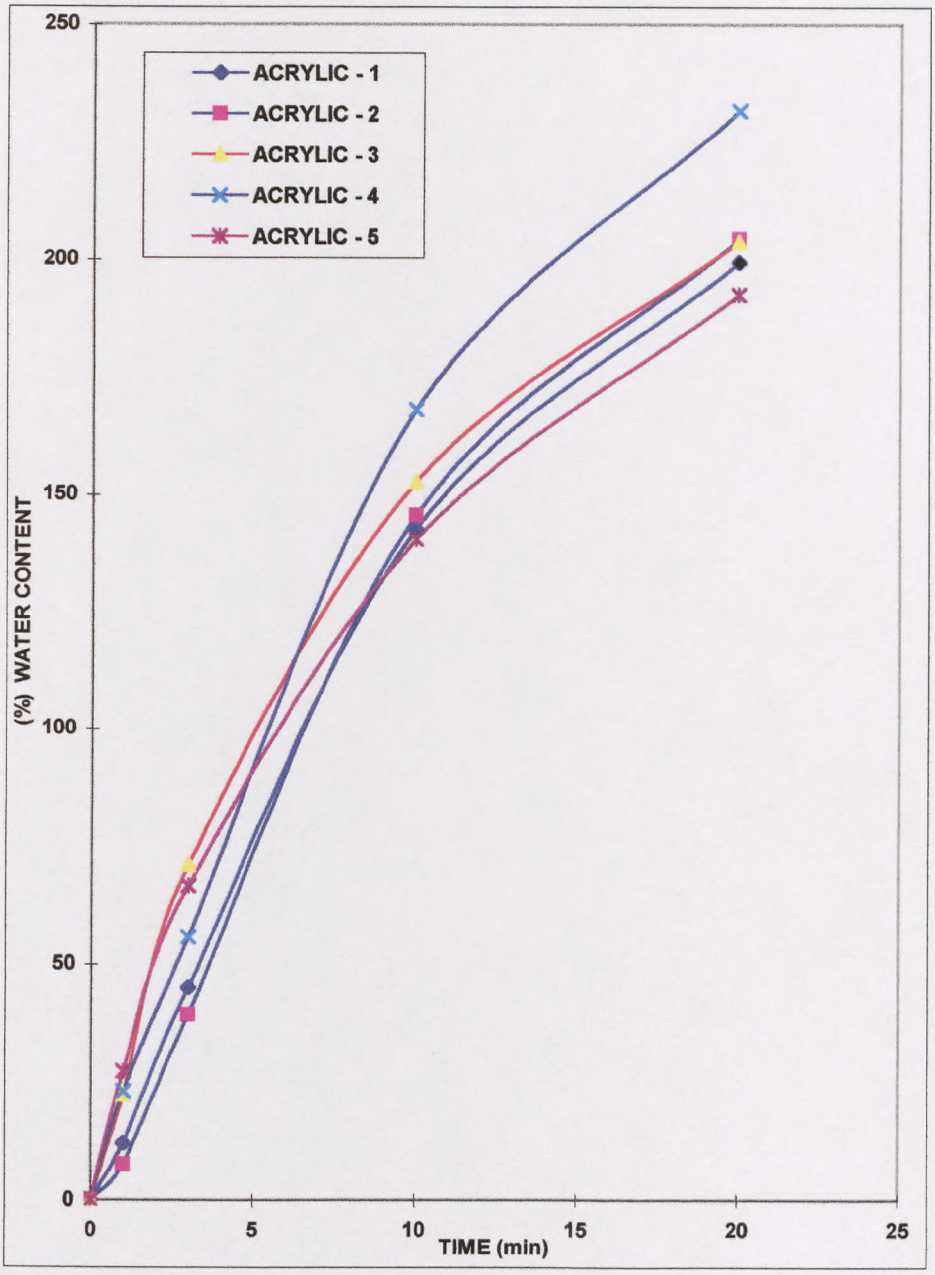
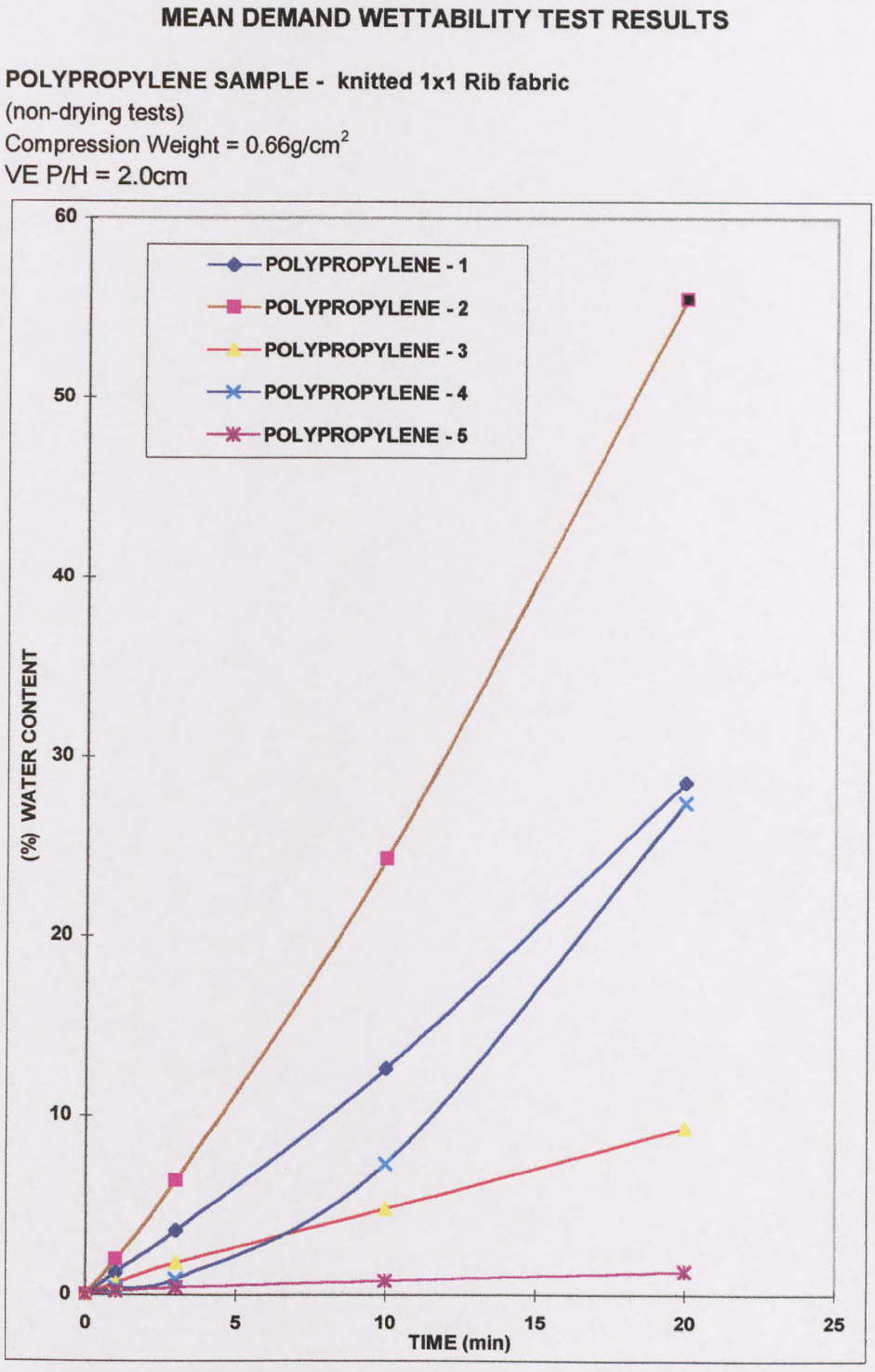


Fig. 68


MEAN DEMAND WETTABILITY TEST RESULTS
POLYPROPYLENE SAMPLE - knitted 1x1 Rib fabric
(non-drying tests)
Compression Weight = 0.66g/cm2
VE P/H = 2.0cm
POLYPROPYLENE - 1
POLYPROPYLENE - 2
POLYPROPYLENE - 3
POLYPROPYLENE - 4
POLYPROPYLENE - 5
(%) WATER CONTENT
TIME (min)
0
10
20
30
40
50
60
0
5
10
15
20
25

4.1.2 DYNAMIC DEMAND WETTABLILITY METHOD

A series of tests were carried out to determine the most effective time interval for the dynamic wettability tests. The initial intervals used were 1 minute intervals as initially used in the static wettability tests. However as determined by the static tests a longer time interval was thought necessary. Therefore 5 minute intervals were also used, and compared with 1 minute interval tests. The results can be seen in Tables 33 to 35 , and Figures 69 and 71.

Three fabrics were chosen for these tests, Nomex, Acrylic and Coolmax (PET), and the tests were performed in the static state.

The Nomex produced the lowest water uptake, and both time intervals produced similar water uptake values at 5 minute and 10 minute time intervals. The increased number of breaks between wicking in 1 minute tests seems to have produced only a slight increase in water uptake.

However this is not the case with the acrylic samples. The 1 minute time intervals in the acrylic samples have a much higher water uptake than the 5 minute intervals. As suggested earlier the ability to wick liquid from one layer to the next is highly dependent on the surface contacts of one layer with the other. It would appear that the ability to establish a number of good inter-fabric contacts is increased because of the frequent fabric removal and return in the 1 minute time interval tests. A possible 5 chances in the first 5 minutes of the 1 minute test, and only 2 chances in the 5 minute test. However this is not always the case as the results from both the Nomex and Coolmax samples have shown. This could be the result of different fibre types reacting to the different time intervals. Because wicking once started is an almost continuous process, it was thought that longer time periods with fewer interruptions would be better for observation of the wicking process. However this does not appear to be always the case, but in general both time intervals appear to follow similar rates of liquid uptake. However it was considered that the disruption of the wicking process and the continued reassembling of the sample assemblies may generate a greater number of fabric contact points, which may accelerate the rate of wicking. Also there was a need to simulate as near as possible the two types of possible contacts occurring between layers i.e. intermittent and steady state contacts , and this resulted in the use of the 5 minute time interval.

Table 33

DYNAMIC DEMAND WETTABILITY TECHNIQUE
STATIC TEST

NOMEX

interval	PERCENTAGE WATER CONTENT														
	0	1	2	3	4	5	6	7	8	9	10	15	20	25	30
1 min	0	0.59	0.79	0.99	1.12	1.18	1.18	1.45	1.51	1.64	1.64				
5 min	0					0.95					1.38	1.60	1.94	2.07	2.24

Table 32

DYNAMIC DEMAND WETTABILITY TECHNIQUE
STATIC TEST

ACRYLIC

interval	PERCENTAGE WATER CONTENT														
	0	1	2	3	4	5	6	7	8	9	10	15	20	25	30
1 min	0	41.06	70.1	88.02	109.1	123.36	133.96	141.75	147.47	151.38	153.72				
5 min	0					18.98					25.85	31.05	35.6	37.26	38.44

Table 35

DYNAMIC DEMAND WETTABILITY TECHNIQUE
STATIC TEST

COOLMAX

interval	PERCENTAGE WATER CONTENT														
	0	1	2	3	4	5	6	7	8	9	10	15	20	25	30
1 min	0	0.48	0.75	2.82	9.57	12.51	12.56	13.63	14.48	14.69	15.17				
5 min	0					3.79					9.83	17.11	24.91	35.23	45.52

Fig. 69 Comparison of time intervals 1 minute and 5 minutes on Nomex fabric using the Dynamic Demand Wettability technique.

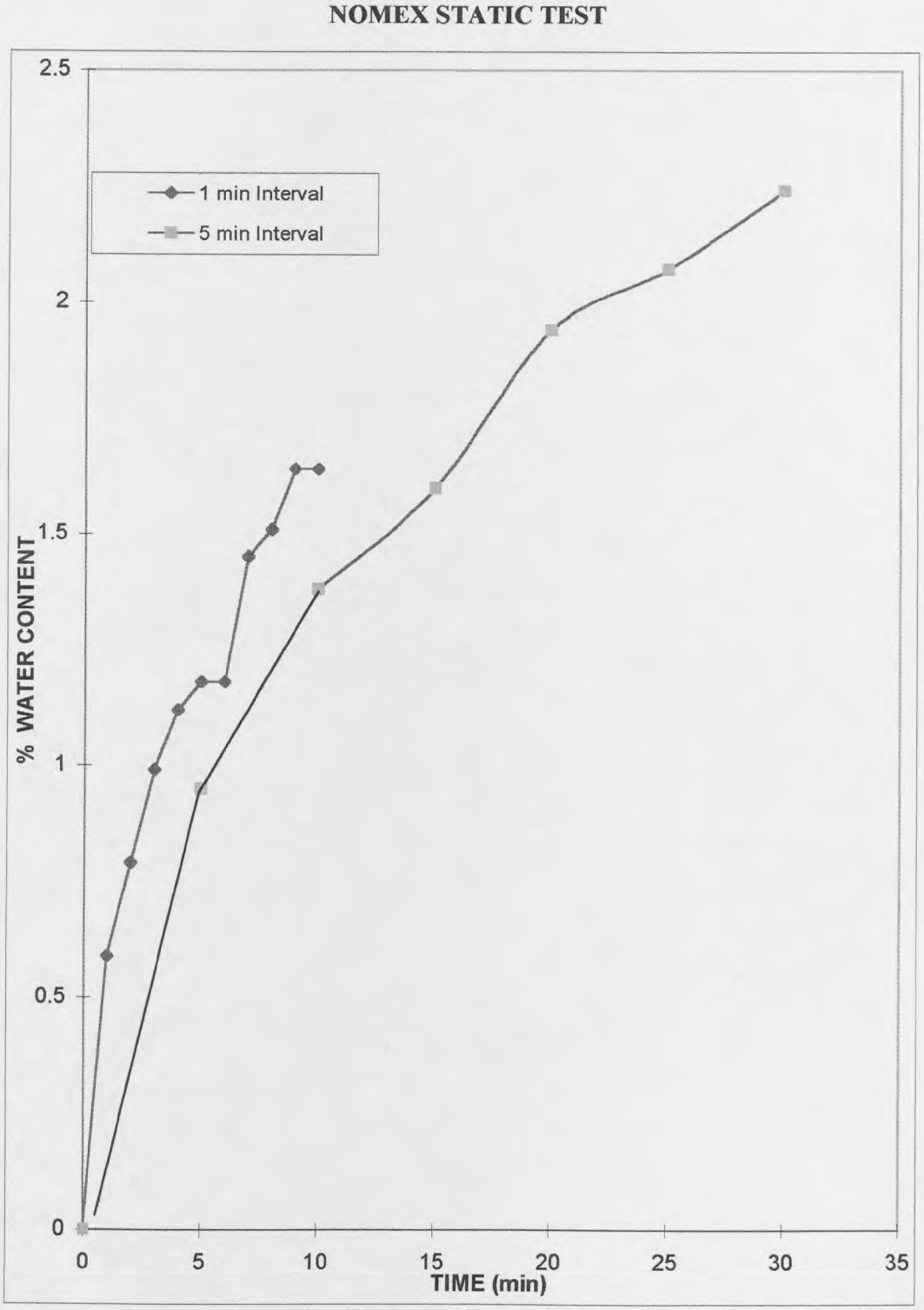


Fig. 70 Comparison of time intervals 1 minute and 5 minutes on Acrylic fabric using the Dynamic Demand Wettability technique.

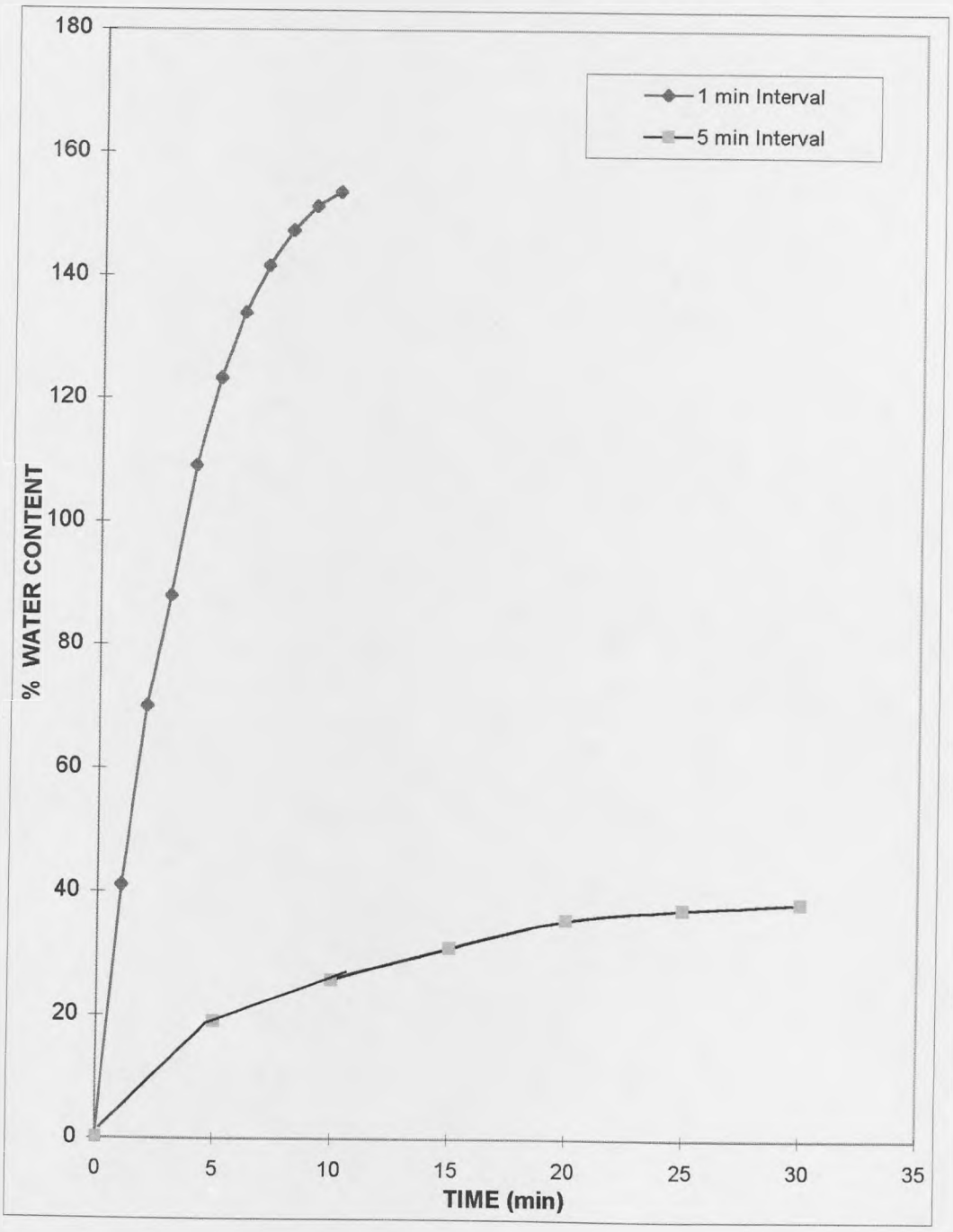
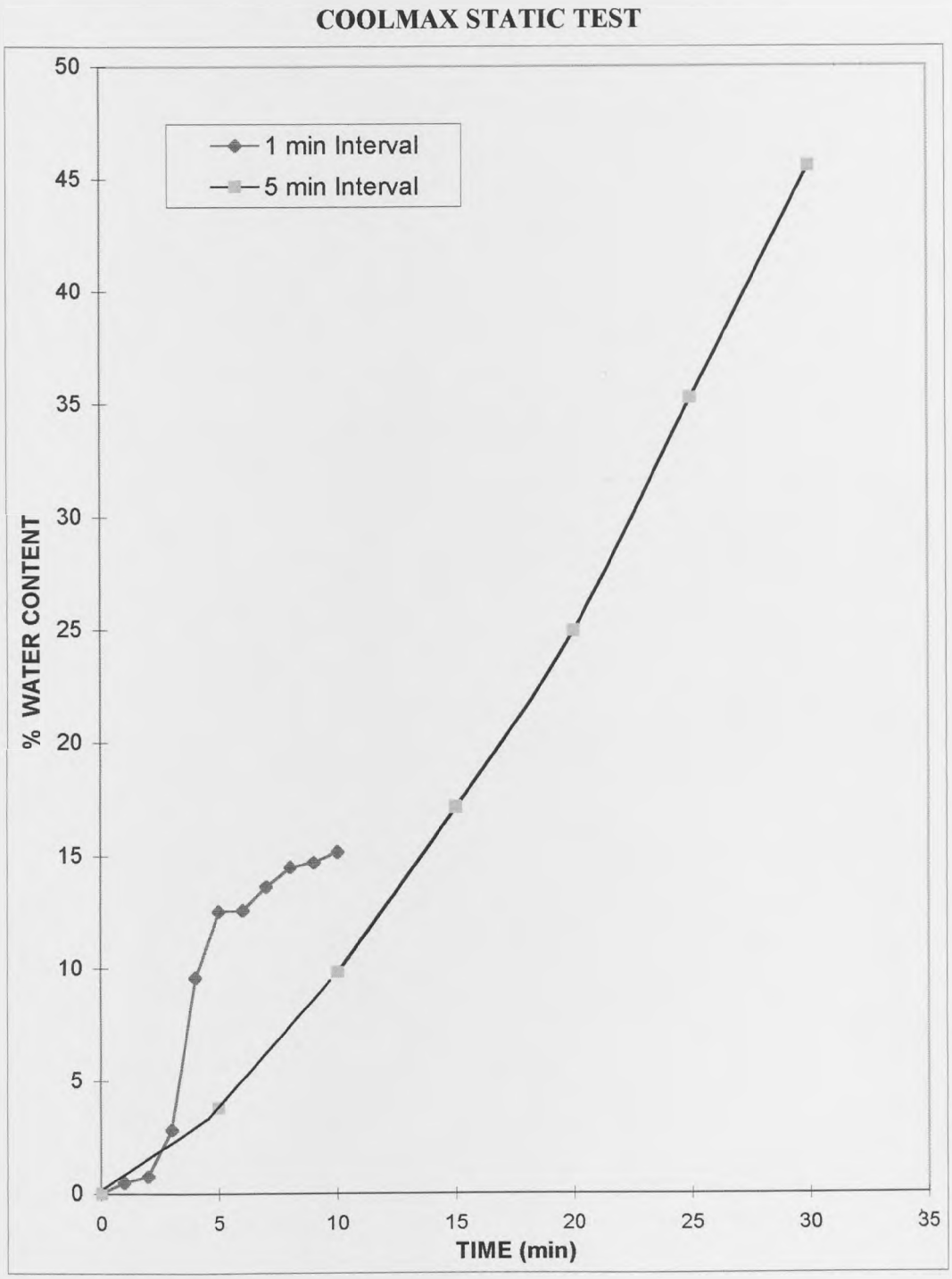


Fig. 71 Comparison of time intervals 1 minute and 5 minutes on Coolmax fabric using the Dynamic Demand Wettability technique.



4.1.3 COMPARISON OF WETTABILITY METHODS IN THE HORIZONTAL STATIC STATE

A comparison was made of the two demand wettability techniques in the static state, using PVC fabric samples and Acrylic fabric samples. This was to compare the static test on both pieces of equipment, and investigate any differences which may occur. These results can be seen in Figures 72 and 73 for the PVC fabric and Acrylic fabric samples.

In both fabric samples the static demand technique produced a greater liquid uptake than the dynamic technique. This may be due to the type of liquid reservoir used in each technique.

In the case of the static demand technique the type of liquid reservoir used means a greater availability of liquid to the fabric being tested (an infinite amount of liquid availability). Therefore the test fabric is free to take on liquid on demand in any amount, at any rate. In the dynamic test the liquid reservoir is smaller and influenced by the temperature and humidity of the test environment, therefore the amount of available liquid is smaller., and this would influence the demand and hence the wicking rate.

Fig. 72 **Comparison of Demand Wettability techniques in the Horizontal mode**

DEMAND WETTABILITY TEST
Static test Comparison

TEST SAMPLE - PVC
Knitted PVC - typical underwear fabric
-VE P/H = 2.0 cm
WEIGHT = 0.66/cm

KEY
SDW - Static Demand wettability Test
DDW - Dynamic Demand wettability Test

	MEAN PERCENTAGE WATER ABSORBED % FOR PVC FABRIC															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SDW	0	26.61	58.99	91.85	124.98	155.42	183.63	209.46	234.20	256.72	279.42	301.34	323.65	344.85	367.31	388.94
DDW	0	32.48	63.01	78.24	87.05	92.97	97.20	100.22	102.73	104.98	107.10	109.02	110.58	111.79	113.74	114.55

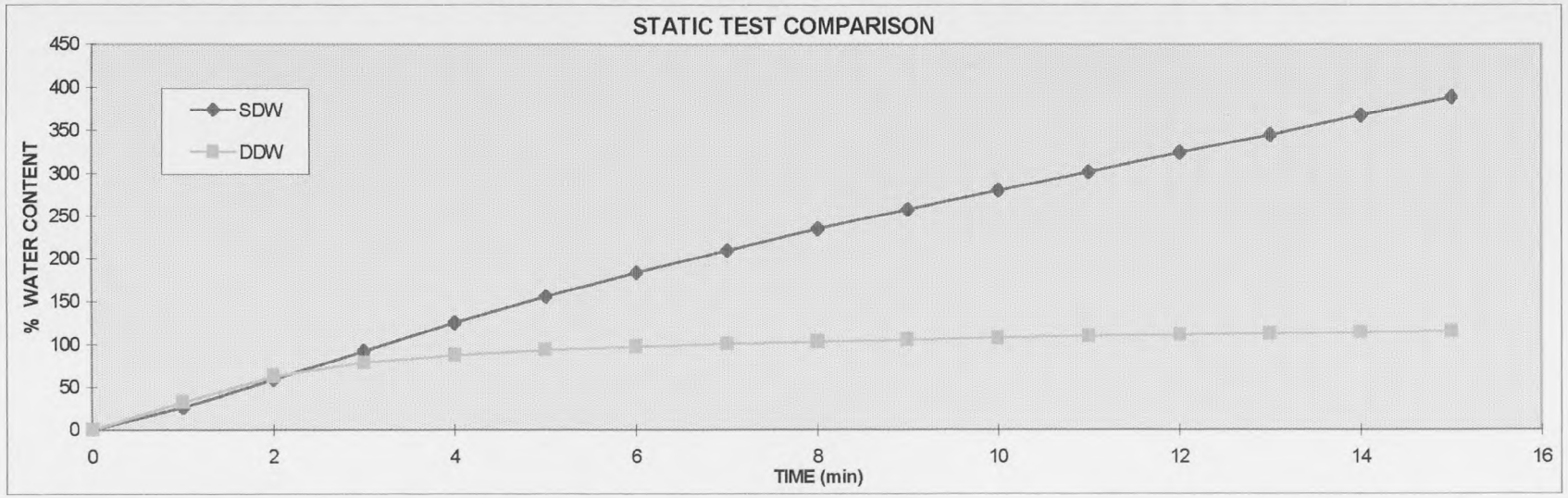


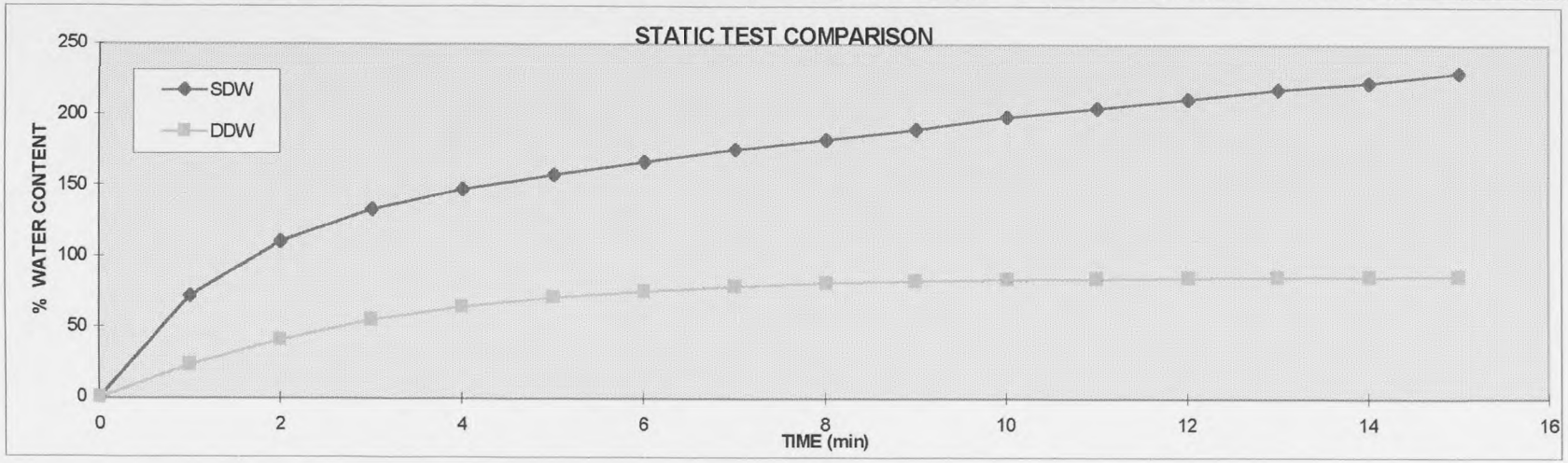
Fig. 73 **Comparison of Demand Wettability techniques in the Horizontal mode**

DEMAND WETTABILITY TEST
Static Test Comparison

TEST SAMPLE - ACRYLIC
Knitted Acrylic - typical underwear fabric
-VE P/H = 2.0 cm
WEIGHT = 0.66g/cm

KEY
SDW - Static Demand wettability Test
DDW - Dynamic Demand wettability Test

	MEAN PERCENTAGE WATER ABSORBED % FOR ACRYLIC FABRIC														
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SDW	0	71.91	110.00	132.76	146.88	157.12	166.11	175.05	182.05	189.22	198.27	204.39	211.09	217.52	222.53	229.72
DDW	0	23.30	40.84	54.64	64.14	70.63	75.24	78.56	81.00	82.27	83.36	84.12	84.77	85.43	85.90	86.12



4.1.4 VERTICAL TRANSPLANAR WICKING METHOD

Using the same four core test fabric samples acrylic, cotton, polypropylene and Nomex, used in the dynamic and static wettability techniques, a test method was developed for investigating transplanar wicking in the vertical state. Using the method described in section 3.3 tests were carried on the above fabrics, and produced results with the exception of polypropylene. The initial wetting of polypropylene fabrics can be extremely difficult and in the case of vertical wicking this made the process almost impossible to observe. When wicking did occur it took an extremely long period of time to occur, and the amount of wicking which took place varied greatly from test to test. Vertical wicking testing was therefore abandoned for the polypropylene fabrics. Vertical testing was carried out with the remaining fabric samples. These results were based on the total percentage water content of the whole of each fabric sample, and can be seen in tables 36 to 38 , and figures 74 to 76 .

Table 36

VERTICAL WICKING TESTS

SAMPLE : ACRYLIC - (Knitted)

Test pair	Ref.No.	MEAN RESULTS			
		Orig.Wt.(g)	Wt. at END	CONTENT(g)	WATER (%)
1	1	0.743	0.897	0.154	20.7
	2	0.719	0.773	0.054	7.5
2	3	0.760	0.922	0.162	21.3
	4	0.788	0.800	0.012	1.5
3	5	0.619	0.810	0.191	30.8
	6	0.563	0.588	0.025	4.4
4	7	0.628	0.808	0.180	28.6
	8	0.612	0.641	0.029	4.7

Ref.nos. 1 – 8 represent individual test samples of the knitted interlock acrylic fabric

Table 37

VERTICAL WICKING TESTS

SAMPLE : COTTON - (Knitted)

Test pair	Ref.No.				
		Orig.Wt.(g)	Wt. at END	CONTENT (g)	WATER (%)
1	A	0.530	0.596	0.066	12.6
	D	0.518	0.548	0.030	5.8
2	C	0.435	0.540	0.105	24.0
	H	0.445	0.466	0.021	4.6
3	E	0.491	0.625	0.134	27.2
	F	0.498	0.503	0.006	1.1
4	B	0.483	0.591	0.108	22.4
	G	0.502	0.547	0.045	8.9

Ref.nos. A –H represent individual test samples of the knitted interlock cotton.L fabric

Fig. 74 VERTICAL WICKING TESTS ON ACRYLIC FABRIC

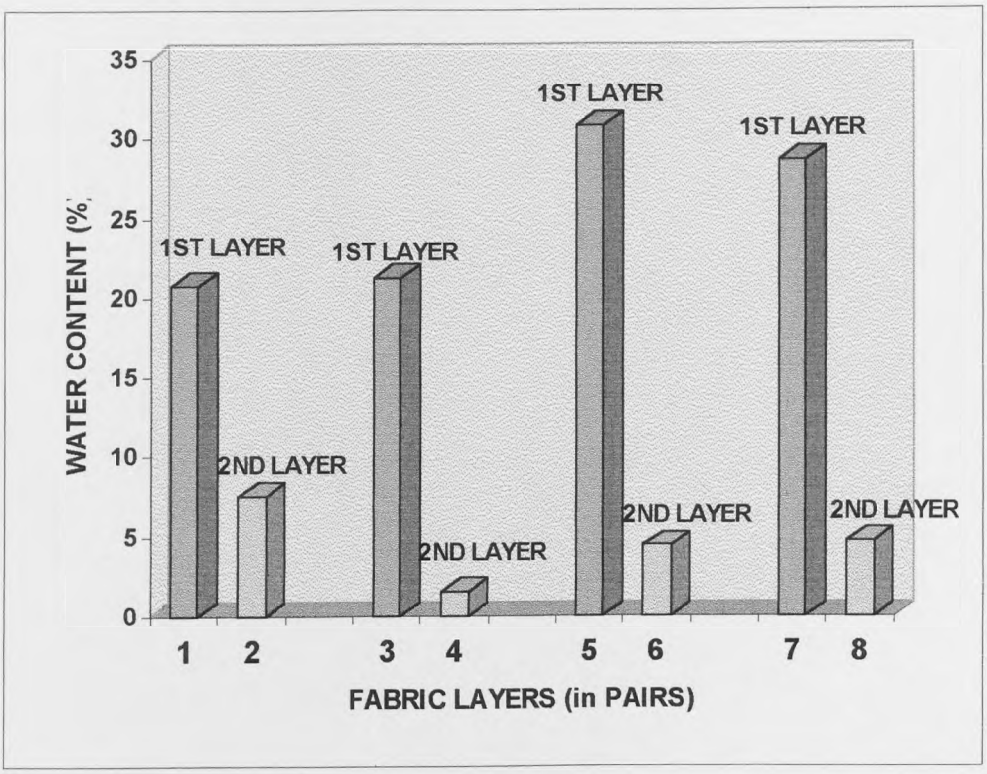


Fig. 75 VERTICAL WICKING TESTS ON COTTON FABRIC

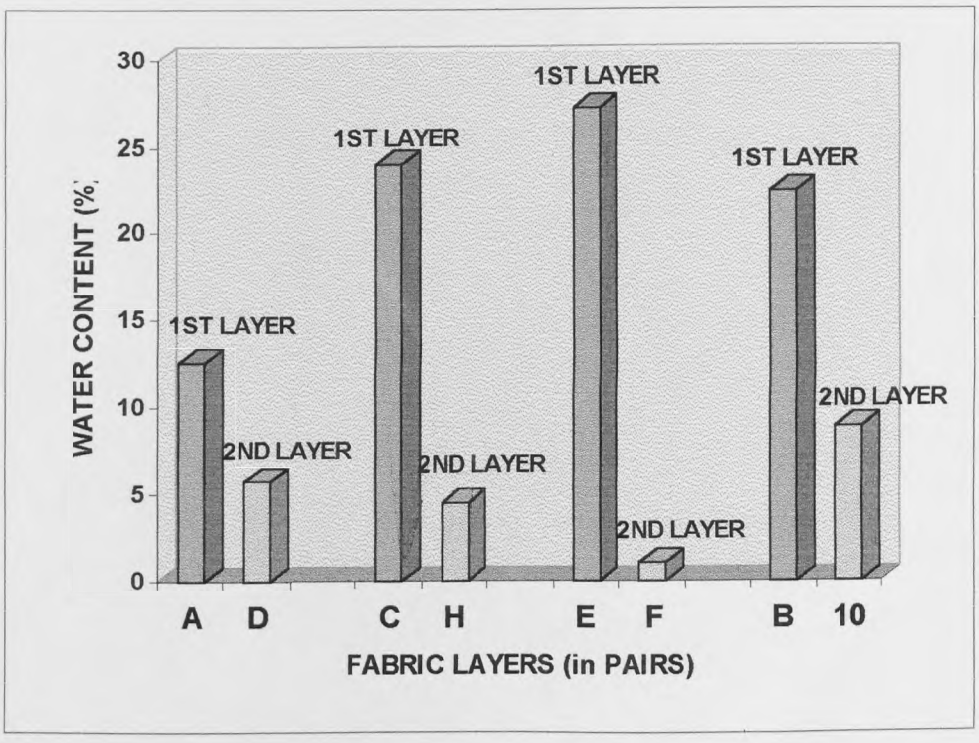


Table 38

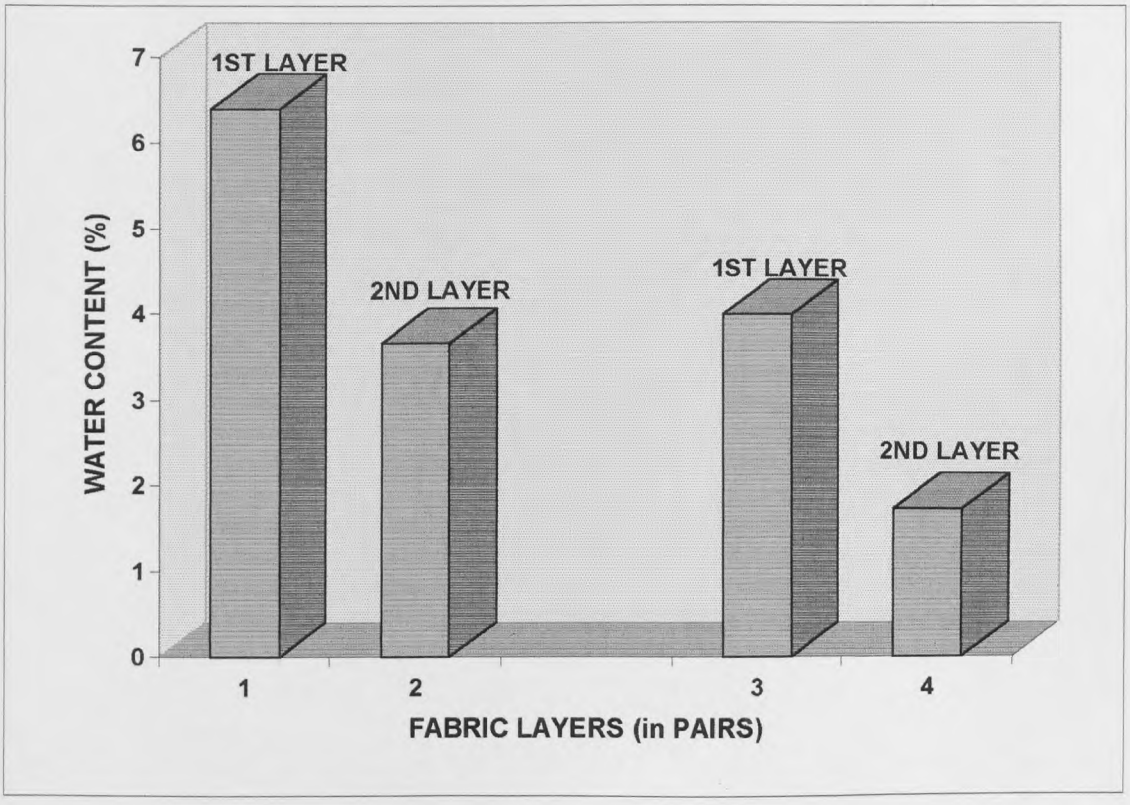
VERTICAL WICKING TESTS

SAMPLE : NOMEX - (Knitted)

Test pair	Ref.No.	MEAN RESULTS			
		Orig.Wt.(g)	Wt. at END	CONTENT(g)	WATER (%)
1	1	0.422	0.449	0.027	6.4
	2	0.409	0.424	0.015	3.7
2	3	0.401	0.417	0.016	4.0
	4	0.403	0.410	0.007	1.7

Ref.nos. 1 – 4 represent individual test samples of the knitted 1x1 rib Nomex fabric

Fig. 76 VERTICAL WICKING TESTS ON NOMEX FABRIC



After examining the initial results a slight modification of the test method was made in order to obtain the water content of the wet areas only and not over the total fabric area.

After each test the wet areas of each layer were cut out of each test sample and weighed individually. Each cut area was left for a minimum 24 hours to dry and then re-weighed. The sample weight in each case corresponded with the original sample weight prior to wetting. The total water content for the saturated area only was then calculated.

Figures 124 to 132 and tables 58 to 66 record results from this new test method.

4.2 RESULTS AND DISCUSSION

4.2.1 HORIZONTAL STATIC DEMAND WETTABILITY TECHNIQUE

Once the time intervals had been established a series of tests were carried out on single and multi-layer assemblies. With the multi-layer fabric assemblies fabrics of different fibre types were mixed within the assemblies and the resulting water uptake was recorded.

Table 39 and figure 77 records the results from single layer tests on Nomex, acrylic and polypropylene fabric samples.

Figures 78-95 records the results from tests carried out on Nomex, acrylic , cotton and polypropylene fabric samples used in various assembly combinations.

In all the fabric/fibre types the ability to retain water is extremely important in these tests, as observations during testing revealed that when a layer is removed for weighing the water front can be seen receding into the previous lower layers when the inter-fabric contacts are broken. The fabrics samples ability to retain water at the moment when the contacts are broken must influence the amount of water present in the test fabrics at the end of the tests.

4.2.1.1 Polypropylene/Acrylic and Acrylic/Polypropylene

The polypropylene/acrylic combination produced predictable effects , and traditional roles were observed. With the acrylic as the bottom layer, acrylic took up the greatest amount of water and polypropylene the least amount of water. The absorption rate of the acrylic samples peaked during the first minute of the tests, with a sudden decreasing rate throughout the rest of the tests.

In this combination the rapid wicking rate in the first minute will be due to the acrylic fibres, ability to take on water quickly via its inter-fibre channels. It is because of the acrylic's round cross-sectional shape with a crinkle edge, giving the ability to create a higher capillary pressure than the polypropylene with a round cross-section, resulting in a more rapid initial liquid uptake. This is clearly visible in figure 79.

In the reverse order a different phenomenon was observed, namely a much lower uptake in both samples was observed. However although the polypropylene commenced with a lower liquid uptake at approximately half way through the test, the liquid uptake increased and overtook the acrylic sample (which is usually a higher wicker), and this was observed in all the repeat tests. It appears that this combination of fibres in this order has an unusual effect on their traditional wicking properties.

This time the polypropylene was next to the water source, and the acrylic still behaved as before with a high initial wicking rate, decreasing with time. This may have occurred because the acrylic as a high wicking fabric was taking on water quicker than the polypropylene during that first minute. Consequently the acrylic fabric was robbing the polypropylene fabric of water during the time period where the largest uptake of liquid occurred, (the first minute of the test). After this first minute, the rate of liquid uptake was reduced, and controlled by the polypropylene fabric.

However the polypropylene was also able to produce a rapid initial wicking rate in the first minute, decreasing after that minute, but after the third minute producing an increased wicking rate (this proved to be a repeatable phenomena in this combination), during a 7 minute wicking period in both fabrics. At the last time interval, 20 minutes, a wicking period of 10 minutes it appears that at this stage gravity is beginning to affect the wicking rate. Overall the water uptake is greatly reduced by the polypropylene being the bottom layer, and the acrylic has to work harder to take on water in the same amount of time, and this may explain the drop in the liquid uptake and then the levelling off of water uptake as there is less water to be affected by gravity.

Table 39.

MEAN STATIC DEMAND WETTABILITY TEST RESULTS
Single Layer Tests

Test Samples	Mean Water content (%)				
	0	1	3	10	20
Nomex	0	4.2	9.6	22.3	34.01
Acrylic	0	18.4	55.6	150	206.4
Polypropylene	0	0.88	2.6	9.96	24.4

Fig. 77 Horizontal Static demand wettability single layer test results

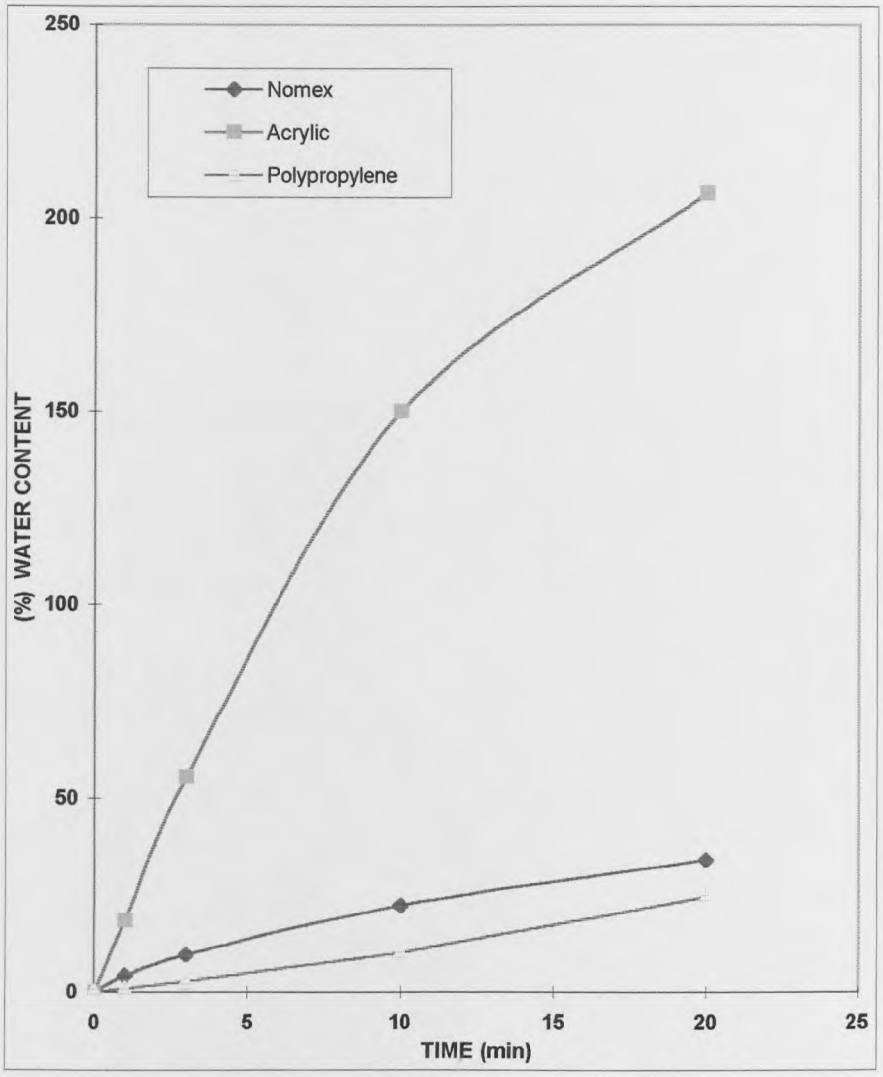
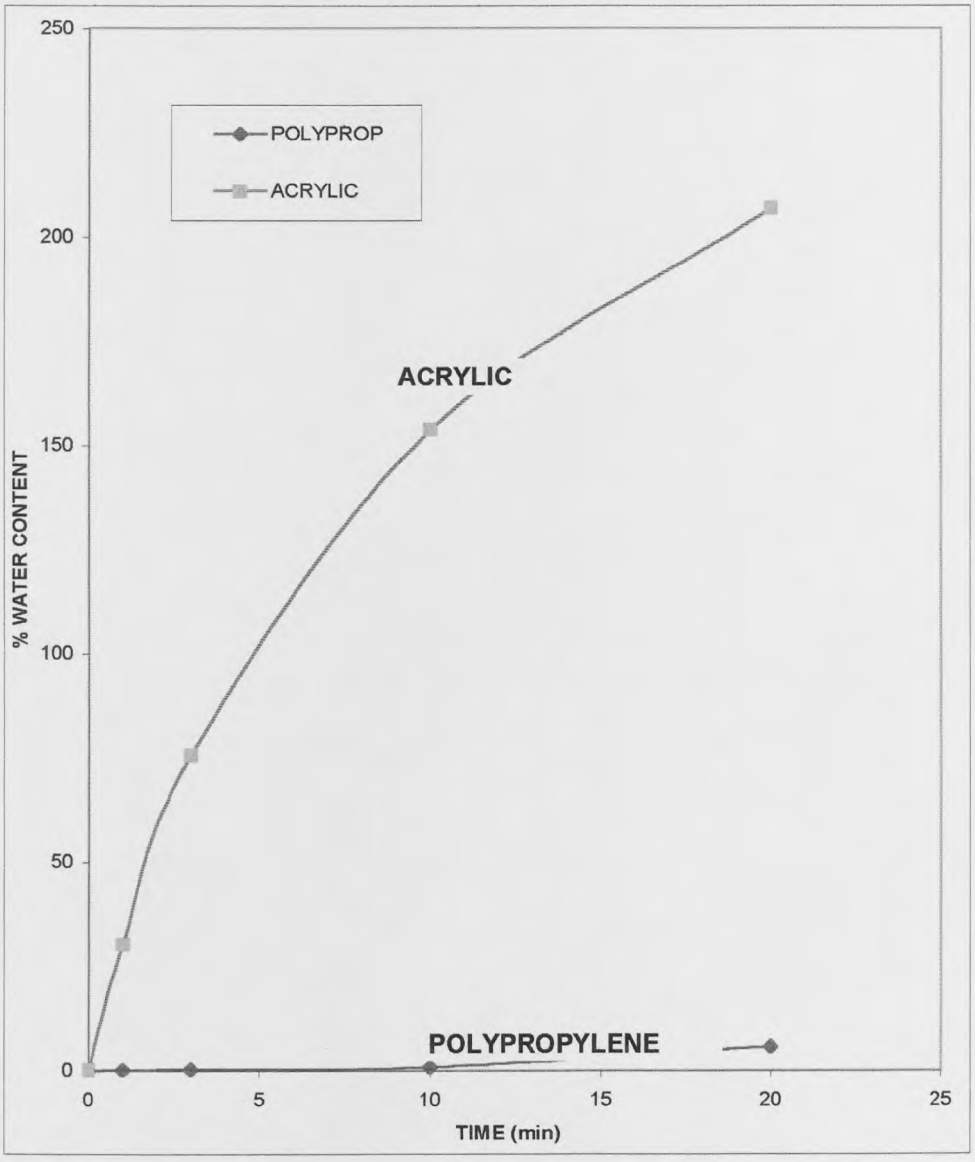


Fig. 78 **Horizontal static transplanar wicking**

DEMAND WETTABILITY MEAN TEST RESULTS

MULTI-LAYER TESTS (MIXED)

POLYPROP	**- TOP**
ACRYLIC	**- BOTTOM**
COMPRESSION WEIGHT = 0.66g/cm^2	
-VE P/H = 2.0 cm	water pH = 7.0



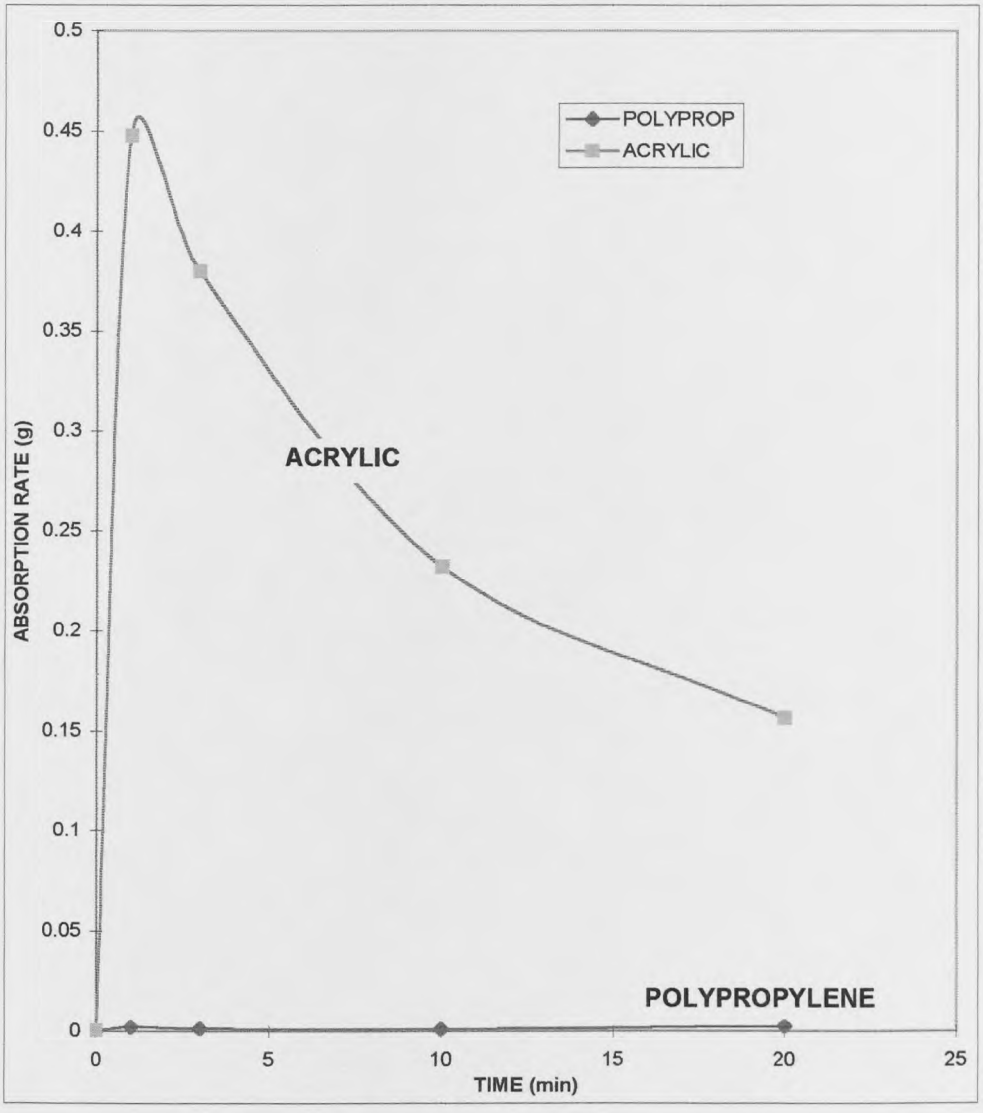
	WATER CONTENT/MIN (%)				
	0	**1**	**3**	**10**	**20**
POLYPROPYLENE	0	0.16	0.32	0.93	5.75
ACRYLIC	0	30.09	75.66	153.82	206.84

Fig. 79 **Horizontal static transplanar wicking**

DEMAND WETTABILITY MEAN TEST RESULTS

MULTI-LAYER TESTS (MIXED)

POLYPROP	**- TOP**
ACRYLIC	**- BOTTOM**
COMPRESSION WEIGHT = 0.66g/cm^2	
-VE P/H = 2.0 cm	water pH = 7.0

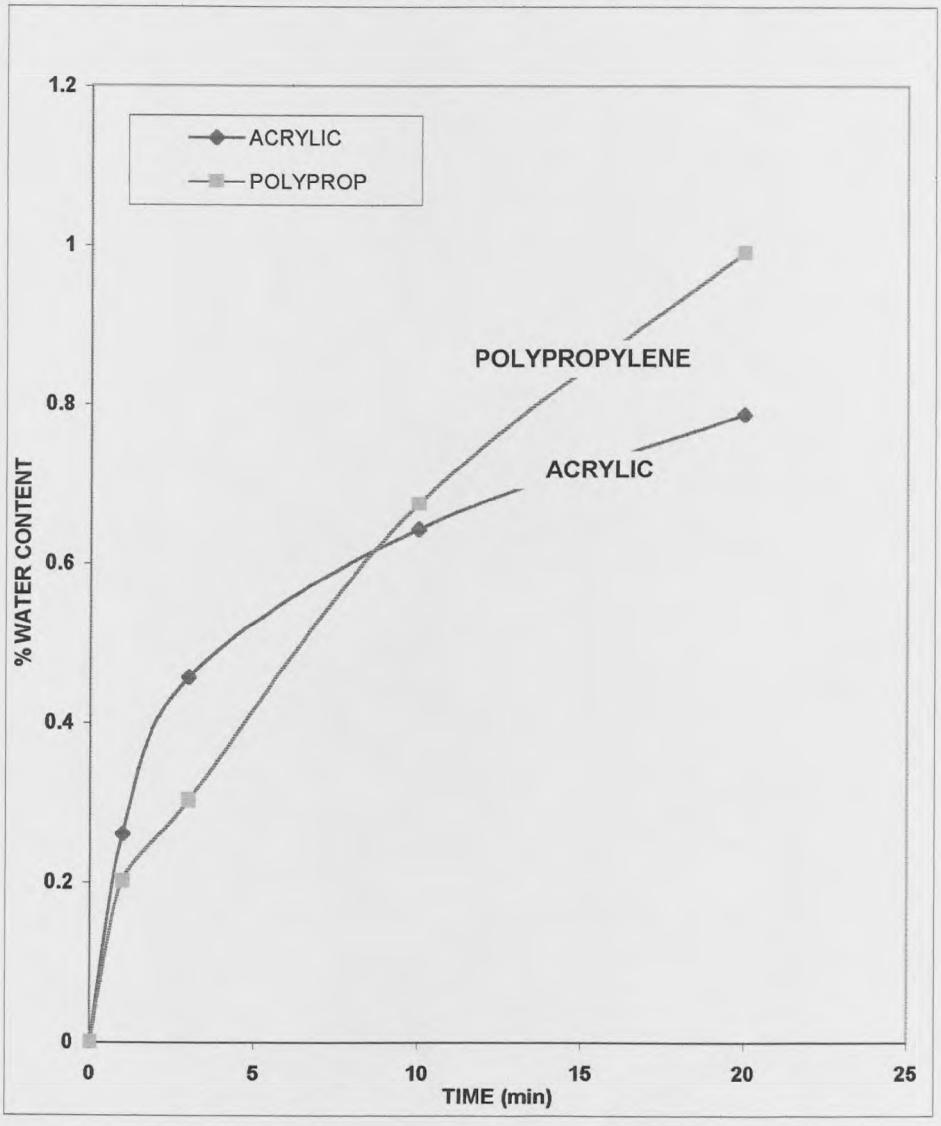


		ABSORPTION RATE /MIN (g)			
	0	**1**	**3**	**10**	**20**
POLYPROPYLENE	0	0.002	0.001	0.001	0.002
ACRYLIC	0	0.448	0.380	0.232	0.156

Fig. 80 **Horizontal static transplanar wicking**

DEMAND WETTABILITY MEAN TEST RESULTS
MULTI-LAYER TESTS (MIXED)

ACRYLIC	**- TOP**
POLYPROPYLENE	**- BOTTOM**
COMPRESSION WEIGHT = 0.66g/cm^2	
-VE P/H = 2.0 cm	water pH = 7.0



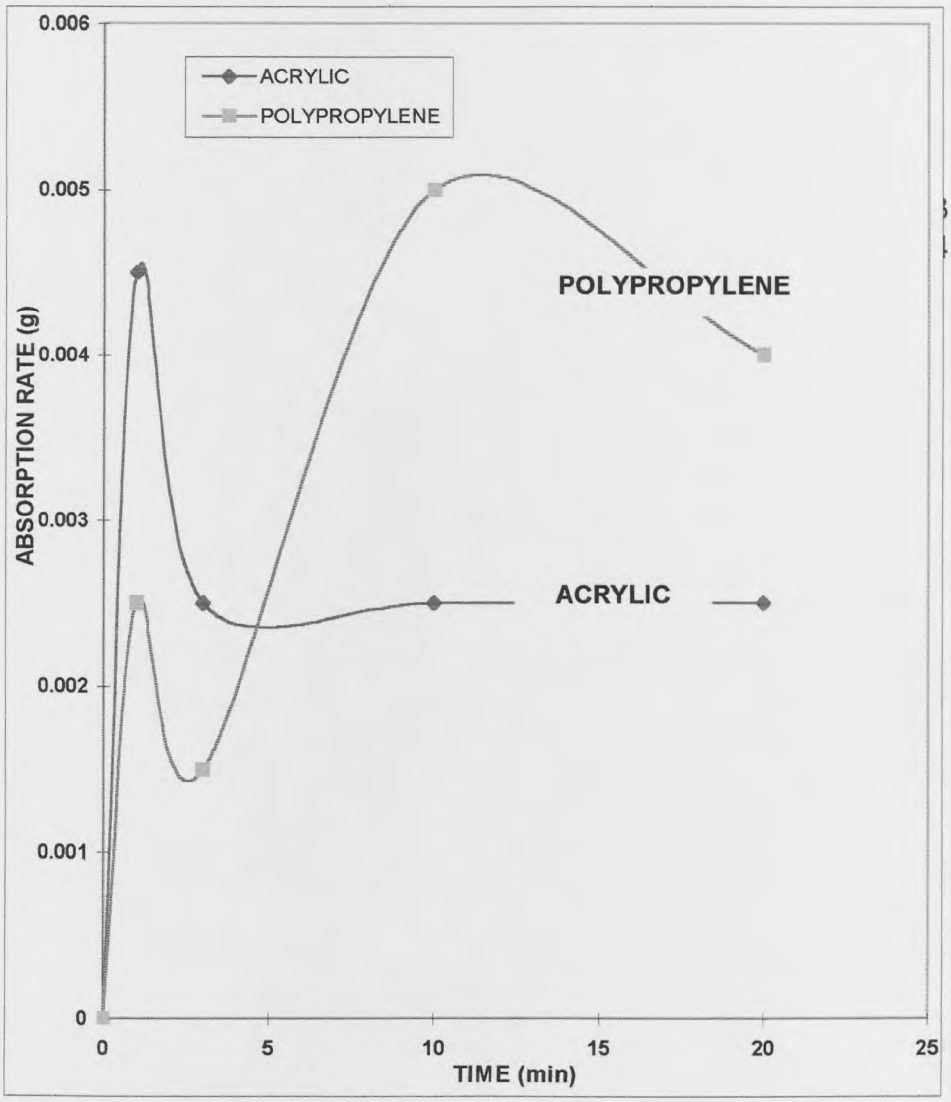
	(%) WATER CONTENT/MIN				
	0	**1**	**3**	**10**	**20**
ACRYLIC	0	0.26	0.46	0.64	0.79
POLYPROPYLENE	0	0.20	0.30	0.68	0.99

Fig. 81 **Horizontal static transplanar wicking**

DEMAND WETTABILITY MEAN TEST RESULTS

MULTI-LAYER TEST RESULTS (MIXED)

ACRYLIC - TOP
POLYPROPYLENE - BOTTOM
COMPRESSION WEIGHT = 0.66g/cm^2
-VE = 2.0cm water pH = 7.0



	ABSORPTION RATE /MIN (g)				
	0	**1**	**3**	**10**	**20**
ACRYLIC	0	0.005	0.003	0.003	0.003
POLYPROPYLENE	0	0.003	0.002	0.005	0.004

4.2.1.2 Polypropylene/Nomex and Nomex/Polypropylene

The Nomex and polypropylene fabric samples exhibited different properties when placed together. Polypropylene traditionally a poor wicking fibre, in combination with Nomex produced different results. As individual layers Nomex took up more liquid than the polypropylene, and is represented in figure 77. In figures 82 and 83 respectively with the polypropylene as the top layer produced a lower wicking rate. Once again with the polypropylene as the top layer, the fibre cross-sectional shape seems to have an influence in the first minute. The Nomex fibre has a 'dog-bone' cross-section, and it produced a higher initial wicking rate. However the polypropylene in this combination has also produced a more rapid water uptake than in the polypropylene /acrylic combination. This may be influenced by the fabric structures in these combination, both polypropylene and Nomex are 1x1 rib structures (the acrylic samples were interlock).

However with the fabric layers reversed and with polypropylene as the bottom layer, this absorption rate could be increased using Nomex as the top layer, see figure 84 and 85. Polypropylene is shown as taking up more water than the Nomex sample, which in individual tests was not the case, (see Fig. 77 and table 39).

With polypropylene as the bottom layer an overall decrease in water uptake was expected, however this was not the case. The amount of water taken up in the bottom layer hardly changed (Nomex – 33.7% ; Polypropylene - 38.4% in total) performed as they had done in earlier single layer tests, with Nomex taking on more water than the polypropylene as expected.

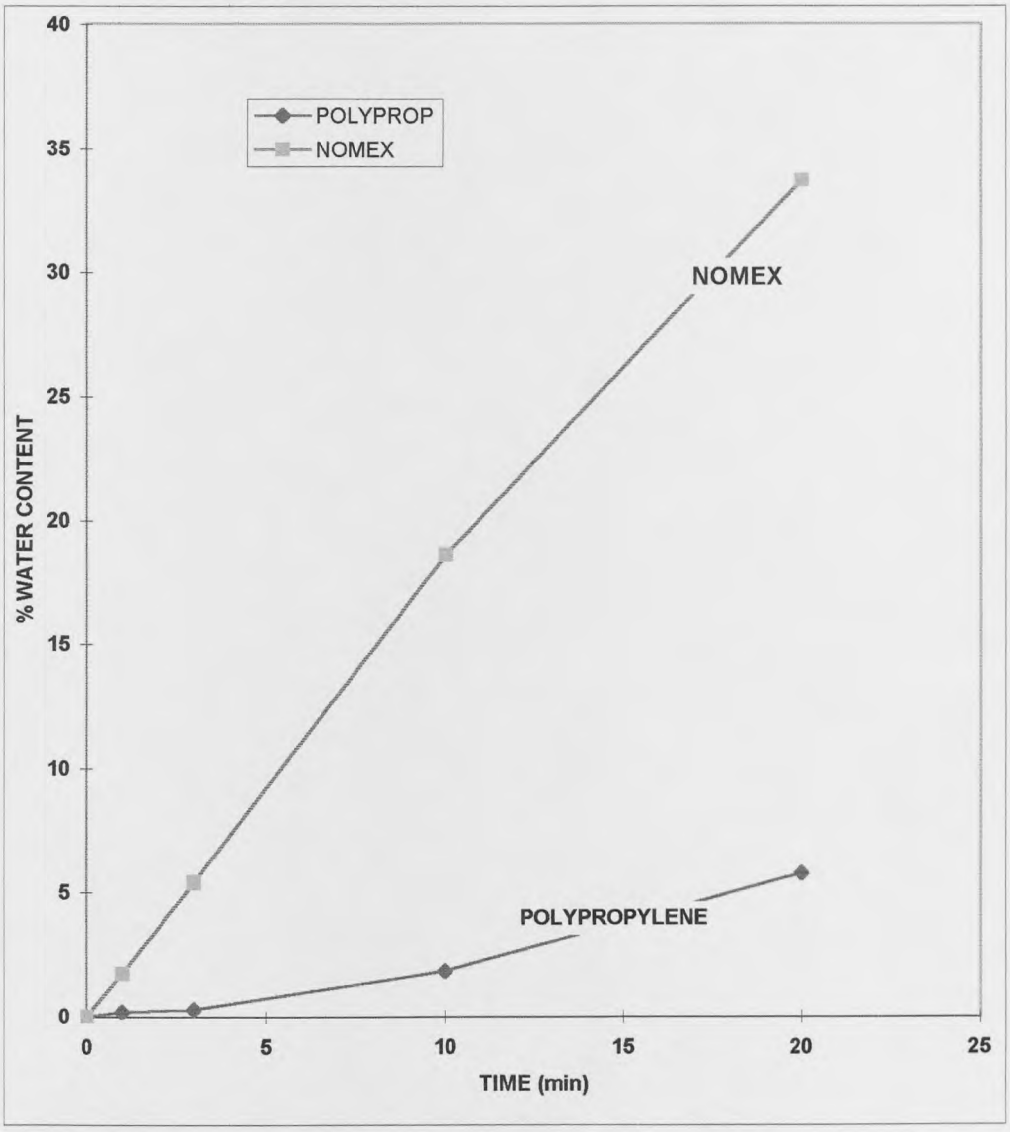
It should be noted that the results on the polypropylene fabric were not very consistent, presumably because of the poor wicking characteristics of this hydrophobic fibre. The improved test method gave improved experimental reproducibility on the acrylic and Nomex fabrics, but the results on the polypropylene still exhibited variations (see Appendix 2 and 3, Tables 67 to 73).

Fig. 82 **Horizontal static transplanar wicking**

DEMAND WETTABILITY MEAN TEST RESULTS

MULTI-LAYER TEST RESULTS (MIXED)

POLYPROPYLENE - TOP NOMEX - BOTTOM
COMPRESSION WEIGHT = 0.66g/cm^2
-VE = 2.0cm water pH = 7.0

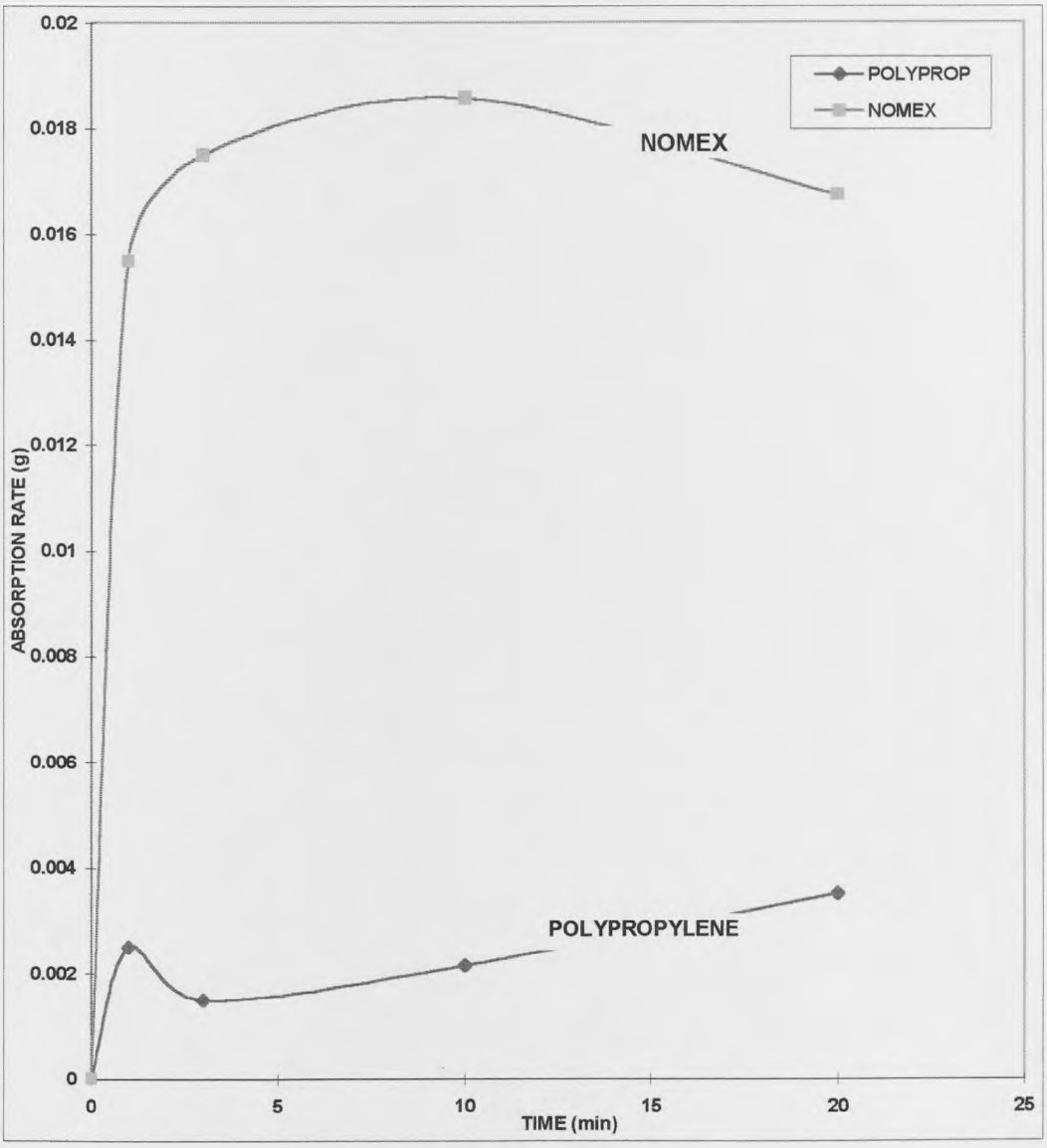


	WATER CONTENT/MIN (%)				
	0	1	3	10	20
POLYPROPYLENE	0	0.17	0.29	1.82	5.77
NOMEX	0	1.71	5.4	18.62	33.7

Fig. 83 **Horizontal static transplanar wicking**

DEMAND WETTABILITY TEST RESULTS
MULTI-LAYER TESTS (MIXED)

POLYPROPYLENE	**- TOP**
NOMEX	**- BOTTOM**
COMPRESSION WEIGHT = 0.66g/cm^2	
-VE P/H = 2.0 cm	water pH = 7.0

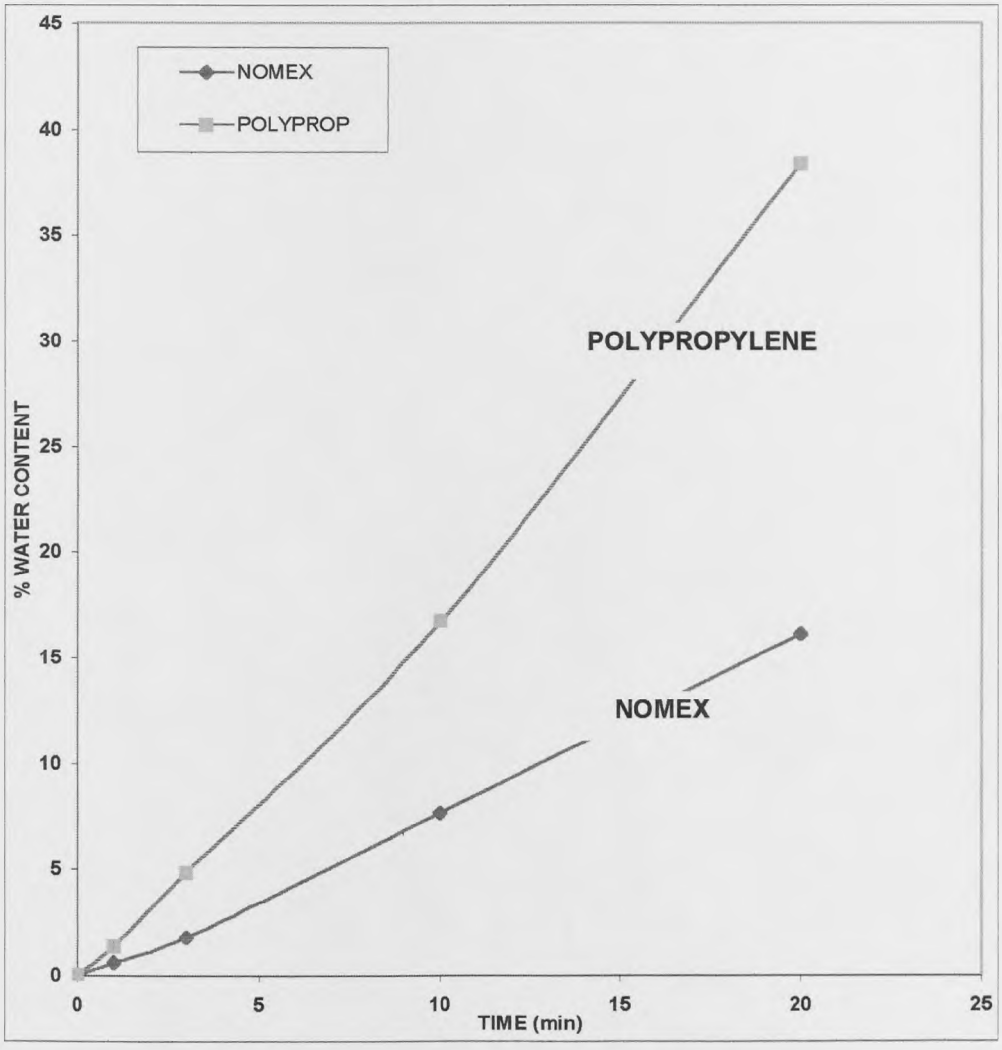


		ABSORPTION RATE /MIN (g)			
	0	**1**	**3**	**10**	**20**
POLYPROPYLENE	0.000	0.003	0.002	0.002	0.004
NOMEX	0.000	0.016	0.018	0.019	0.017

Fig. 84 **Horizontal static transplanar wicking**

DEMAND WETTABILITY MEAN TEST RESULTS
MULTI-LAYER TESTS (MIXED)

NOMEX	**- TOP**
POLYPROPYLENE	**- BOTTOM**
COMPRESSION WEIGHT = 0.66g/cm^2	
-VE P/H = 2.0 cm	water pH = 7.0



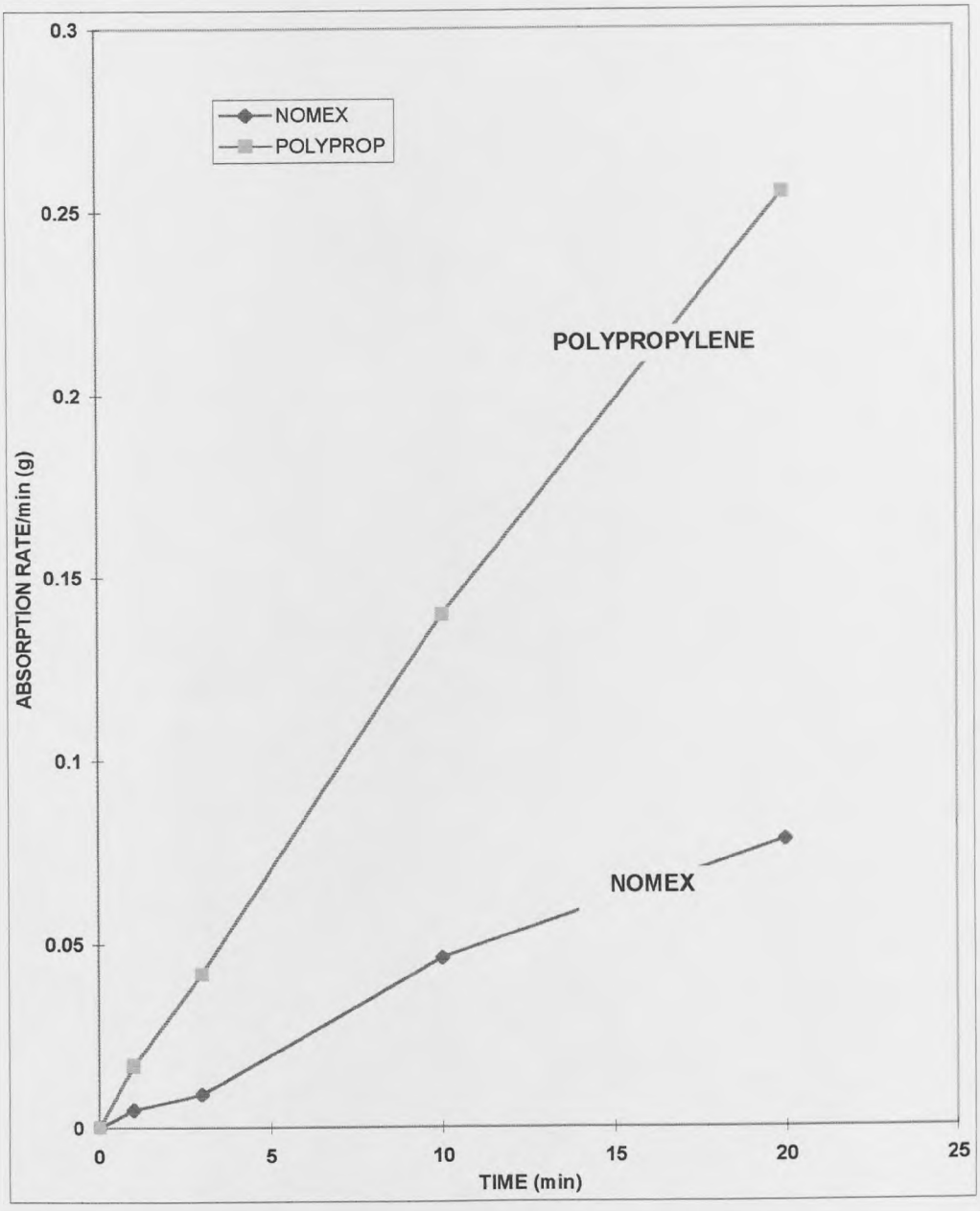
	WATER CONTENT/MIN (%)				
	0	**1**	**3**	**10**	**20**
NOMEX	0	0.58	1.78	7.67	16.09
POLYPROPYLENE	0	1.36	4.85	16.74	38.41

Fig. 85 **Horizontal static transplanar wicking**

DEMAND WETTABILITY MEAN TEST RESULTS

MULTI-LAYER TEST RESULTS (MIXED)

NOMEX - TOP
POLYPROPYLENE - BOTTOM
COMPRESSION WEIGHT = 0.66g/cm^2
-VE = 2.0cm water pH = 7.0



	ABSORPTION RATE /MIN (g)				
	0	1	3	10	20
NOMEX	0	0.005	0.009	0.046	0.078
POLYPROPYLENE	0	0.017	0.042	0.14	0.255

4.2.1.3 Nomex /Acrylic and Acrylic /Nomex

This combination produced predictable results in the testing with Nomex as the top layer, and acrylic as the bottom layer. As acrylic in the single layer tests was traditionally a better wicking fibre than the Nomex, this was expected. However the absorption rate of the acrylic is completely different from rate produced in the polypropylene/acrylic combination. In the Nomex /acrylic combination the wicking rate in the acrylic increases steadily with time, see figure 86, this is not the case in the polypropylene/acrylic combination, see figure 79. This may be due to the liquid retaining properties of the Nomex. As mentioned before when the inter-fabric contacts were broken during removal for weighing during the tests, the liquid front could be clearly seen receding into the lower layer. The amount of liquid lost to the lower layers is dependent on the liquid retaining properties of the layer being removed.

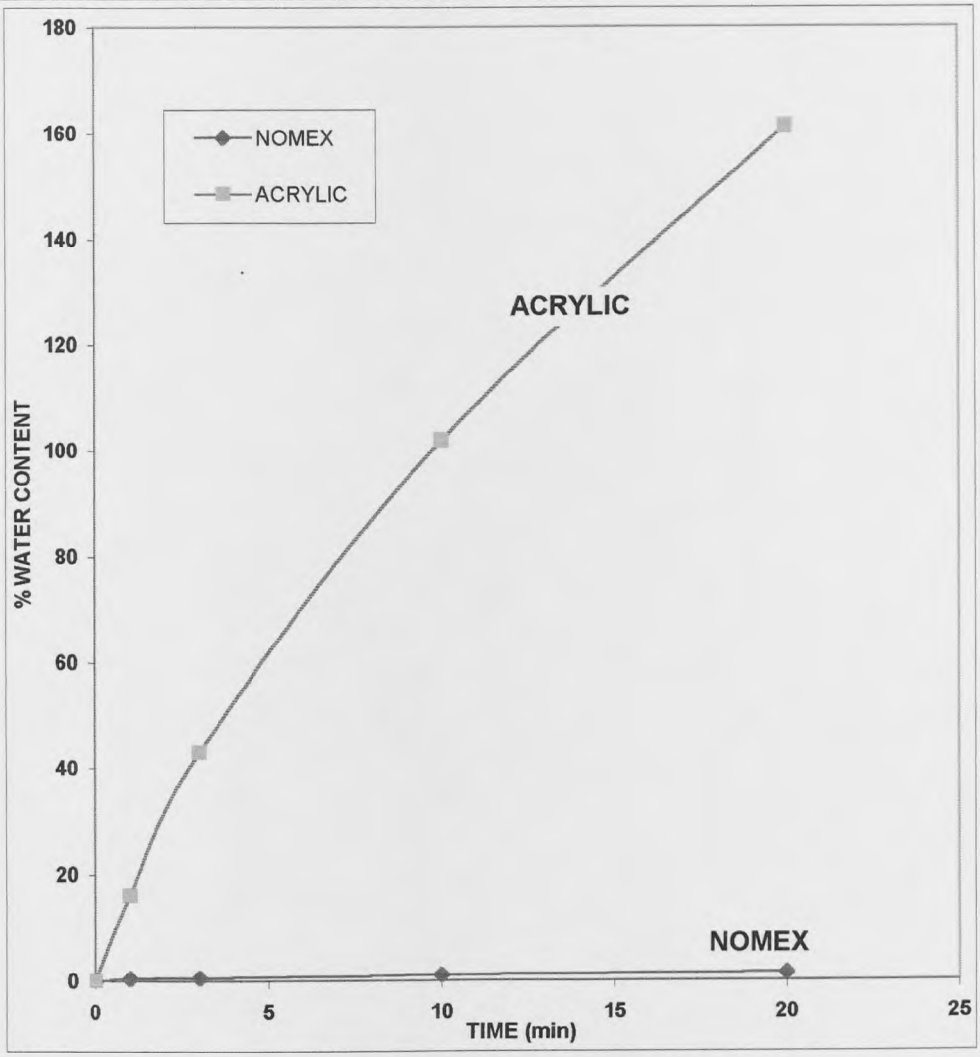
However in the reverse order the results produced have shown that with acrylic as the top layer and Nomex as the bottom layer ,this combination appears to have increased the wicking ability of the Nomex samples and greatly hindered the acrylic. The absorption rate of the first combination, Nomex/acrylic produced a very slow steady increase in liquid uptake in the Nomex. However the acrylic samples produced a slow initial uptake which increased after the first minute, see figure 89.

Fig. 86 Horizontal static transplanar wicking

DEMAND WETTABILITY MEAN TEST RESULTS

MULTI-LAYER TESTS (MIXED)

NOMEX	- TOP
ACRYLIC	- BOTTOM
COMPRESSION WEIGHT = 0.66g/cm^2	
-VE P/H = 2.0 cm	water pH = 7.0



WATER CONTENT/MIN (%)

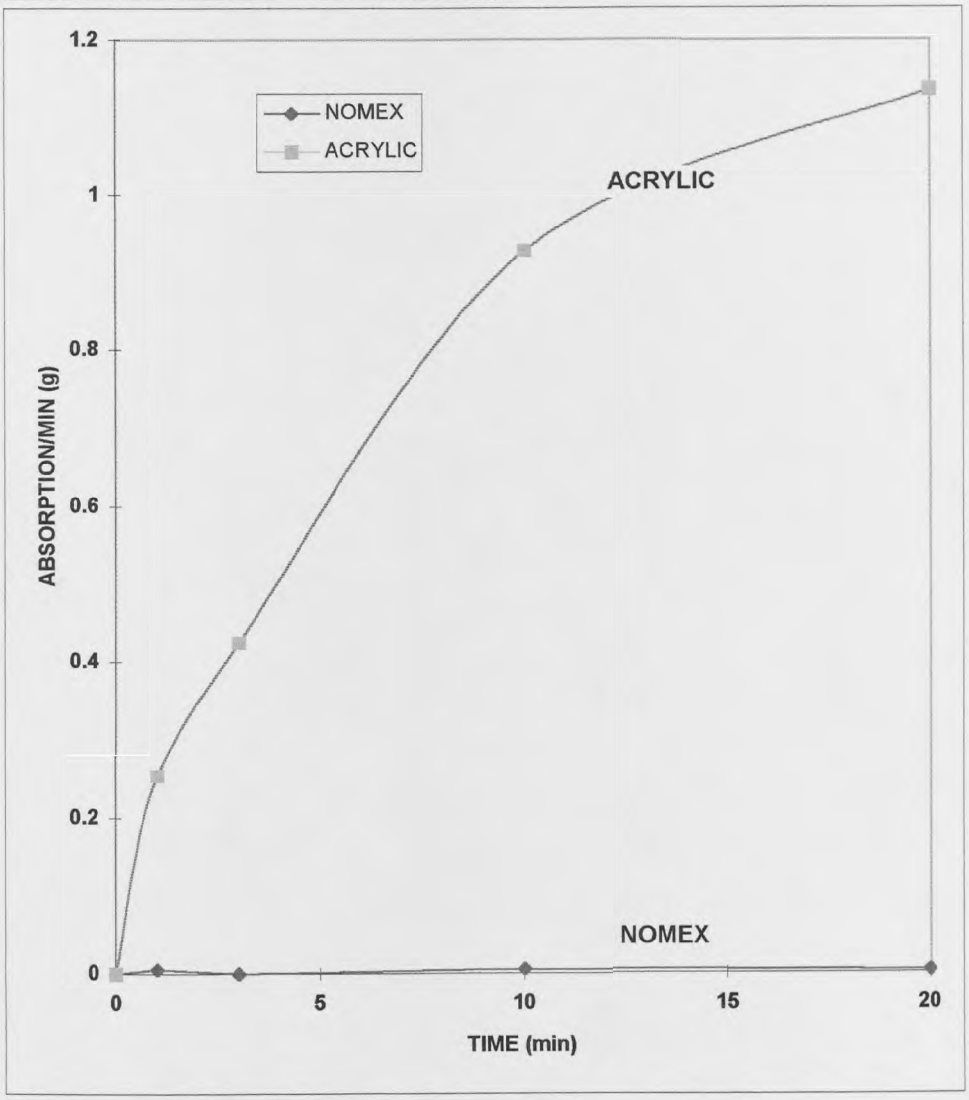
	0	1	3	10	20
NOMEX	0	0.50	0.66	1.16	1.49
ACRYLIC	0	16.08	43.05	102.06	161.22

Fig. 87 Horizontal static transplanar wicking

DEMAND WETTABILITY MEAN TEST RESULTS

MULTI-LAYER TEST RESULTS (MIXED)

NOMEX	**- TOP**
ACRYLIC	**- BOTTOM**
COMPRESSION WEIGHT = .66g/cm^2	
-VE = 2.0cm	water pH = 7.0



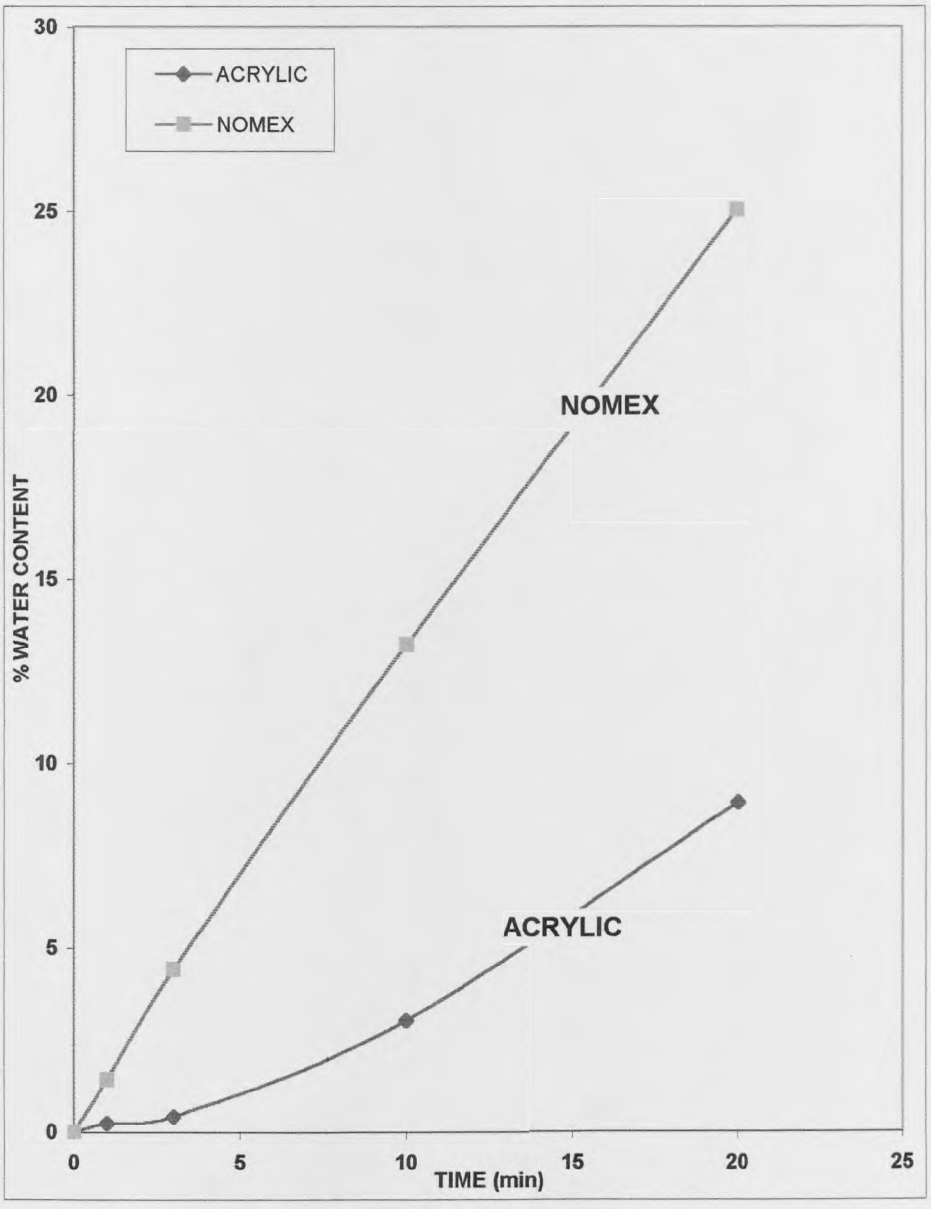
	ABSORPTION RATE /MIN (g)				
	0	**1**	**3**	**10**	**20**
NOMEX	0	0.0050	0.0010	0.0045	0.0035
ACRYLIC	0	0.254	0.425	0.929	1.135

Fig. 88 Horizontal static transplanar wicking

DEMAND WETTABILITY MEAN TEST RESULTS

MULTI-LAYER TESTS (MIXED)

ACRYLIC	**- TOP**
NOMEX	**- BOTTOM**
COMPRESSION WEIGHT = 0.66g/cm^2	
-VE P/H = 2.0 cm	water pH = 7.0



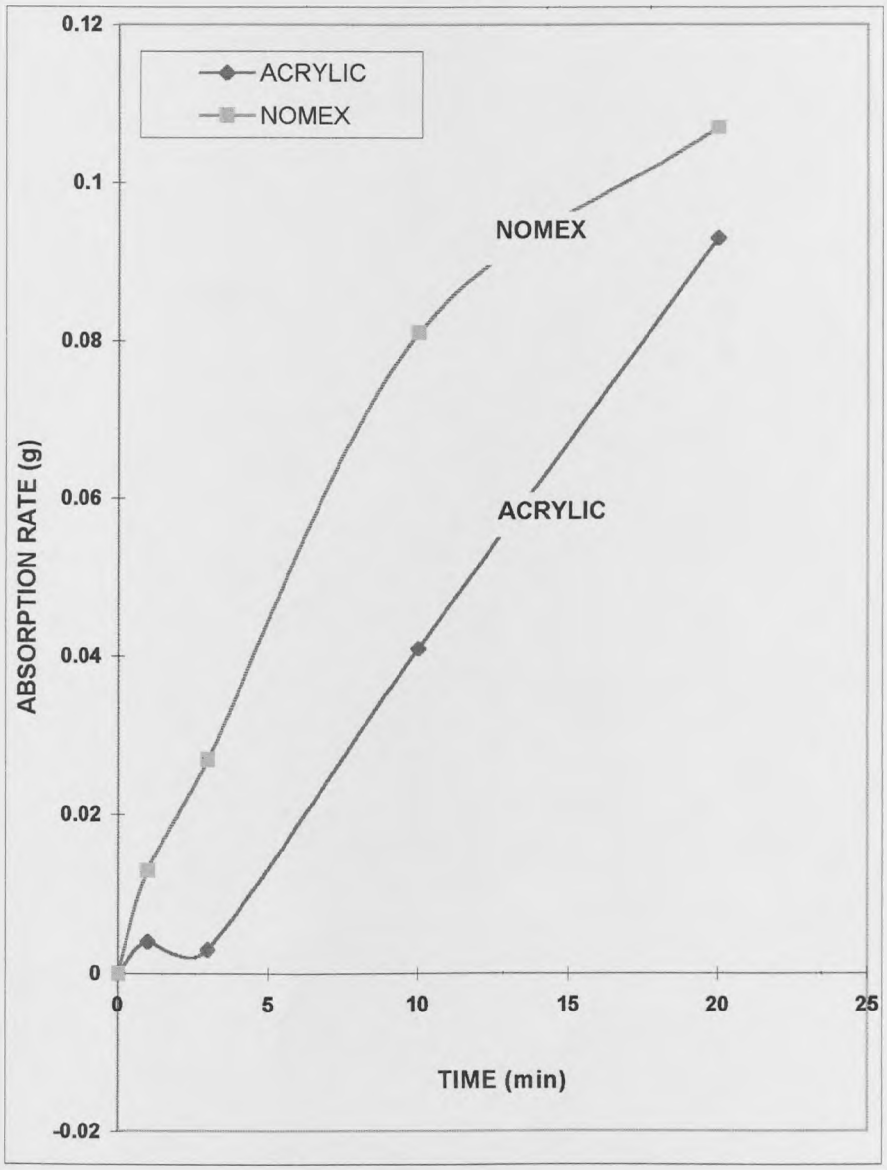
	WATER CONTENT/MIN (%)				
	0	**1**	**3**	**10**	**20**
ACRYLIC	0	0.24	0.43	3.02	8.94
NOMEX	0	1.43	4.40	13.24	25.04

Fig. 89 Horizontal static transplanar wicking

DEMAND WETTABILITY MEAN TEST RESULTS

MULTI-LAYER TEST RESULTS (MIXED)

ACRYLIC	**- TOP**
NOMEX	**- BOTTOM**
COMPRESSION WEIGHT = 0.66g/cm^2	
-VE = 2.0cm	water pH = 7.0



	ABSORPTION RATE /MIN (g)				
	0	**1**	**3**	**10**	**20**
ACRYLIC	0	0.004	0.003	0.041	0.093
NOMEX	0	0.013	0.027	0.081	0.107

4.2.1.4 Cotton/Polypropylene

The cotton/polypropylene combination with cotton as the top layer produced results indicating that the presence of polypropylene in the assembly had a hindering effect on the liquid uptake of cotton. It would appear that a slow wicking fabric as the lower layer has an adverse influence on the top layer fabric, even if the top layer fabric is a high wicking fabric.

4.2.1.5 Cotton/Acrylic

In the cotton/acrylic combination, an assembly of good wicking fibres, the results observed were of high liquid uptake in the bottom layer, the acrylic, and an unexpected much lower uptake in the cotton - the top layer, see figure 92 and 93. The absorption rate in this combination increased throughout both layers, with the absorption rate for acrylic producing a hyperbolic curve, a steep increase in liquid absorption initially which decreased with time. Cotton as the top layer produced absorption results which performed with a slow absorption rate which increased with time.

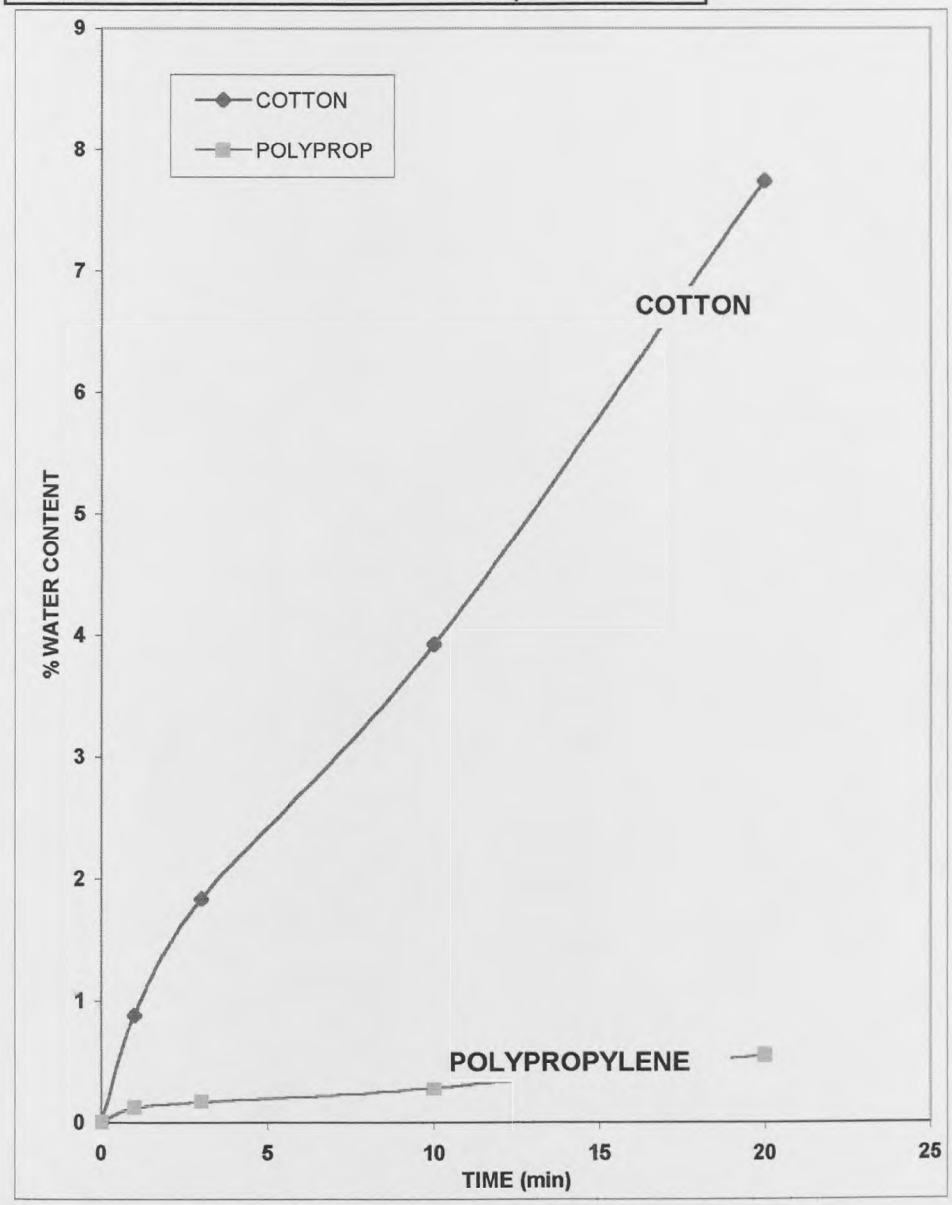
4.2.1.6 Cotton/Nomex

The cotton/Nomex combination also produced unexpected results even though Nomex was not a particularly good wicking fibre especially in comparison with cotton. However the Nomex produced results very close to that of the cotton samples. With the Nomex fabric as the bottom layer, a higher initial liquid uptake than the cotton sample (the top layer) was observed However this situation gradually reversed with the cotton sample in the final stages of the test, exhibiting the highest liquid uptake. In figure 95 after the initial uptake the absorption rate in the Nomex drops, allowing the cotton sample to overtake the Nomex as it increases its absorption rate. This may be due to the cotton fabric wicking at a quicker rate than the Nomex, and removing water from the Nomex at a quicker rate than the Nomex can wick from the water reservoir below.

Fig. 90 **Horizontal static transplanar wicking**

DEMAND WETTABILITY MEAN TEST RESULTS
MULTI-LAYER TESTS (MIXED)

COTTON	**- TOP**
POLYPROPYLENE	**- BOTTOM**
COMPRESSION WEIGHT = 0.66g/cm^2	
-VE P/H = 2.0 cm	water pH = 7.0



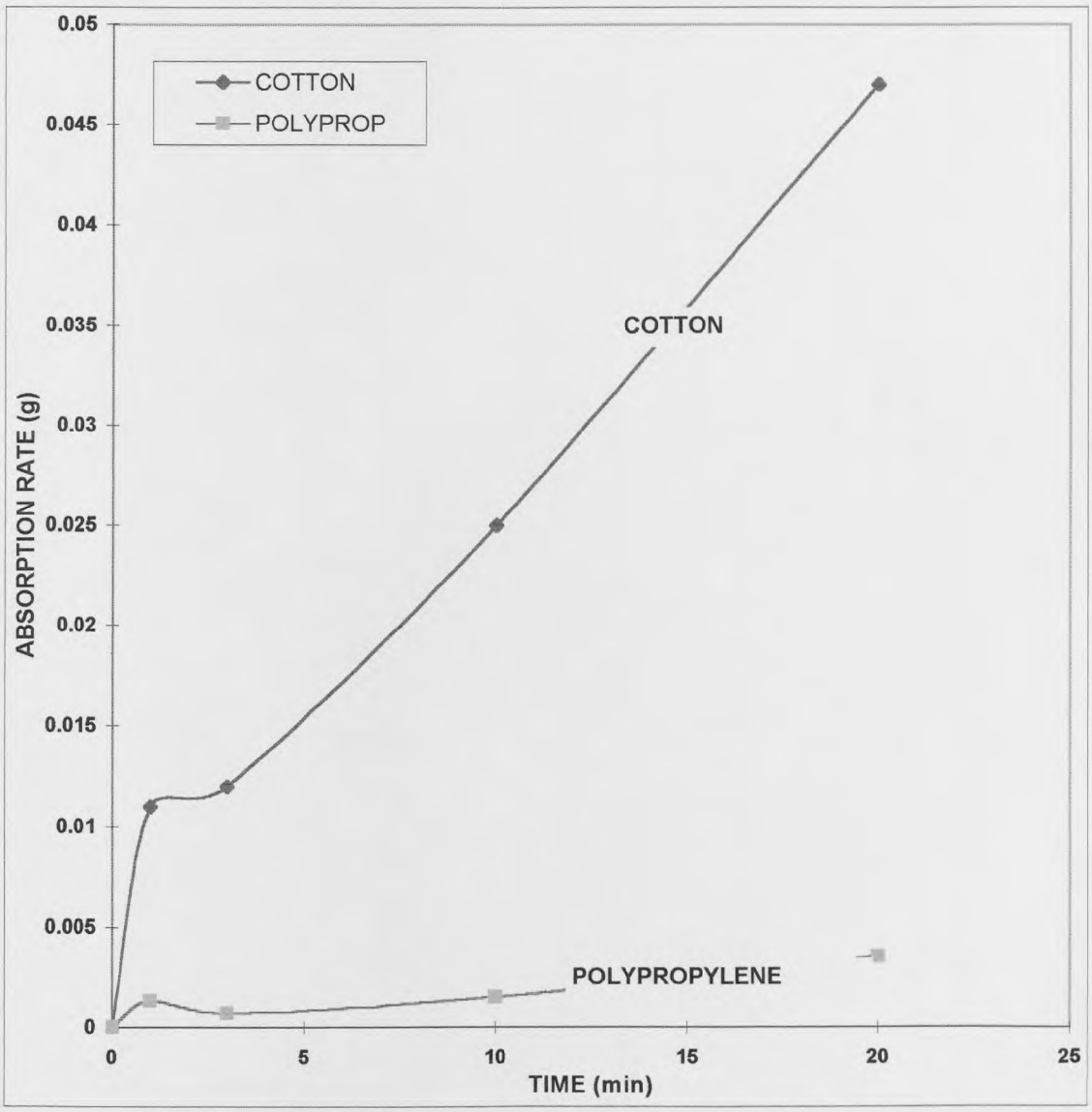
	(%) WATER CONTENT/MIN				
	0	**1**	**3**	**10**	**20**
COTTON	0	0.88	1.84	3.93	7.74
POLYPROPYLENE	0	0.12	0.17	0.28	0.55

Fig. 91 **Horizontal static transplanar wicking**

DEMAND WETTABILITY MEAN TEST RESULTS

MULTI-LAYER TEST RESULTS (MIXED)

COTTON - TOP
POLYPROPYLENE - BOTTOM
COMPRESSION WEIGHT = 0.66g/cm^2
-VE = 2.0cm water pH = 7.0

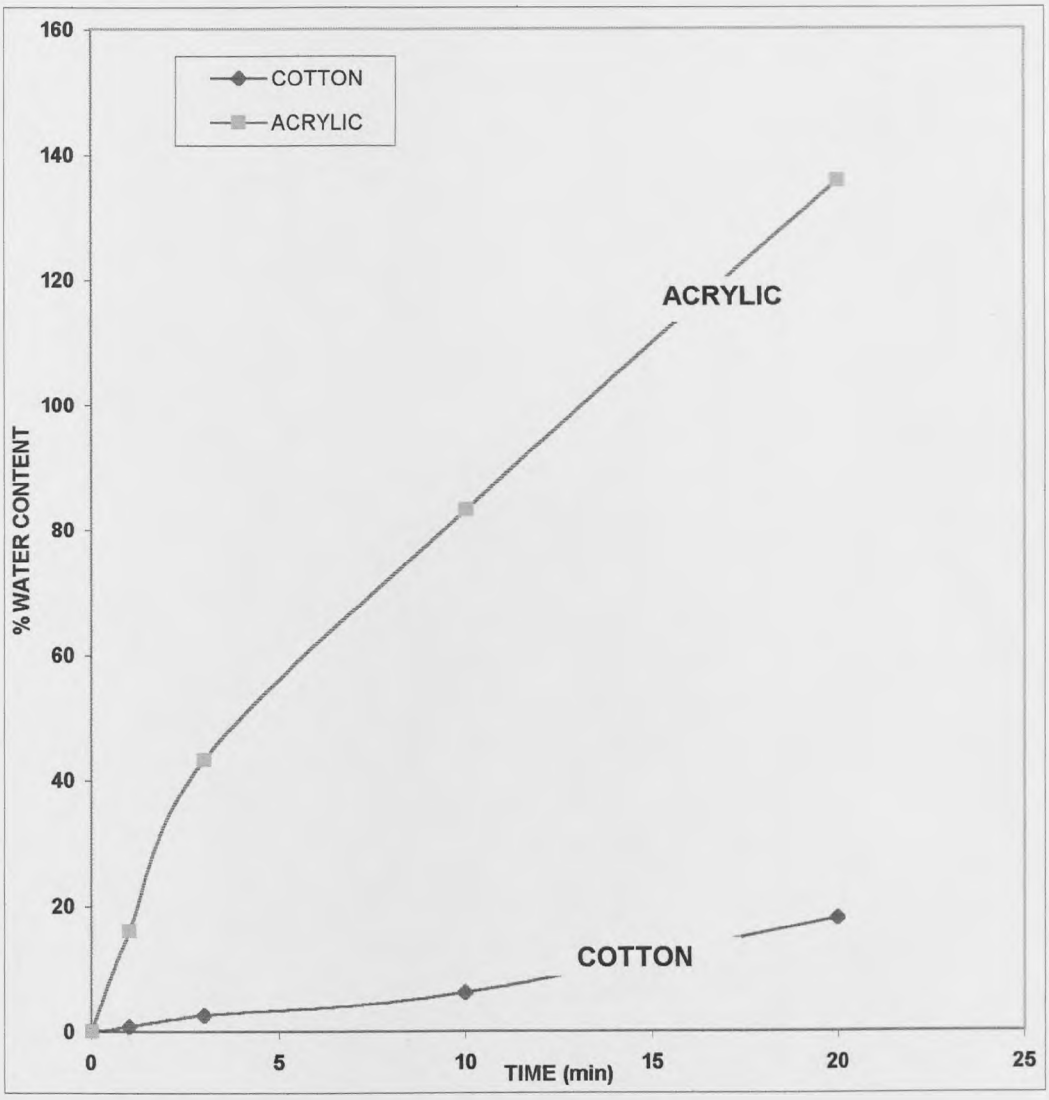


	ABSORPTION RATE /MIN (g)				
	0	**1**	**3**	**10**	**20**
COTTON	0	0.0110	0.0120	0.0250	0.0470
POLYPROPYLENE	0	0.0013	0.0007	0.0015	0.0035

Fig. 92 **Horizontal static transplanar wicking**

DEMAND WETTABILTY MEAN TEST RESULTS
MULTI-LAYER TESTS (MIXED)

COTTON	**- TOP**
ACRYLIC	**- BOTTOM**
COMPRESSION WEIGHT = 0.66g/cm^2	
-VE P/H = 2.0 cm	water pH = 7.0



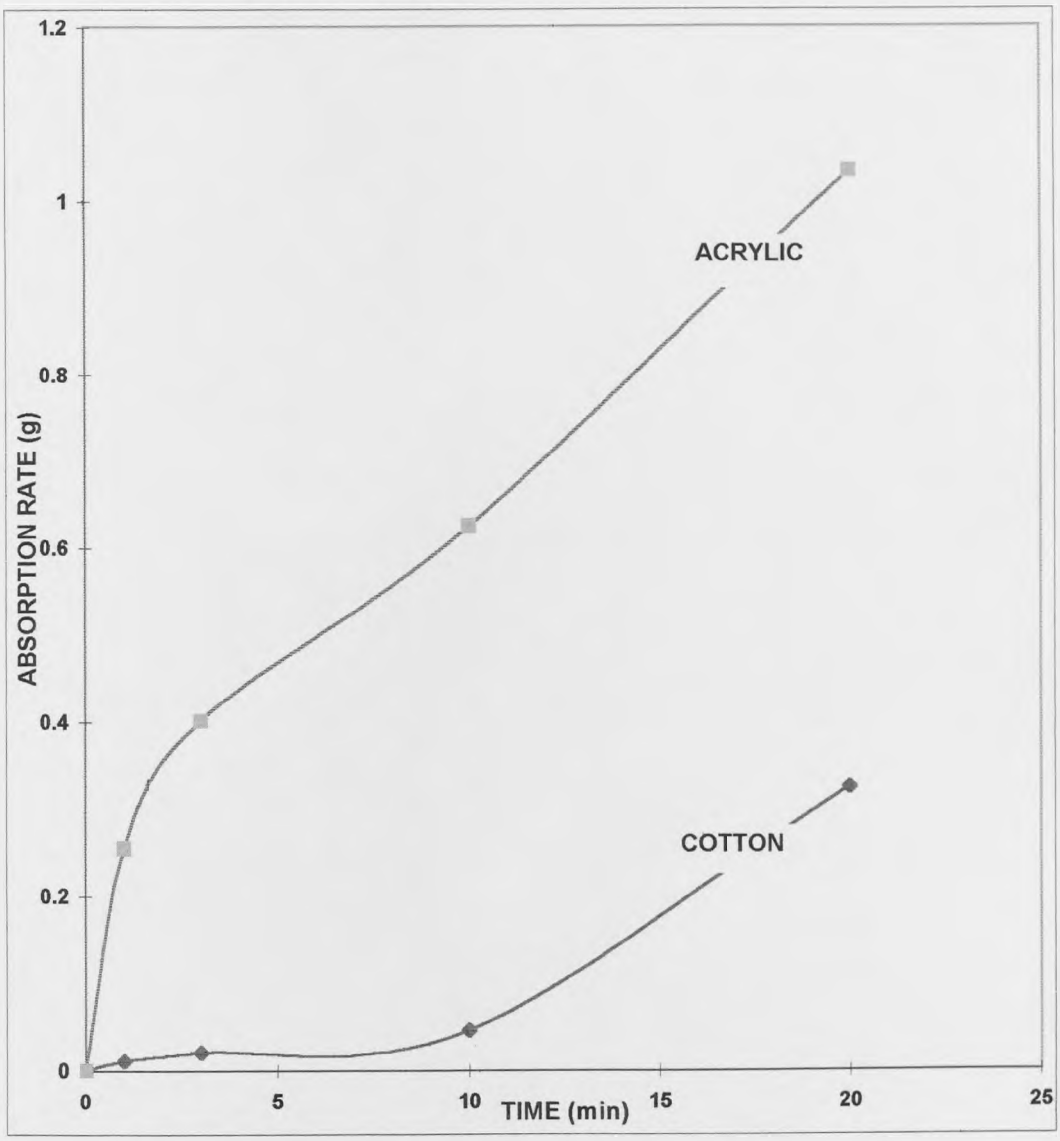
	WATER CONTENT/MIN (%)				
	0	**1**	**3**	**10**	**20**
COTTON	0	0.87	2.55	6.15	17.94
ACRYLIC	0	15.99	43.35	83.42	135.68

Fig. 93 **Horizontal static transplanar wicking**

DEMAND WETTABILITY MEAN TEST RESULTS

MULTI-LAYER TEST RESULTS (MIXED)

COTTON	**- TOP**
ACRYLIC	**- BOTTOM**
COMPRESSION WEIGHT = 0.66g/cm^2	
-VE = 2.0cm	water pH = 7.0

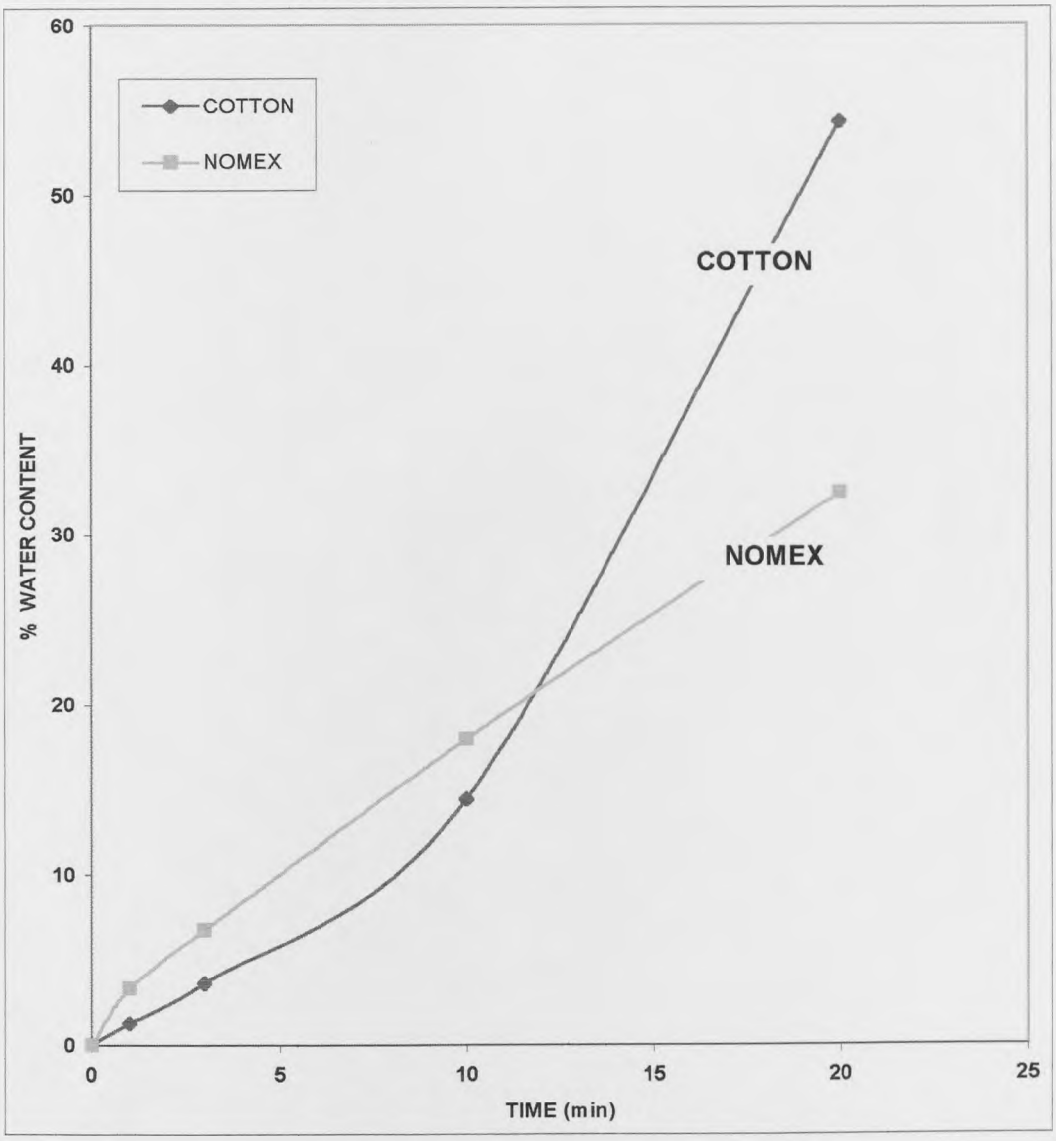


	ABSORPTION RATE /MIN (g)				
	0	**1**	**3**	**10**	**20**
COTTON	0	0.011	0.021	0.046	0.324
ACRYLIC	0	0.255	0.402	0.626	1.034

Fig. 94 **Horizontal static transplanar wicking**

DEMAND WETTABILITY MEAN TEST RESULTS
MULTI-LAYER TESTS (MIXED)

COTTON	**- TOP**
NOMEX	**- BOTTOM**
COMPRESSION WEIGHT = 0.66g/cm^2	
-VE P/H = 2.0 cm	water pH = 7.0



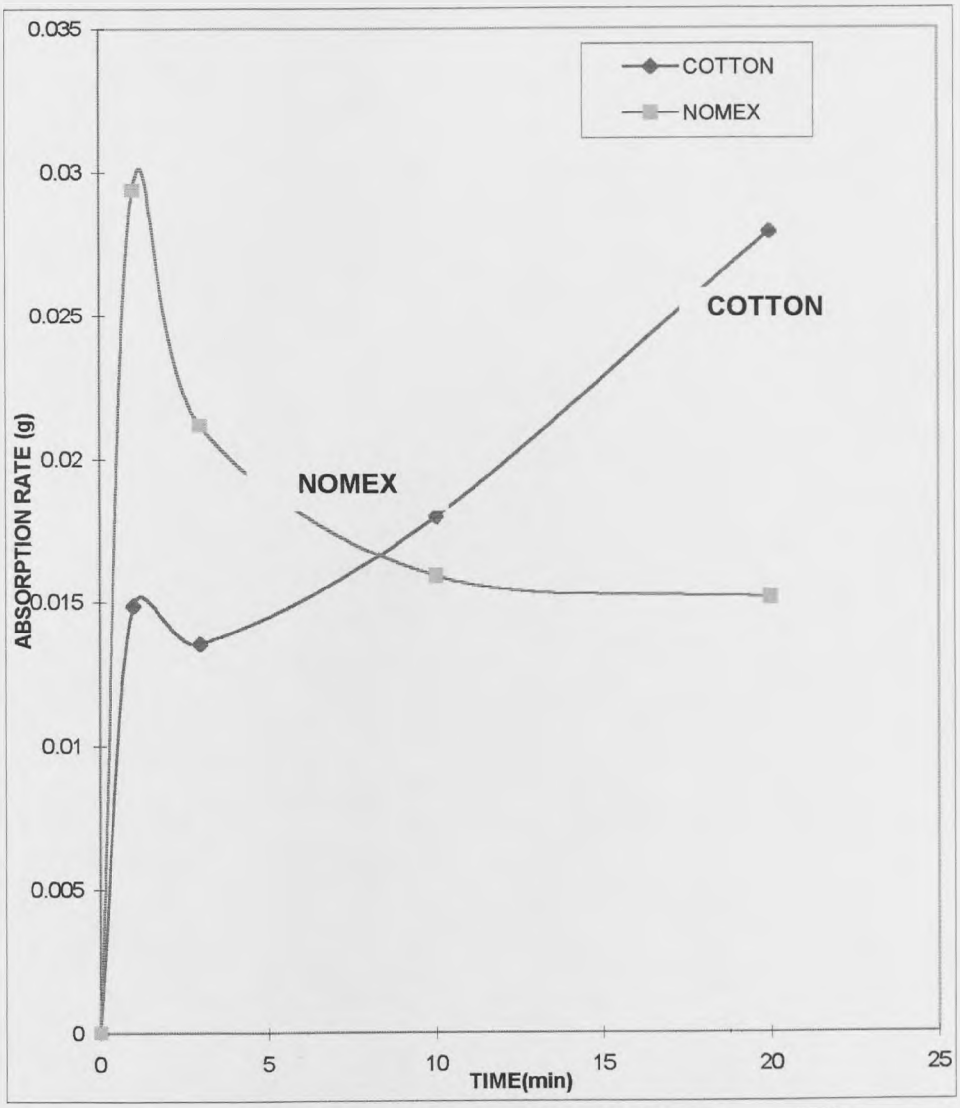
	(%) WATER CONTENT/MIN				
	0	**1**	**3**	**10**	**20**
COTTON	0	1.28	3.64	14.42	54.29
NOMEX	0	3.35	6.76	17.98	32.40

Fig. 95 **Horizontal static transplanar wicking**

DEMAND WETTABILITY MEAN TEST RESULTS

MULTI-LAYER TESTS (MIXED)

COTTON	**- TOP**
NOMEX	**- BOTTOM**
COMPRESSION WEIGHT = 0.66g/cm^2	
-VE P/H = 2.0 cm	water pH = 7.0



	ABSORPTION RATE /TIME PERIOD				
	0	**1**	**3**	**10**	**20**
COTTON	0	0.015	0.0135	0.018	0.028
NOMEX	0	0.029	0.021	0.016	0.015

4.2.2 HORIZONTAL DYNAMIC DEMAND WETTABILITY TECHNIQUE

Using the acrylic and Nomex fabric samples comparison tests were carried out using the dynamic demand wettability test apparatus, in the static mode and in the dynamic mode. The comparisons are illustrated in Tables 40 and 41, and Figures 96 and 97.

These results show almost immediately the increase in wicking produced by the introduction of movement between the test sample and the skin simulant, one type of action which may occur naturally during normal clothing wear.

Table 40

DYNAMIC 'DEMAND WETTABILITY TEST
Static and Dynamic Comparison tests

TEST SAMPLE - ACRYLIC.L.
Knitted ACRYLIC.L. - typical underwear fabric
COMPRESSIONAL WEIGHT = 0.68g/cm
AVERAGE WET WEIGHT OF SPONGE = 90g

	MEAN PERCENTAGE WATER ABSORBED %						
	0	**5**	**10**	**15**	**20**	**25**	**30**
Static	0	18.98	25.85	31.05	35.60	37.26	38.44
Dynamic	0	31.20	54.10	65.34	72.54	77.76	82.71

Table 41

DYNAMIC 'DEMAND WETTABILITY TEST
Static and Dynamic Tests

TEST SAMPLE - NOMEX
Knitted NOMEX- typical underwear fabric
COMPRESSIONAL WEIGHT = 0.68g/cm
WET WEIGHT OF SPONGE = 90g

	PERCENTAGE WATER ABSORBED %						
	0	**5**	**10**	**15**	**20**	**25**	**30**
Static	0	0.95	1.38	1.60	1.94	2.07	2.24
Dynamic	0	4.98	9.05	12.83	16.90	20.89	26.45

Fig. 96

HORIZONTAL DYNAMIC 'DEMAND WETTABILITY TEST
Static and Dynamic Comparison tests

TEST SAMPLE - ACRYLIC.L.
Knitted ACRYLIC.L. - typical underwear fabric

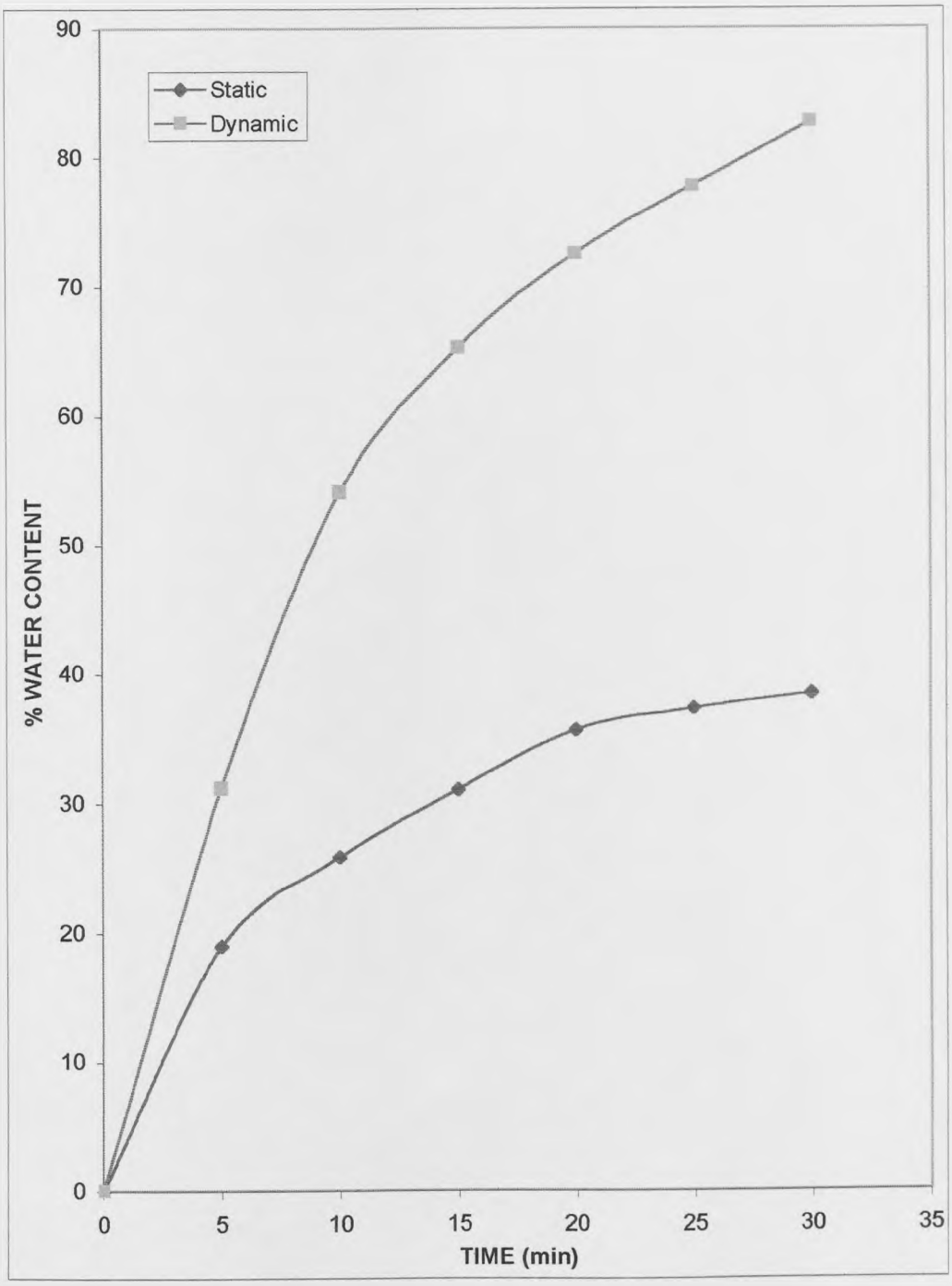
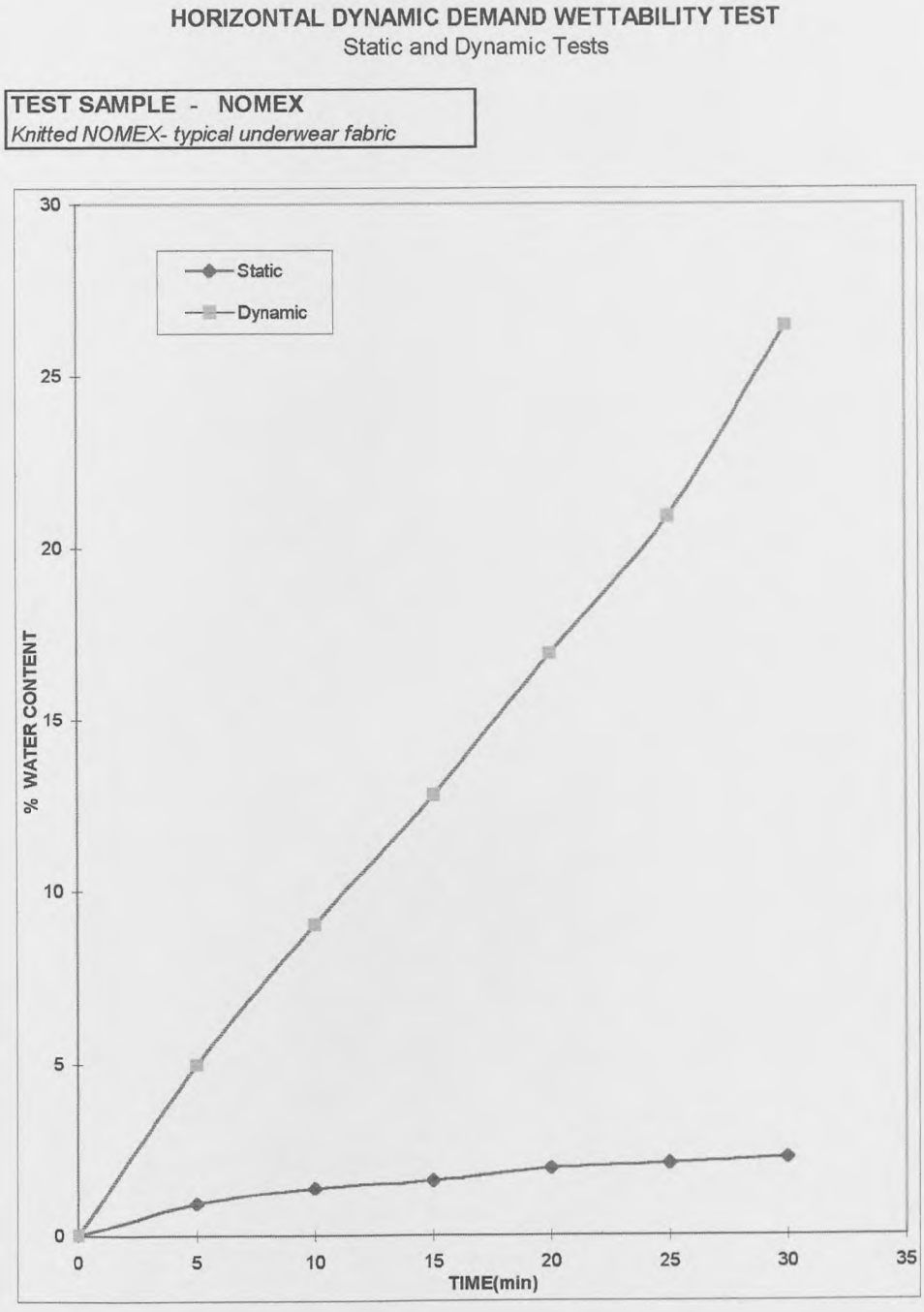


Fig. 97



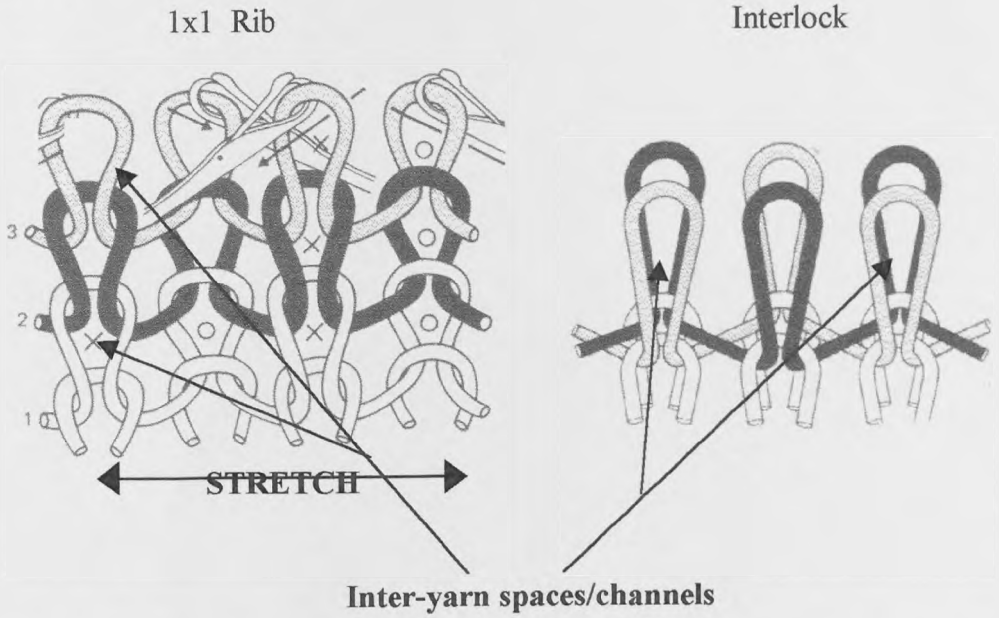
Results from both the Acrylic-(interlock structure) and Nomex-(1x1 rib structure) samples determined immediately the influence that movement had on the wicking rate, whether the sample was a good wicking fabric or a low wicking fabric. In the case of the Nomex sample at the time period of 30 minutes the liquid uptake for the Nomex sample increased from 2.2% to 25.4% liquid content with the introduction of movement between the sample and the skin simulant.

The knitted structure of the Nomex samples were 1x1 rib structure, which although is a more stable structure than a plain knitted structure does incorporate a lot of stretch within its matrix, especially in the wale direction. This will encourage more distortion in the knitted fabric during movement than an interlock structure. An interlock fabric structure is a more stable knitted structure than a 1x1 rib structure, due to the fact that the wales on each side of an interlock fabric structure are the exact opposite to each other and are locked together , and therefore can not be stretched to reveal the reversed loops [79], see figure 98.

Continual movement may drive liquid into both the rib and the interlock structures but the rib structure may have more difficulty retaining the liquid due to the ease with which the changing of the loop shape and size may occur.

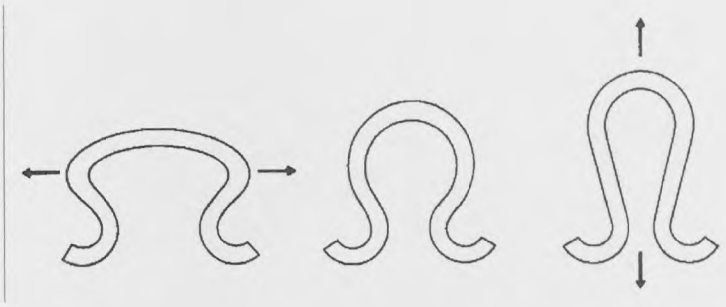
The stability of the interlock structure may help to reduce the amount of structural distortion during movement.

Fig. 98



With the inclusion of movement the distortion of the loops in the knitted structure can take many forms, see figure 99.

Fig. 99 Possible distortion of knitted loops during inter-fabric movement



4.2.2.1 Interlayer Tests

After the initial testing determining the influence of movement on the wicking rate and liquid uptake interlayer tests were carried out.

These were primarily carried out to determine the influence of different fibre assembly combinations, as used in the static demand technique, see section 4.2.1. in combination with movement, as present in a normal clothing assembly.

Each test sample was tested with another test sample placed on top of the skin simulant as a second layer.

Table 42.

DYNAMIC DEMAND WETTABILITY TESTS - MULTI-LAYER RESULTS
INTER-LAYER MOTION TESTS

TEST SAMPLE - ACRYLIC
WEIGHT APPLIED = 0.68g/cm^2
SPEED = SLOWEST
ACRYLIC/TEST SAMPLE/SKIN SIM

ACRYLIC ON		MEAN PERCENTAGE WATER CONTENT (%)					
	0	5	10	15	20	25	30
NOMEX	0	2.73	5.09	8.30	13.37	17.82	23.61
ACRYLIC	0	8.95	19.11	29.70	38.89	52.42	57.51
POLY	0	17.82	45.62	85.98	101.17	107.31	112.00
COTTON	0	15.30	43.36	75.81	93.51	102.29	109.70

Table 43

DYNAMIC DEMAND WETTABILITY TESTS - MULTI-LAYER RESULTS
INTER-LAYER STATIC TESTS

TEST SAMPLE - ACRYLIC
WEIGHT APPLIED = 0.68g/cm^2
SPEED = STATIC
ACRYLIC/TEST SAMPLE/SKIN SIM

ACRYLIC ON		MEAN PERCENTAGE WATER CONTENT (%)					
	0	5	10	15	20	25	30
NOMEX	0	0.59	0.69	0.76	0.79	0.81	0.87
ACRYLIC	0	0.33	0.43	0.47	0.53	0.56	0.56
POLY	0	0.44	0.53	0.64	0.73	0.77	0.82
COTTON	0	5.64	9.67	11.93	16.25	18.44	20.05

Fig. 100

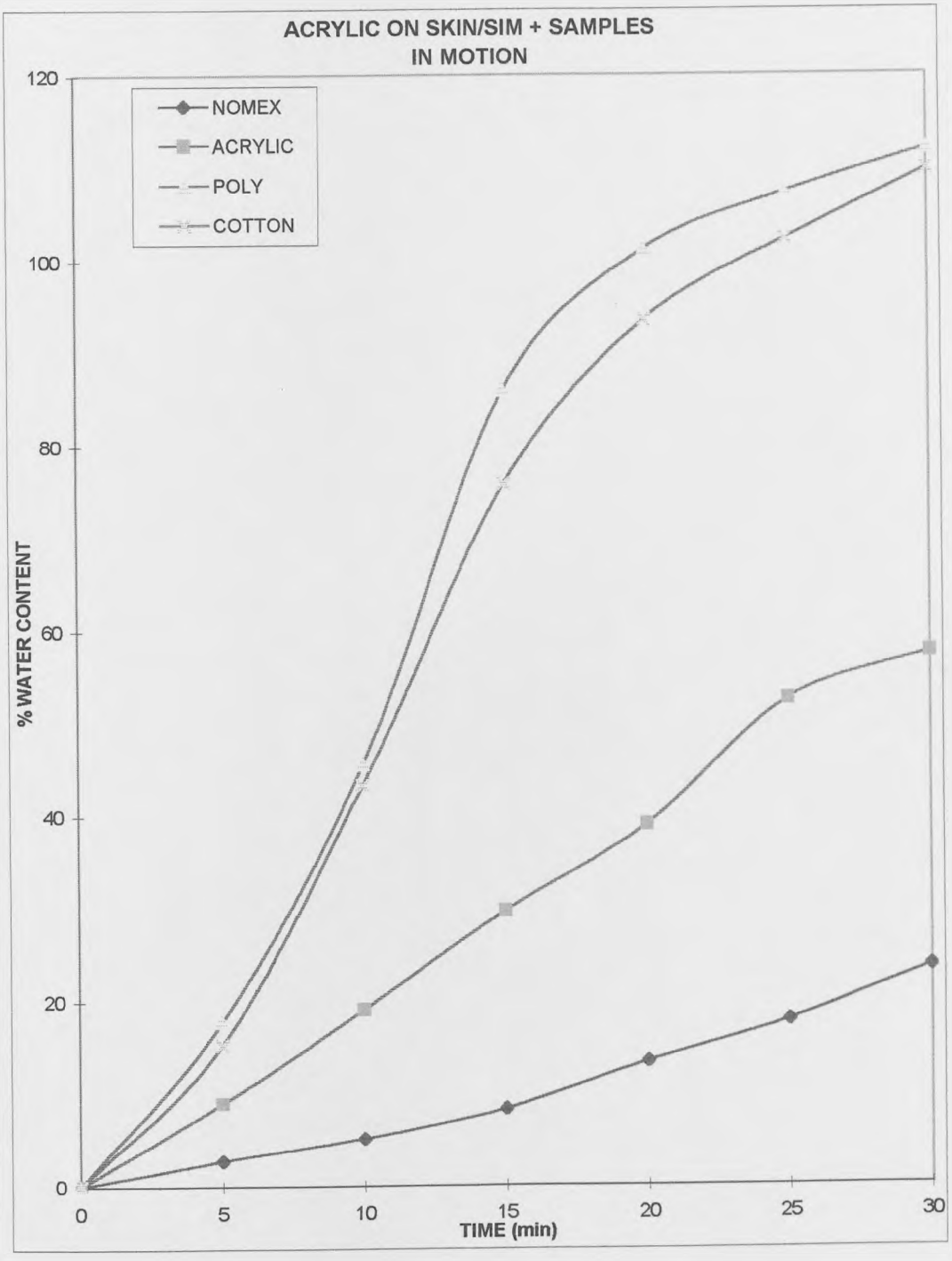

ACRYLIC ON SKIN/SIM + SAMPLES
IN MOTION
NOMEX
ACRYLIC
POLY
COTTON
% WATER CONTENT
TIME (min)
0
20
40
60
80
100
120
0
5
10
15
20
25
30

Fig. 101

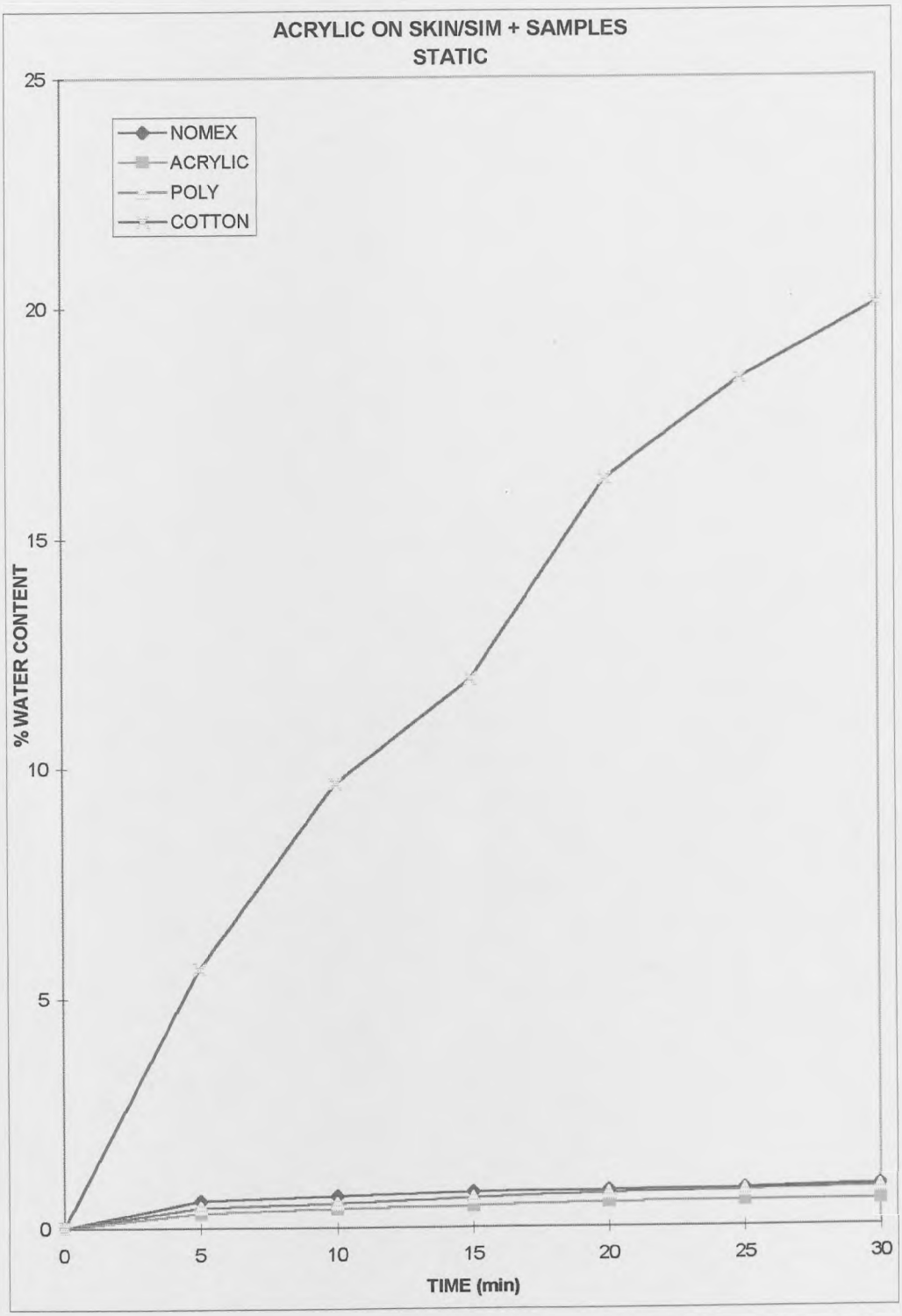

ACRYLIC ON SKIN/SIM + SAMPLES
STATIC
NOMEX
ACRYLIC
POLY
COTTON
% WATER CONTENT
TIME (min)
0
5
10
15
20
25
30

Table 44.

DYNAMIC DEMAND WETTABILITY TESTS - MULTI-LAYER RESULTS
INTER-LAYER MOTION TESTS

TEST SAMPLE - COTTON
WEIGHT APPLIED = 0.68g/cm^2
SPEED = SLOWEST
COTTON/TEST SAMPLE/SKIN SIM

COTTON ON		MEAN PERCENTAGE WATER CONTENT (%)					
	0	5	10	15	20	25	30
NOMEX	0	35.92	66.31	115.00	165.75	209.22	247.66
ACRYLIC	0	206.16	260.57	279.78	290.15	295.13	298.26
POLY	0	11.11	24.80	40.49	55.98	72.77	89.90
COTTON	0	277.79	290.77	296.04	296.90	297.69	299.57

Table 45

DYNAMIC DEMAND WETTABILITY TESTS - MULTI-LAYER RESULTS
INTER-LAYER STATIC TESTS

TEST SAMPLE - COTTON
WEIGHT APPLIED = 0.68g/cm^2
SPEED = STATIC
COTTON/TEST SAMPLE/SKIN SIM

COTTON ON		MEAN PERCENTAGE WATER CONTENT (%)					
	0	5	10	15	20	25	30
NOMEX	0	3.16	4.67	5.89	6.75	9.38	10.71
ACRYLIC	0	14.20	18.99	22.09	28.22	29.09	29.68
POLY	0	2.28	3.38	4.04	5.25	5.65	6.09
COTTON	0	203.15	213.78	219.41	223.05	225.65	227.93

Fig. 102

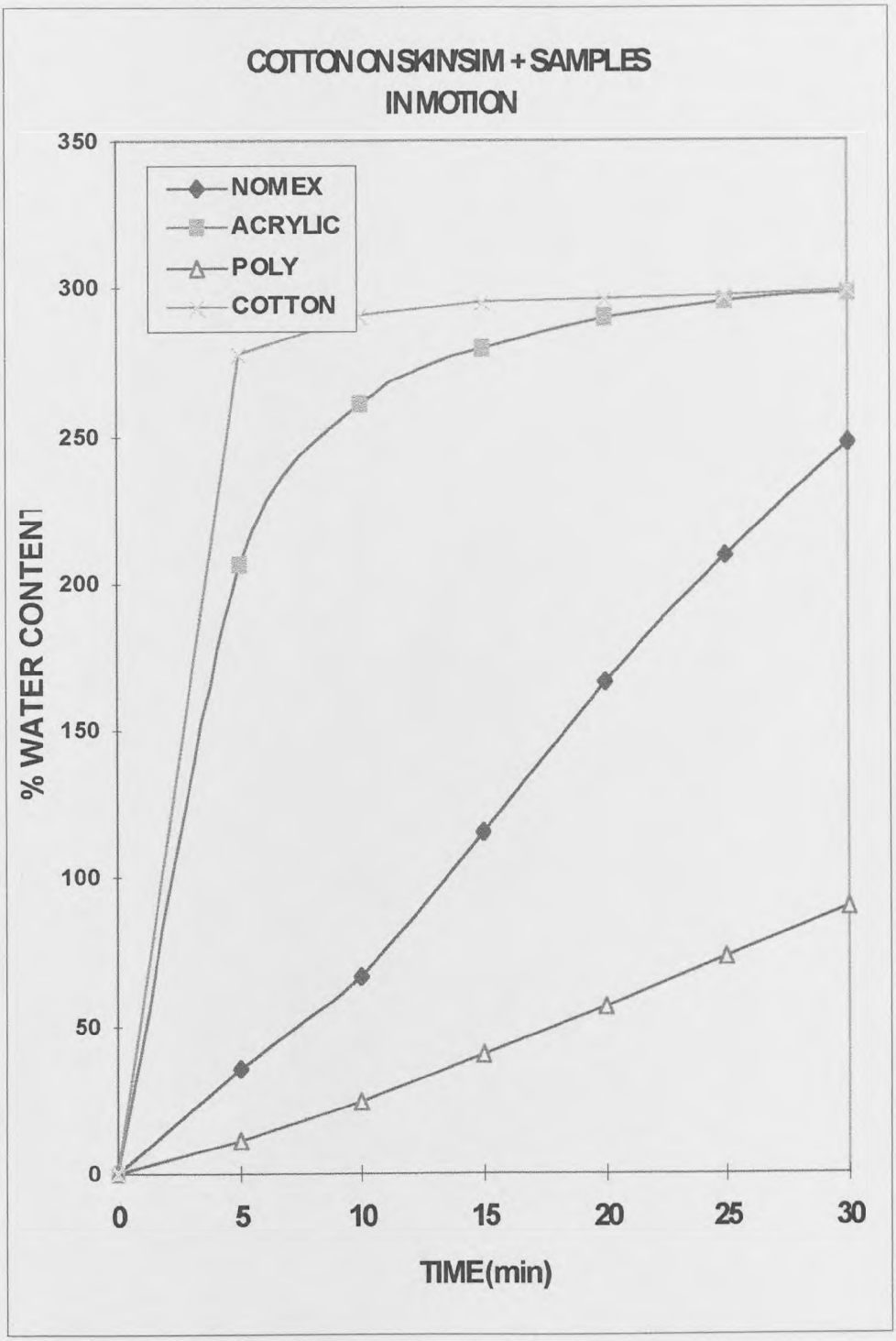

COTTON ON SKIN'SIM + SAMPLES IN MOTION
NOMEX
ACRYLIC
POLY
COTTON
% WATER CONTENT
TIME(min)
0
50
100
150
200
250
300
350
0
5
10
15
20
25
30

Fig. 103

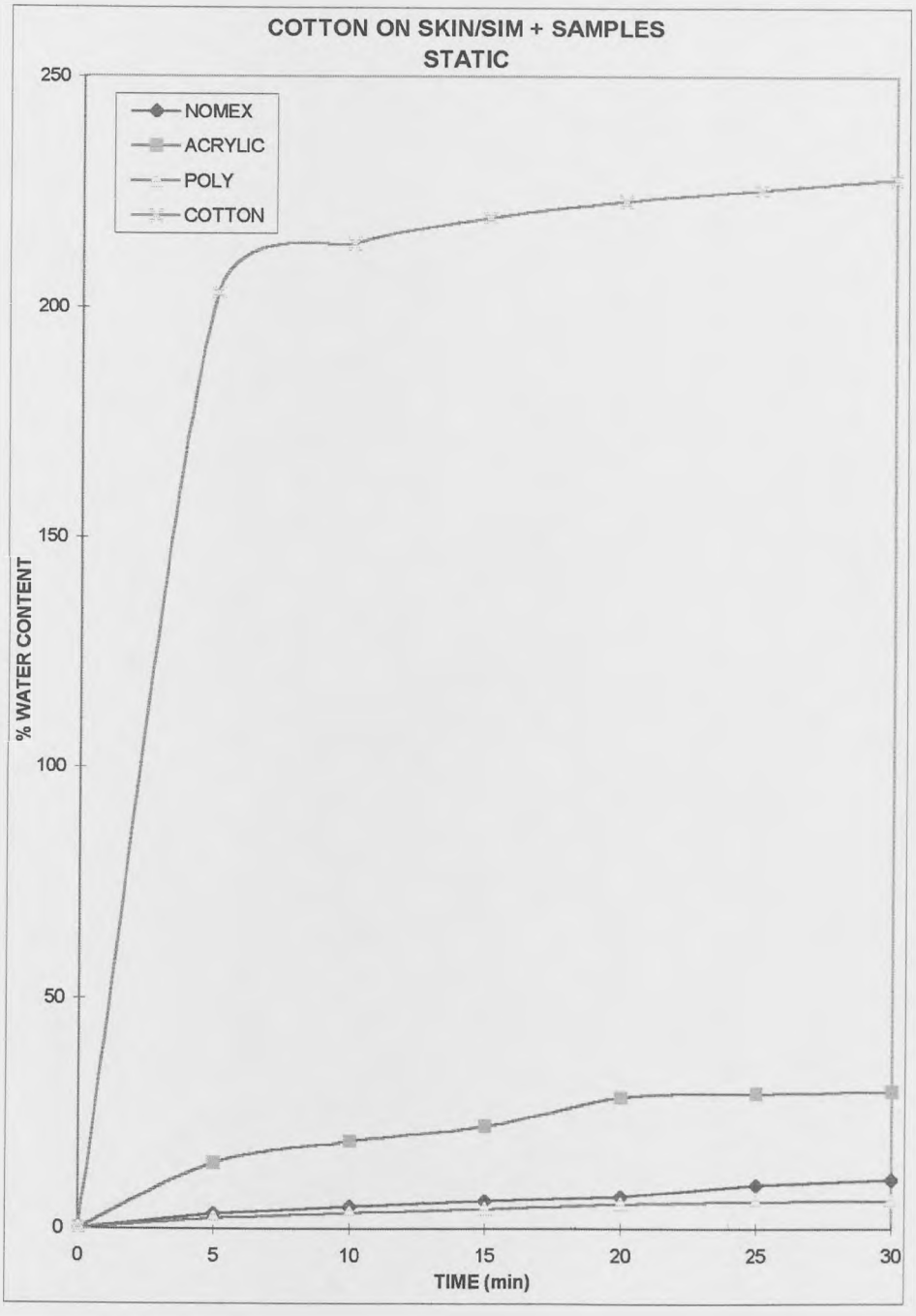

COTTON ON SKIN/SIM + SAMPLES
STATIC
NOMEX
ACRYLIC
POLY
COTTON
% WATER CONTENT
250
200
150
100
50
0
0
5
10
15
20
25
30
TIME (min)

Table 46

DYNAMIC DEMAND WETTABILITY TESTS - MULTI-LAYER RESULTS
INTER-LAYER MOTION TESTS

TEST SAMPLE - NOMEX
WEIGHT APPLIED = 0.68g/cm2
SPEED = SLOWEST
NOMEX/TEST SAMPLE/SKIN SIM

NOMEX ON	MEAN PERCENTAGE WATER CONTENT (%)						
	0	5	10	15	20	25	30
NOMEX	0	2.73	5.09	8.30	13.37	17.82	23.61
ACRYLIC	0	8.95	19.11	29.70	38.89	52.42	57.51
POLY	0	0.74	0.89	0.94	1.00	1.09	1.16
COTTON	0	0.73	0.88	0.93	1.12	1.07	1.14

Table 47

DYNAMIC DEMAND WETTABILITY TESTS - MULTI-LAYER RESULTS
INTER-LAYER STATIC TESTS

TEST SAMPLE - NOMEX
WEIGHT APPLIED = 0.68g/cm^2
SPEED = STATIC
NOMEX/TEST SAMPLE/SKIN SIM

NOMEX ON	MEAN PERCENTAGE WATER CONTENT (%)						
	0	5	10	15	20	25	30
NOMEX	0	0.73	0.92	1.00	1.07	1.14	1.20
ACRYLIC	0	0.85	0.97	1.04	1.08	1.11	1.15
POLY	0	0.69	0.87	0.93	1.02	1.07	1.12
COTTON	0	1.05	1.86	2.49	2.94	3.48	4.00

Fig. 104

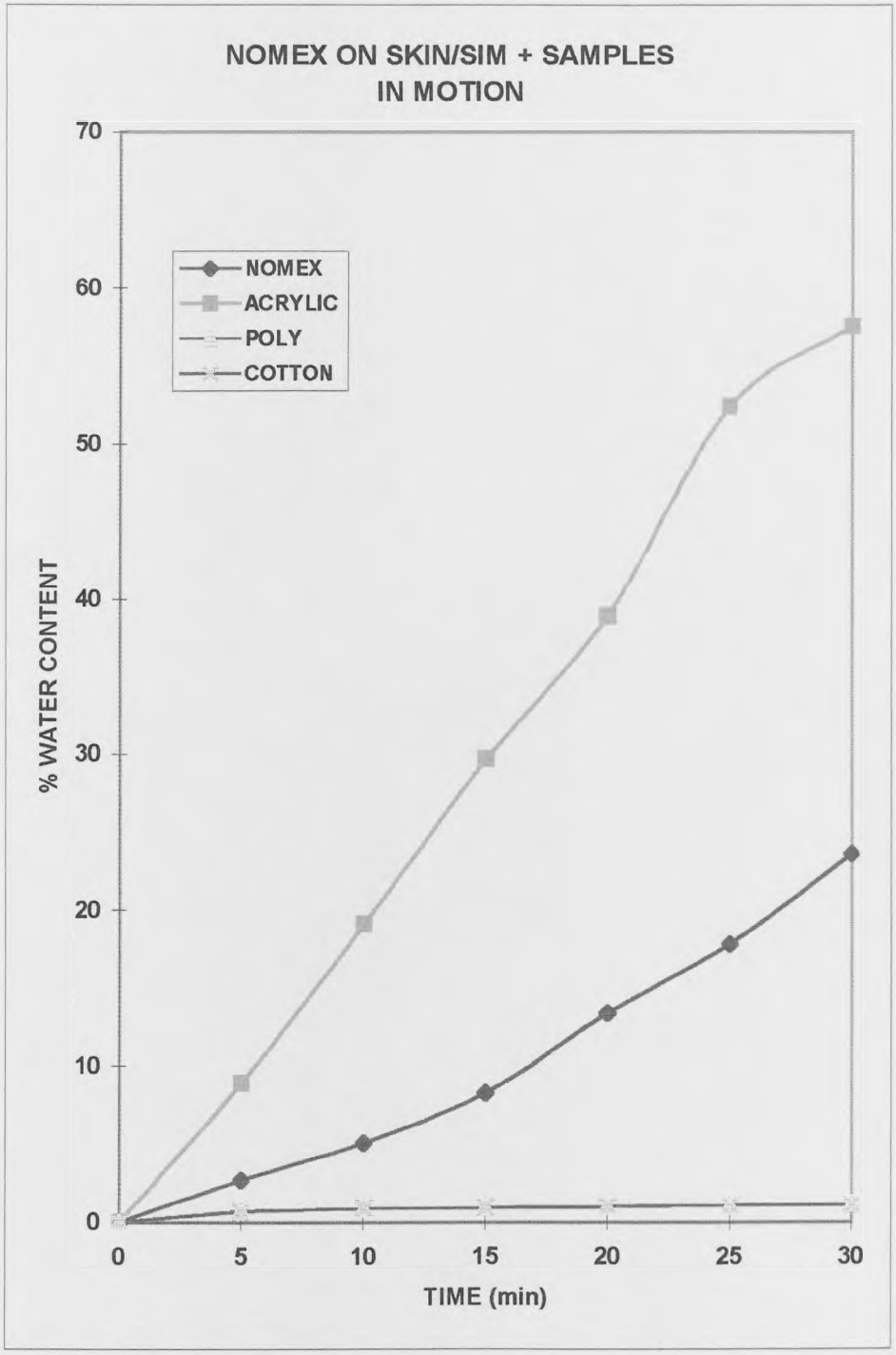

NOMEX ON SKIN/SIM + SAMPLES
IN MOTION
NOMEX
ACRYLIC
POLY
COTTON
% WATER CONTENT
TIME (min)
0
10
20
30
40
50
60
70
0
5
10
15
20
25
30

Fig. 105

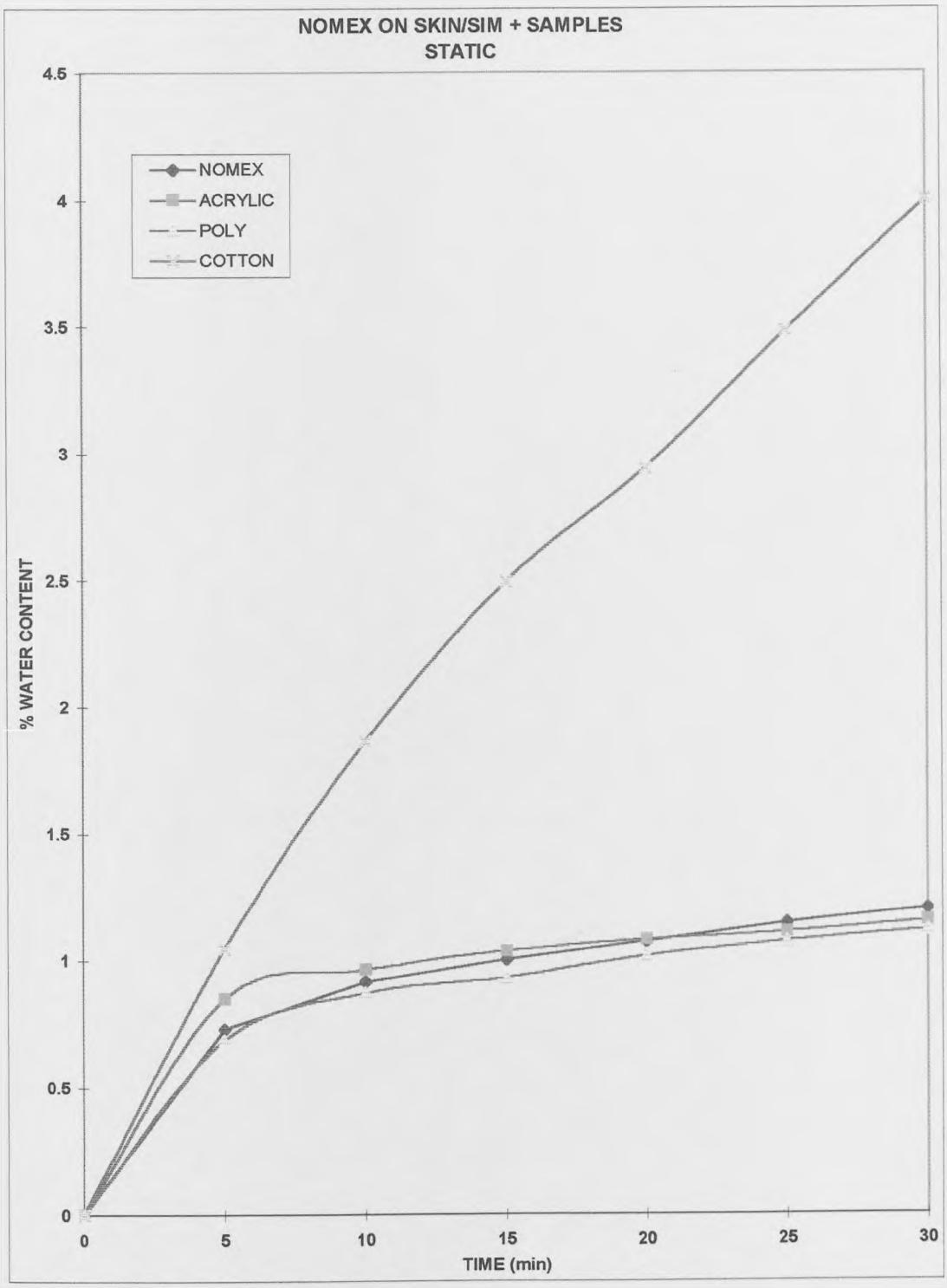

NOMEX ON SKIN/SIM + SAMPLES
STATIC
NOMEX
ACRYLIC
POLY
COTTON
% WATER CONTENT
TIME (min)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
0
5
10
15
20
25
30

Table 48

DYNAMIC DEMAND WETTABILITY TESTS - MULTI-LAYER RESULTS
INTER-LAYER MOTION TESTS

TEST SAMPLE - POLYOROPYLENE
WEIGHT APPLIED = 0.68g/cm^2
SPEED = SLOWEST
POLYPROPYLENE/TEST SAMPLE/SKIN SIM

POLY ON	MEAN PERCENTAGE WATER CONTENT (%)						
	0	5	10	15	20	25	30
NOMEX	0	1.21	2.26	2.94	3.48	3.91	4.42
ACRYLIC	0	2.73	5.09	8.30	13.37	17.82	23.61
POLY	0	0.32	0.61	0.84	1.01	1.27	1.46
COTTON	0	9.81	18.22	25.98	32.39	38.91	44.60

Table 49

DYNAMIC DEMAND WETTABILITY TESTS - MULTI-LAYER RESULTS
INTER-LAYER STATIC TESTS

TEST SAMPLE - POLYOROPYLENE
WEIGHT APPLIED = 0.68g/cm^2
SPEED = STATIC
POLYPROPYLENE/TEST SAMPLE/SKIN SIM

POLY ON	MEAN PERCENTAGE WATER CONTENT (%)						
	0	5	10	15	20	25	30
NOMEX	0	0.33	0.41	0.47	0.51	0.53	0.55
ACRYLIC	0	0.32	0.44	0.49	0.55	0.56	0.63
POLY	0	0.22	0.25	0.30	0.30	0.33	0.38
COTTON	0	0.16	0.26	0.36	0.38	0.45	0.50

Fig. 106

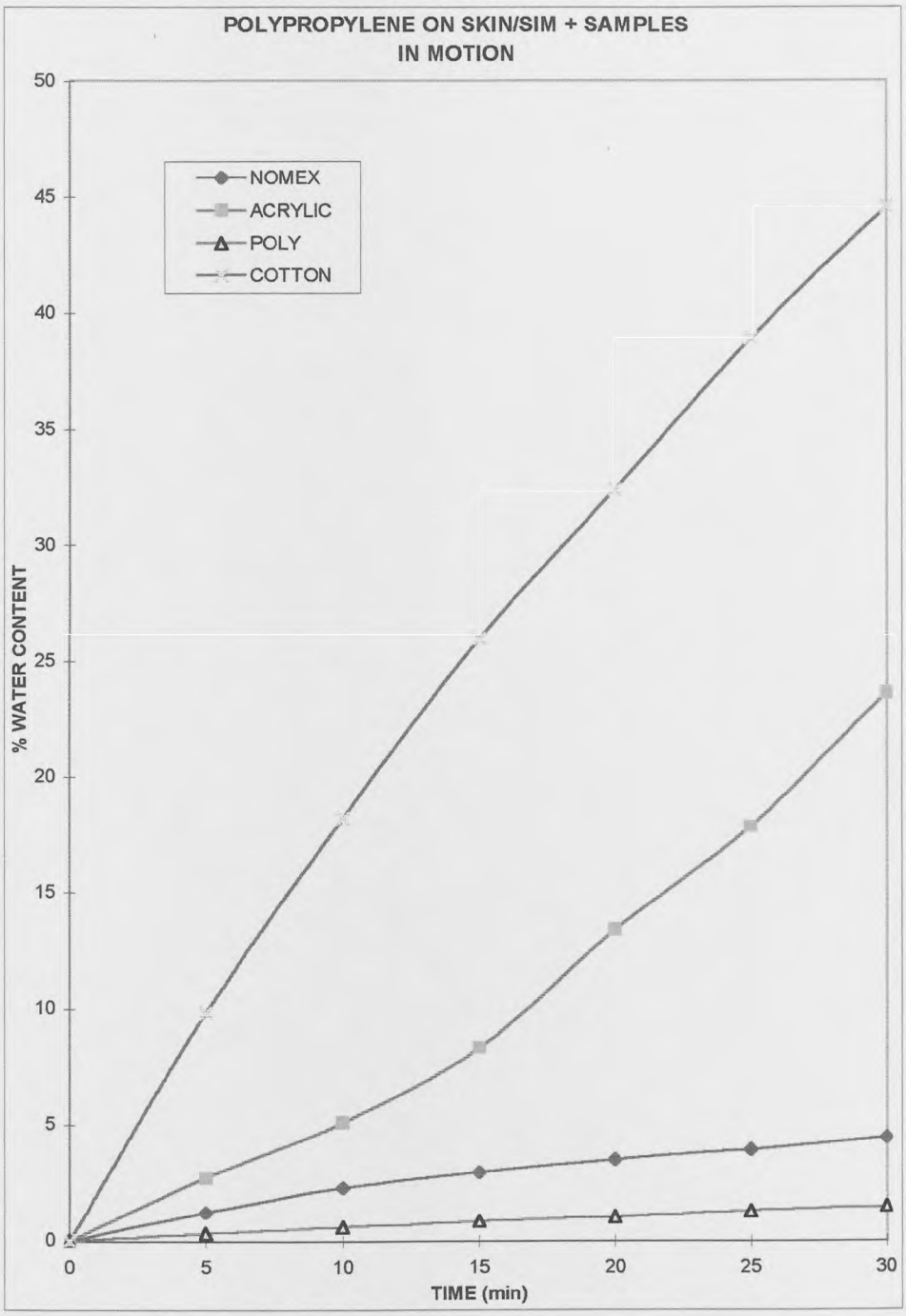
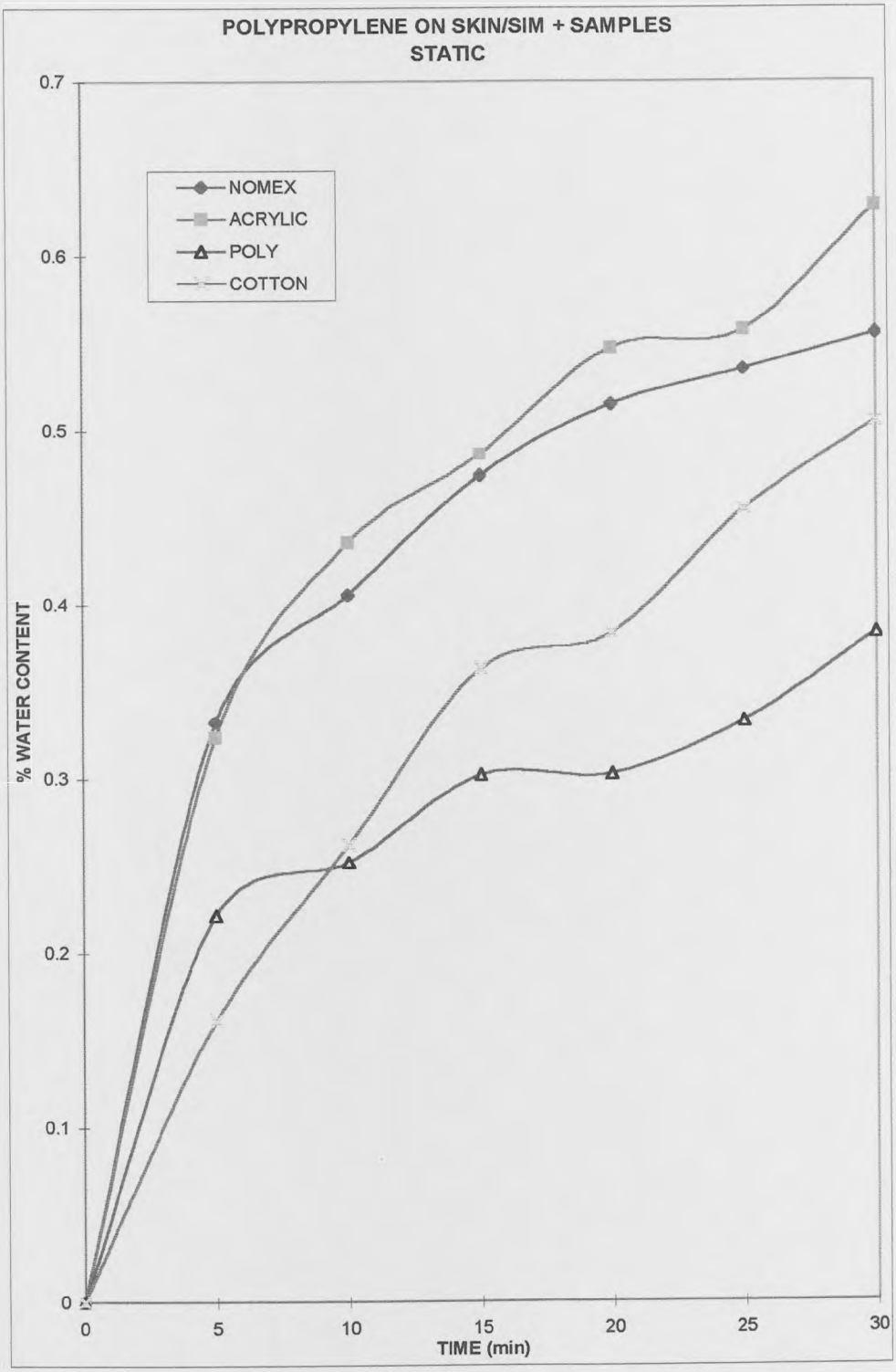

POLYPROPYLENE ON SKIN/SIM + SAMPLES
IN MOTION
NOMEX
ACRYLIC
POLY
COTTON
% WATER CONTENT
TIME (min)
0
5
10
15
20
25
30
35
40
45
50

Fig. 107


POLYPROPYLENE ON SKIN/SIM + SAMPLES
STATIC
NOMEX
ACRYLIC
POLY
COTTON
% WATER CONTENT
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20
25
30
TIME (min)

- **Inter-layer Results – (Table 42 - 49, and figures 100 – 107)**

The acrylic sample produced traditional results in both the static and the dynamic tests. In combination with the polypropylene sample, the acrylic had the smallest liquid uptake in the dynamic test, and the largest with the cotton sample. In the static test the cotton fabric produced the higher water in the acrylic fabric. The initial wicking rate was fairly steady in all cases, and high wicking rates were not observed.

The cotton fabric sample produced more expected results, under both conditions the cotton sample had a high water uptake. The lowest uptake was produced on the polypropylene fabric sample. Cotton on cotton produced a classic hyperbolic curve, illustrating a rapid initial wicking rate which settled down to a steady increase in liquid uptake, this occurred in both the static and dynamic states.

The greater liquid uptake in the Nomex fabric was achieved on the acrylic fabric in the dynamic test, however in the static test the greater uptake occurred on the cotton fabric. Liquid uptake on the Nomex, acrylic and polypropylene all produced initially rapid liquid uptake which reduced to a slower steady state. In the static state.

Polypropylene followed a fairly predictable sequence taking up the majority of water on the cotton fabric , and the least amount on polypropylene in the dynamic state.

The static state produced results which were illustrated by very uncertain hyperbolic curves. Although all four fabrics produced rapid water uptake in the first five minutes, uptake from five minutes on was variable.

4.2.3 COMPARISON OF SURFACE TYPES IN COTTON INTERLOCK FABRIC

Due to observation in earlier tests it was revealed that during the dynamic tests wear on the samples may begin to affect the results obtained.
Therefore another set of experiments were carried out on the cotton interlock fabric samples only to determine the effect of fabric surface change if any.
Four sample types with the following surface types were tested in the static state on the horizontal dynamic apparatus. :

Normal - no wear applied to the surface ;

Singed - surface hairs removed by flame ;

Rubbed - surface rubbed against another fabric surface ;

Brushed - surface has been brushed.

The samples were tested under three different weights, 0.68g/cm^2 ; 1.0g/cm^2 ; 3.0g/cm^2.

Under the lowest weight, the 0.68g/cm^2 there was little difference in water uptake between the normal and the singed surface samples. There was a greater difference in uptake between the rubbed and the brushed (see table 50 and fig. 108).
However with an increase in weight application this difference between the rubbed and brushed surfaces was reduced, see table 51 and fig 110. At the final weight 3.0g/cm^2 the singed, rubbed and brushed surfaces produced results closer together, with the normal surface continuing the trend with the highest liquid uptake.

Tables 53 to 56 and figures 114 to 121 represent the comparison of the compression effect on each surface type.
The singed surface sample produced no significant difference in water uptake between the applied weights of 1.0g and 3.0g, which probably means that an increase in weight much above 3.0g would begin to hinder the liquid uptake. It is assumed that the increase in liquid uptake from the 0.68g to the 1.0g weight is due to a better contact being achieved between the skin simulant and the sample, and an increase in weight much above 3.0g would begin to have the opposite affect.
It would also appear that this type of surface is more conducive to wicking than a surface disrupted by abrasion.

The normal surface appears to have performed the best in terms of wicking power, and there seems to be a more significant increase in water uptake with an increase in the weight applied to the sample

Table 50

COMPARISON OF COTTON SURFACES

(ON SKIN SIM ONLY)
WEIGHT APPLIED =0.68g/cm^2
SPEED = NO MOTION

SURFACE TYPES	WATER CONTENT (%)						
	0	5	10	15	20	25	30
NORMAL	0	216.3	225.8	231.0	234.9	237.8	240.2
SINGED	0	215.3	224.5	229.4	233.2	236.1	238.6
RUBBED	0	197.9	209.6	215.6	219.2	222.3	224.7
BRUSHED	0	150.2	187.1	199.1	206.8	211.4	214.1

	t / Δω (g) v t (Time) min						
	0	5	10	15	20	25	30
NORMAL	0	2.28	4.37	6.41	8.41	10.38	12.33
SINGED	0	2.30	4.41	6.48	8.50	10.49	12.46
RUBBED	0	2.39	4.51	6.58	8.64	10.64	12.64
BRUSHED	0	3.23	5.19	7.33	9.40	11.50	13.62

Table 51

COMPARISON OF COTTON SURFACES

(ON SKIN SIM ONLY)
WEIGHT APPLIED =1.0g/cm^2
SPEED = NO MOTION

SURFACE TYPES	WATER CONTENT (%)						
	0	5	10	15	20	25	30
SINGED	0	213.0	228.4	235.4	240.2	244.6	247.3
NORMAL	0	220.4	233.3	241.5	246.9	251.3	255.1
BRUSHED	0	186.6	213.1	220.2	225.2	228.8	231.6
RUBBED	0	201.4	215.8	222.6	227.3	230.8	233.4

	t / Δω (g) v t (Time) min						
	0	5	10	15	20	25	30
NORMAL	0	2.22	4.20	6.09	7.94	9.75	11.53
SINGED	0	2.28	4.26	6.19	8.09	9.93	11.79
RUBBED	0	2.39	4.38	6.37	8.32	10.25	12.16
BRUSHED	0	2.61	4.56	6.63	8.64	10.63	12.60

Table 52

COMPARISON OF COTTON SURFACES

(ON SKIN SIM ONLY)
WEIGHT APPLIED = 3.0g/cm^2
SPEED = NO MOTION

SURFACE TYPES	WATER CONTENT (%)						
	0	5	10	15	20	25	30
NORMAL	0	235.6	250.6	259.7	266.3	270.9	275.5
RUBBED	0	220.9	227.6	235.3	240.9	244.9	248.8
SINGED	0	212.5	277.6	234.8	239.4	243.4	246.0
BRUSHED	0	203.4	221.8	228.3	233.6	237.9	240.4

	$t / \Delta\omega$ (g) v t (Time) min						
	0	5	10	15	20	25	30
BRUSHED	0	2.39	4.37	6.37	8.31	10.19	12.11
SINGED	0	2.28	4.26	6.19	8.10	10.00	11.83
RUBBED	0	2.17	4.15	6.02	7.84	9.64	11.38
NORMAL	0	2.07	3.90	5.64	7.34	9.01	10.64

Fig. 108 Comparison of Different surfaces under a weight of 0.68g/cm^2
Cotton weft knit interlock fabric sample

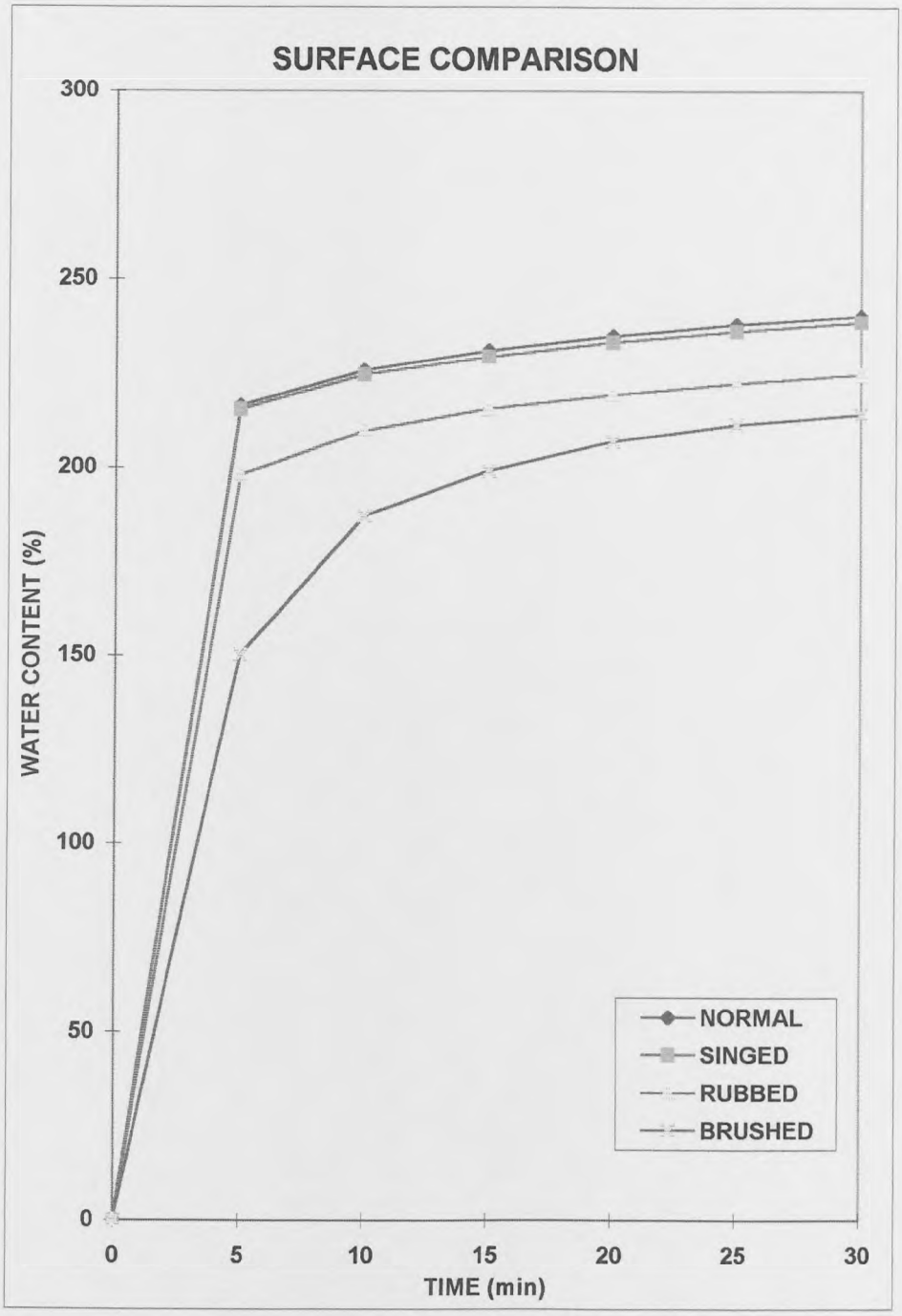


Fig. 109 Comparison of Different surfaces under a weight of 0.68g/cm^2

Cotton weft knit interlock fabric sample

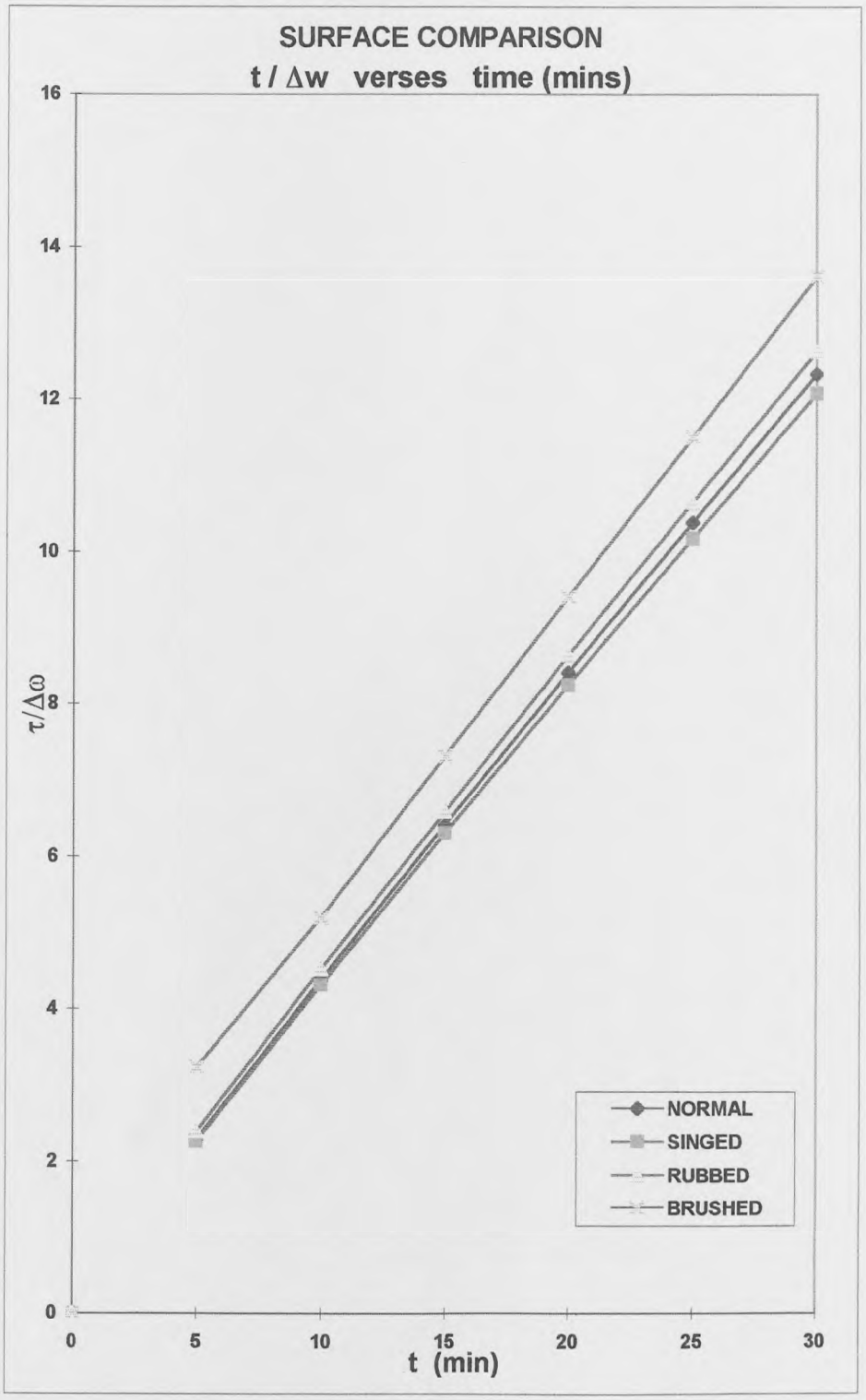


Fig. 110 Comparison of Different surfaces under a weight of 1.0g/cm^2

Cotton weft knit interlock fabric sample

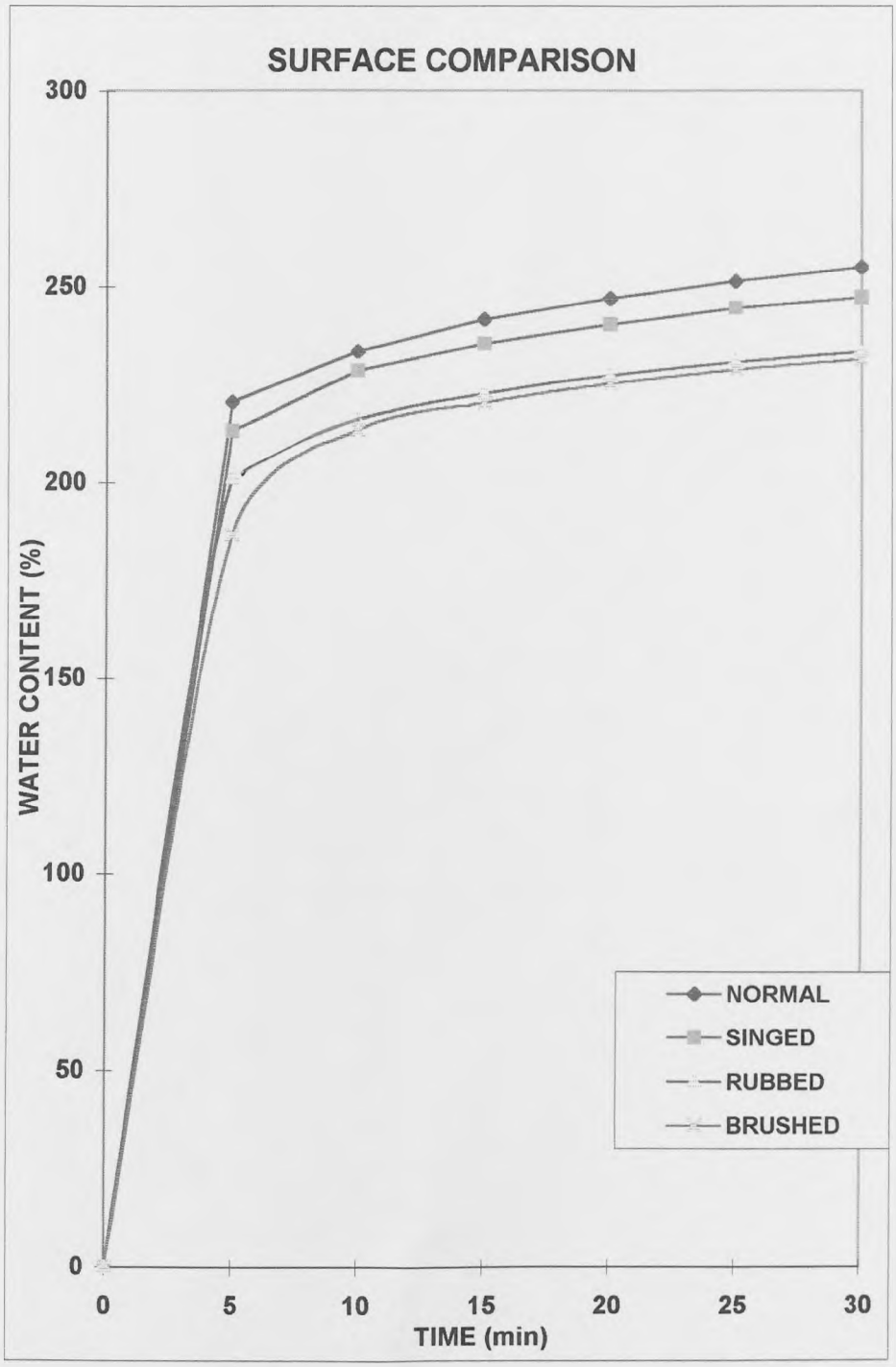


Fig. 111 Comparison of Different surfaces under a weight of 1.0g/cm^2
Cotton weft knit interlock fabric sample

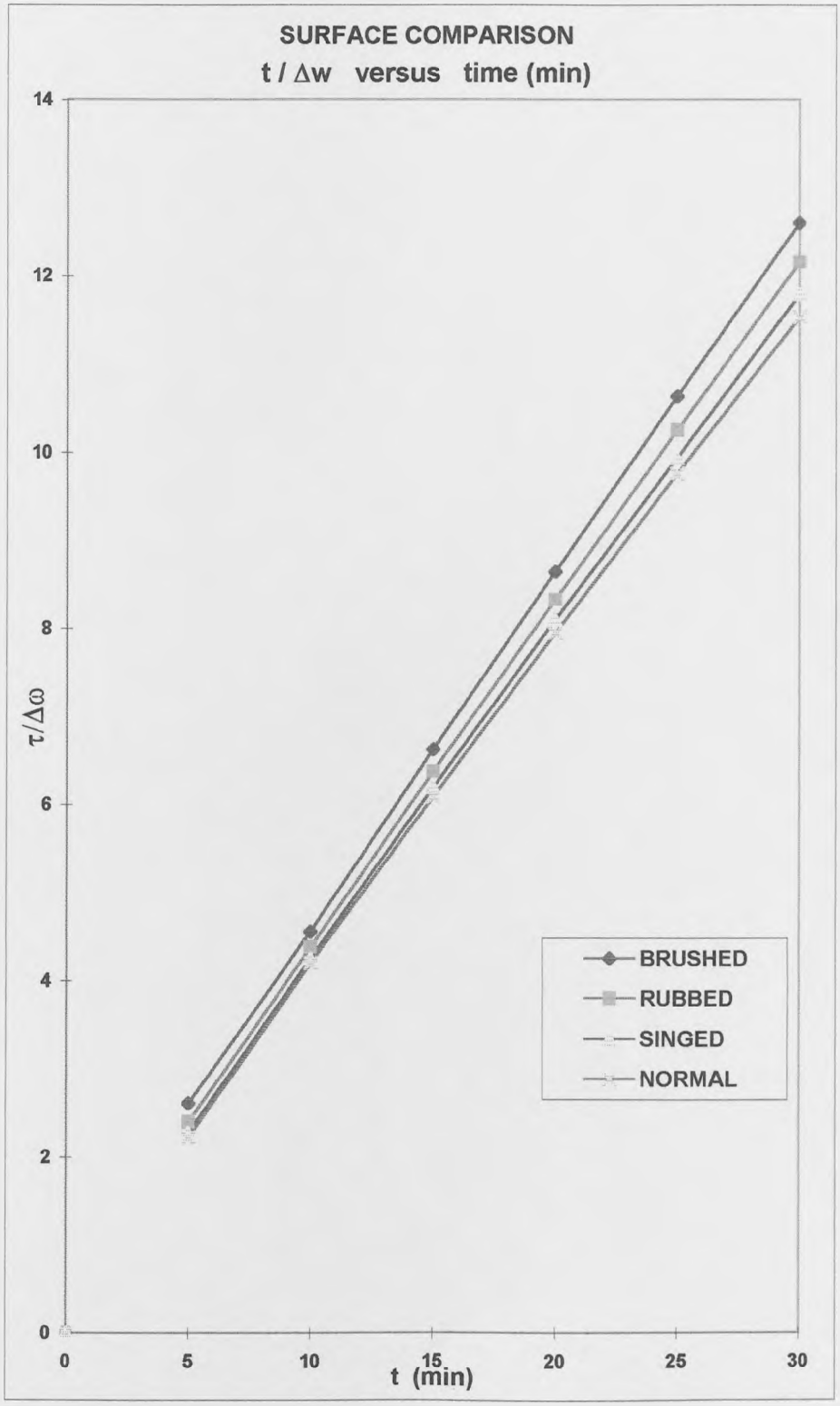


Fig. 112 Comparison of Different surfaces under a weight of 3.0g/cm^2
Cotton weft knit interlock fabric sample

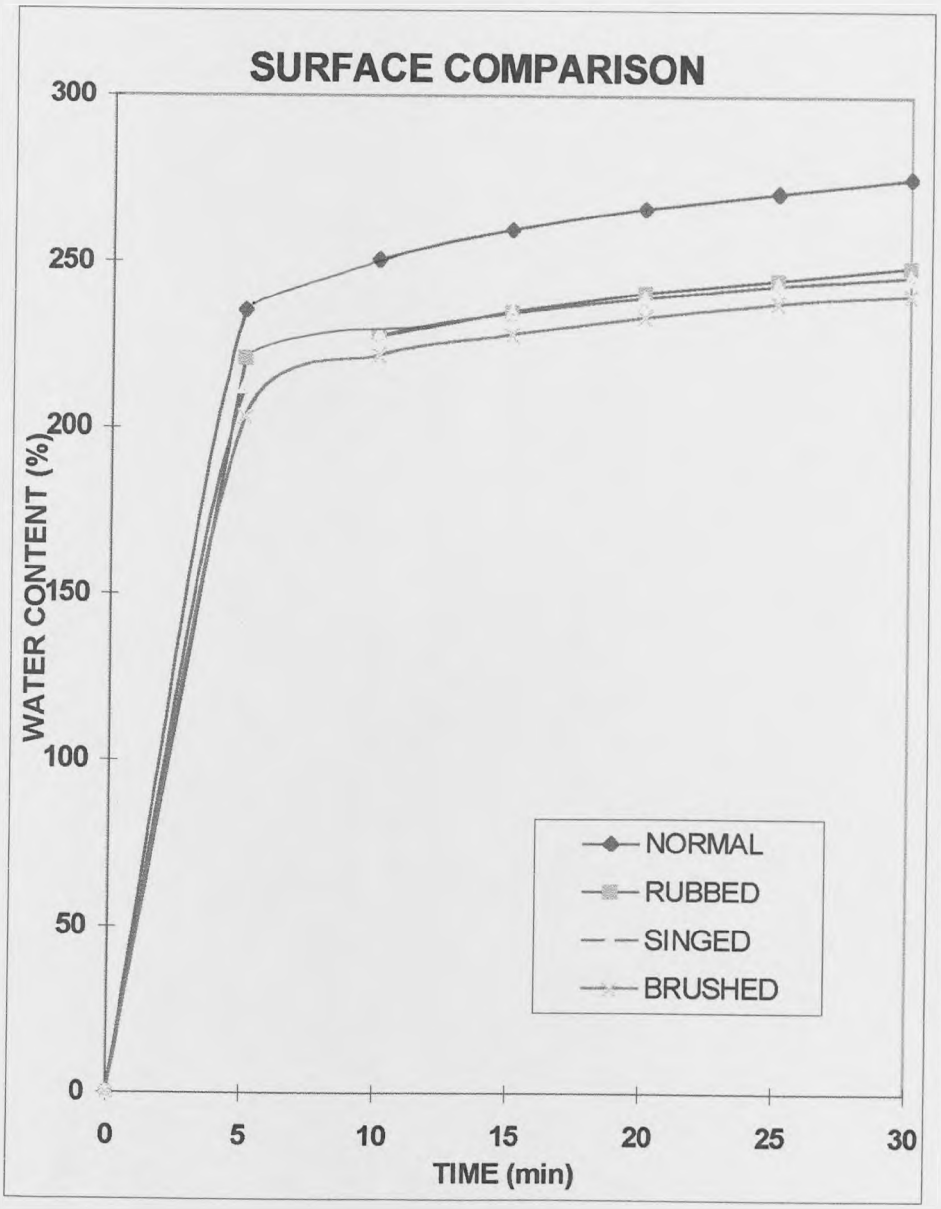


Fig. 113 Comparison of Different surfaces under a weight of 3.0g/cm^2

Cotton weft knit interlock fabric sample

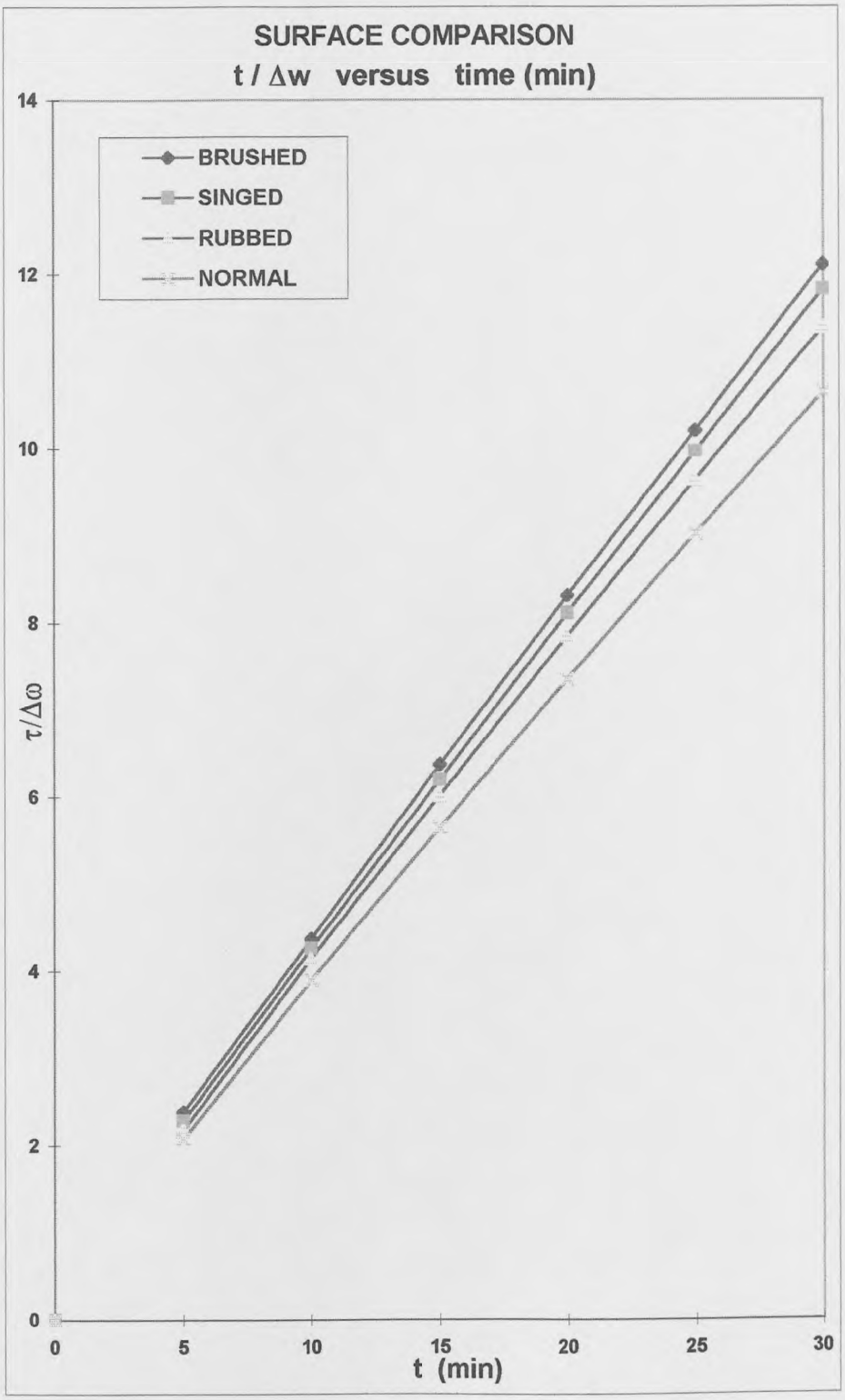


Table 53.

COMPARISON OF COTTON SURFACES
Comparison under different weights

(ON SKIN SIM ONLY)
SPEED = NO
MOTION

WEIGHT APPLIED	NORMAL SURFACE WATER CONTENT (%)						
	0	5	10	15	20	25	30
3.0g/cm^2	0	235.6	250.6	259.7	266.3	270.9	275.5
1.0g/cm^2	0	220.4	233.2	241.5	246.9	251.3	255.1
0.68g/cm^2	0	211.4	220.7	225.9	229.6	232.6	234.9

	t / Δω v t (Time) min						
	0	5	10	15	20	25	30
0.68g/cm^2	0	2.30	4.40	6.45	8.47	10.45	12.42
1.0g/cm^2	0	2.22	4.20	6.09	7.94	9.75	11.53
3.0g/cm^2	0	2.07	3.90	5.64	7.34	9.01	10.64

Fig. 114 **Cotton weft knit interlock fabric sample**

Comparison under different Weights

NORMAL SURFACE

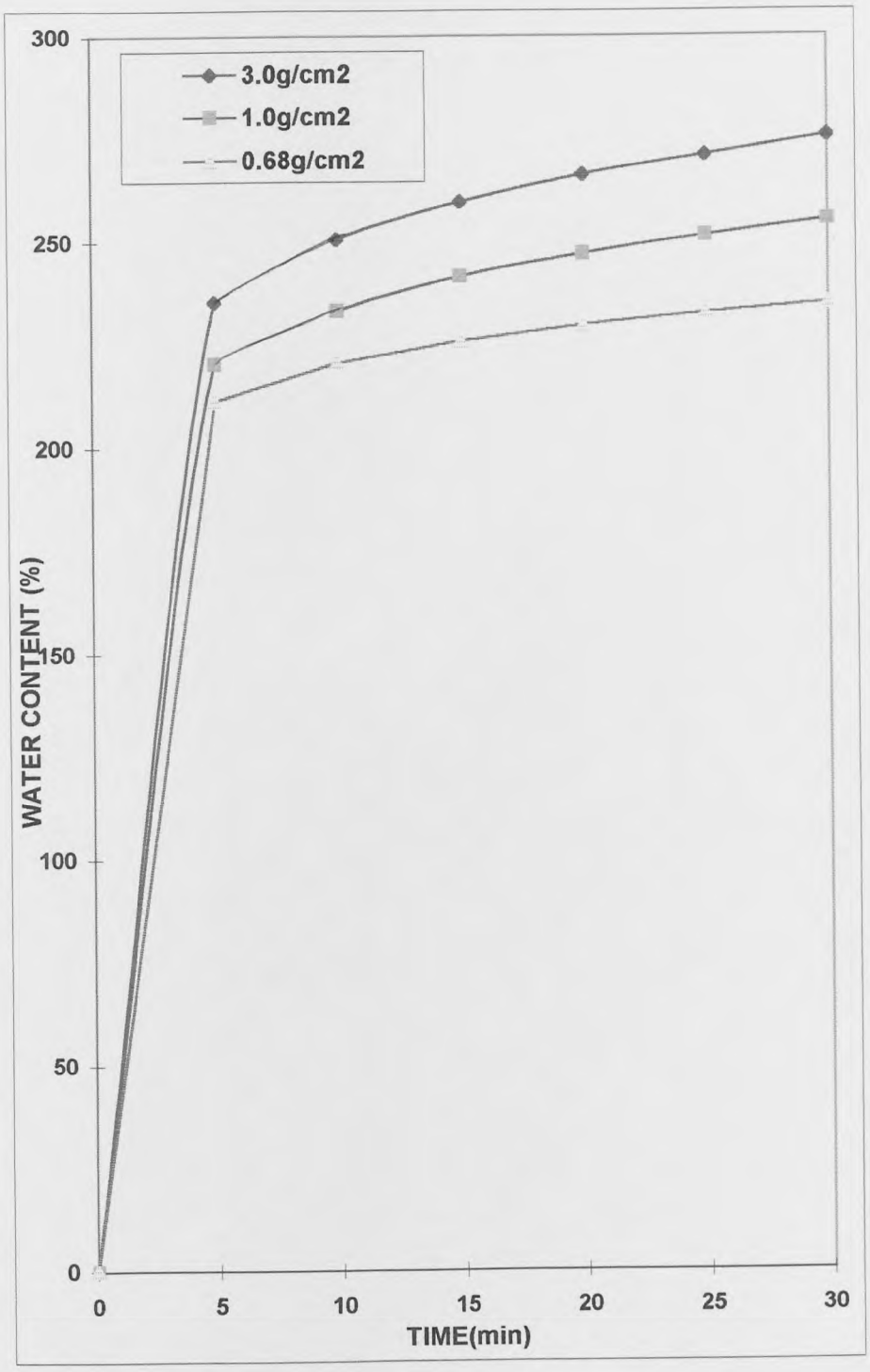


Fig. 115 **Cotton weft knit interlock fabric sample**
Comparison under different weights

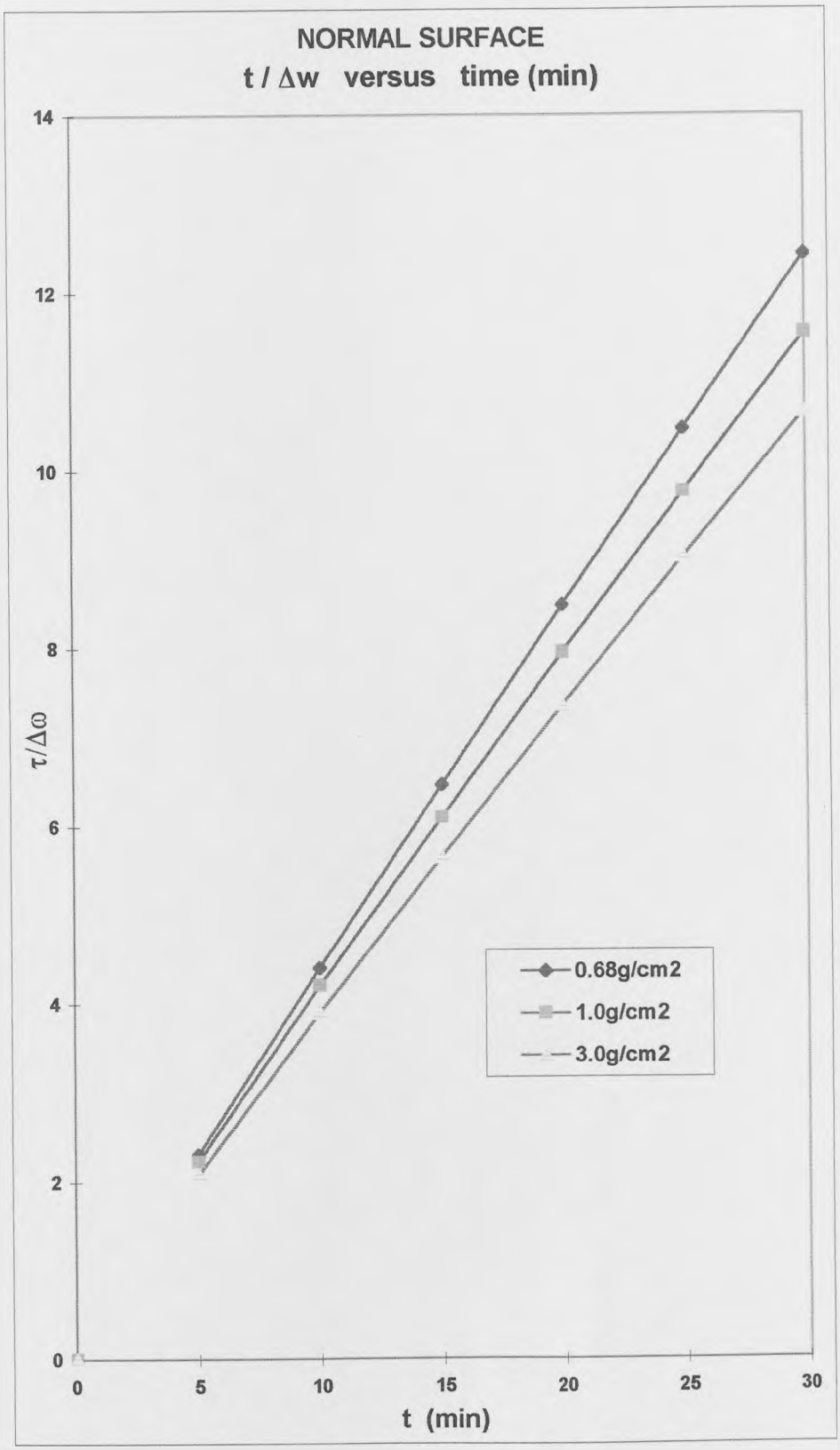


Table 54

COMPARISON OF COTTON SURFACES
Comparison under different weights

(ON SKIN SIM ONLY)
SPEED = NO MOTION

WEIGHT APPLIED	SINGED SURFACE WATER CONTENT (%)						
	0	5	10	15	20	25	30
3.0g/cm^2	0	212.5	227.6	234.8	239.4	243.4	246.0
1.0g/cm^2	0	213.0	228.4	235.4	240.2	244.6	247.3
0.68g/cm^2	0	210.4	219.4	224.3	228.0	230.9	233.3

	t / Δω (g) v t (Time) min						
	0	5	10	15	20	25	30
0.68g/cm^2	0	2.32	4.46	6.53	8.56	10.56	12.54
1.0g/cm^2	0	2.28	4.26	6.19	8.09	9.93	11.79
3.0g/cm^2	0	2.28	4.26	6.19	8.10	9.96	11.83

Fig. 116 **Cotton weft knit interlock fabric sample**

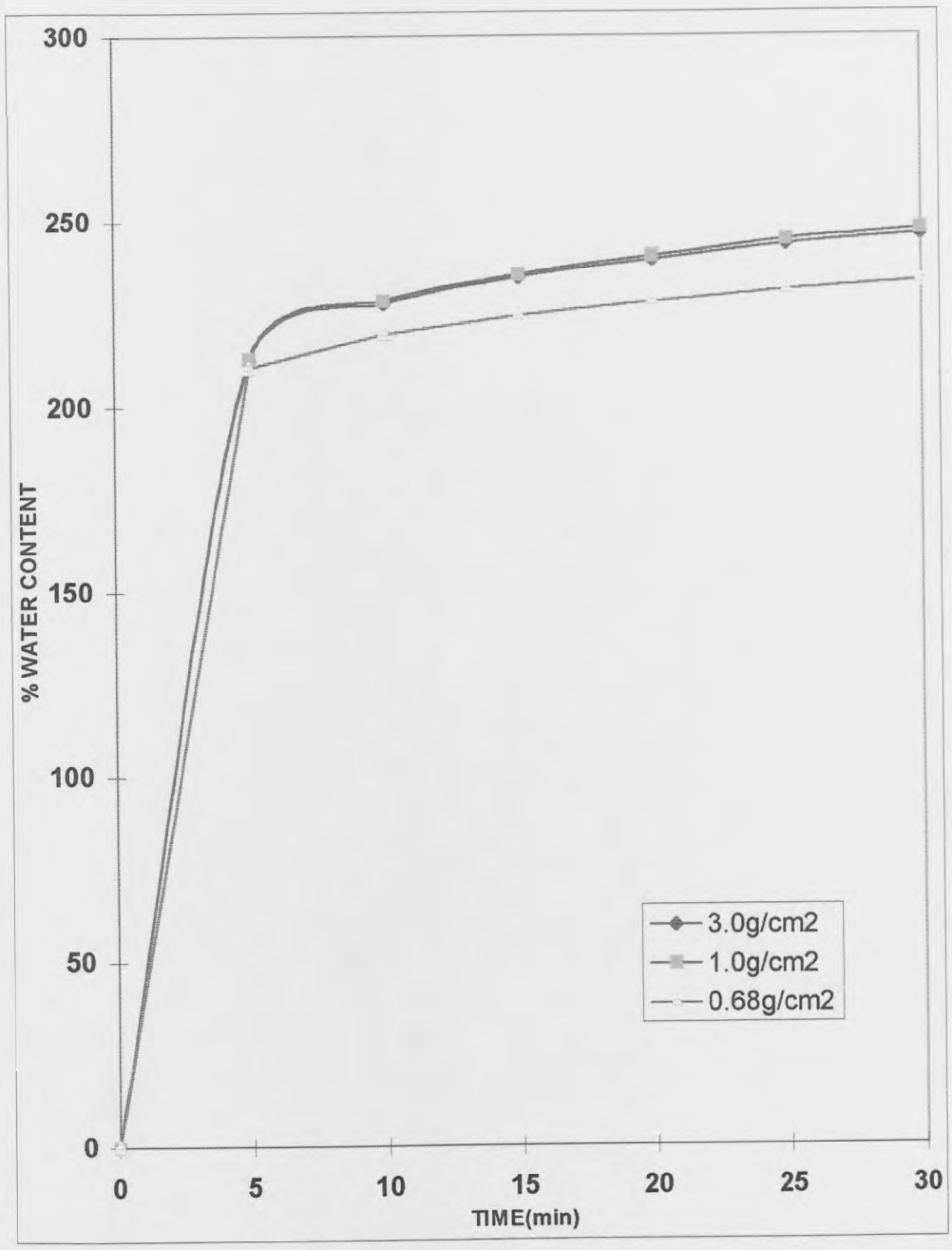
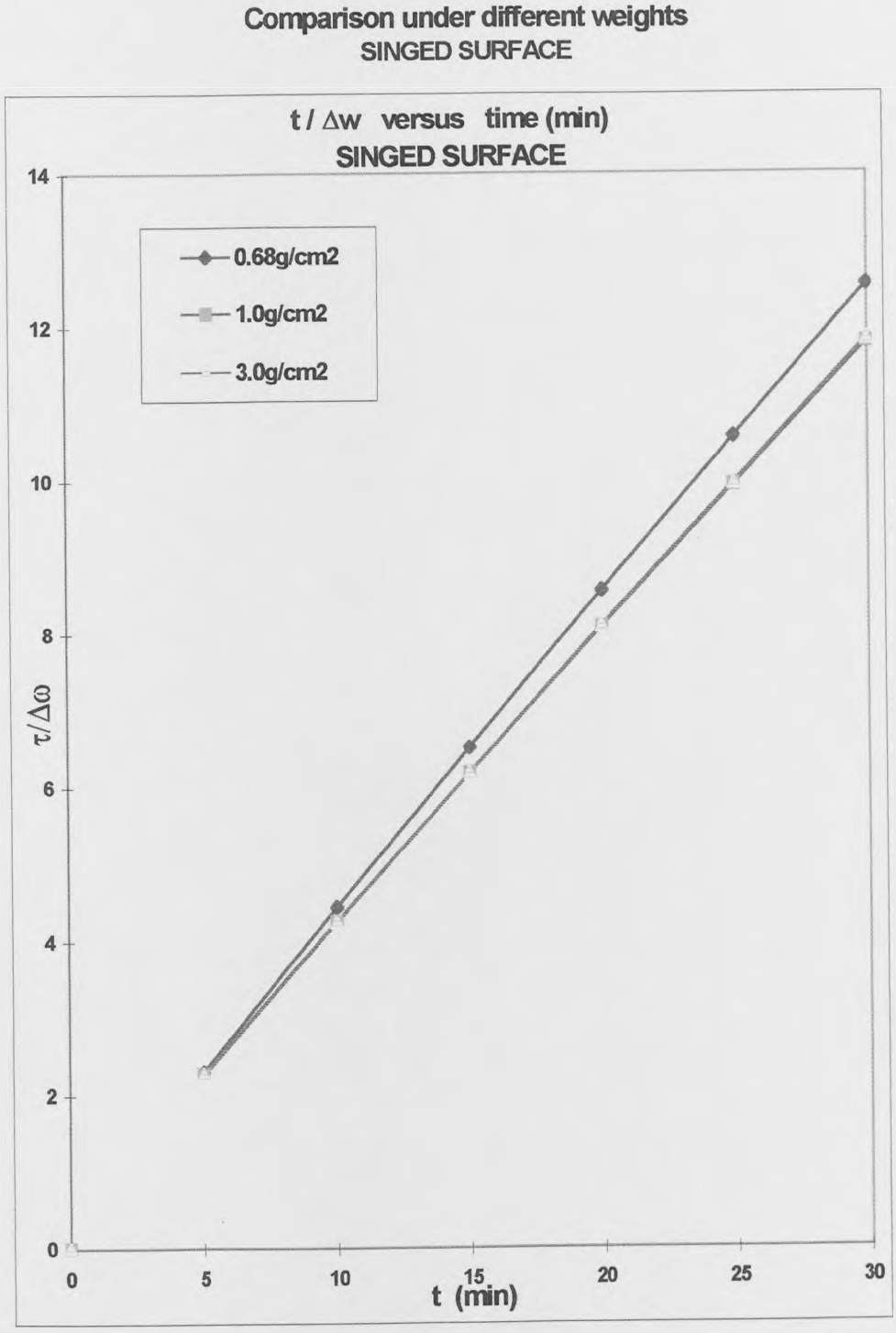


Fig. 117 **Cotton weft knit interlock fabric sample**



4.2.3.1 Results and Discussion

In the rubbed and brushed surface samples an increase in compressional weight produced greater liquid uptake, see table 54 and 55,and figures 118 to 121. For the rubbed surface sample a greater increase in liquid uptake was achieved with the application of the 3.0g/cm^2 weight. For the brushed surface samples it was the application of the 1.0g/cm^2 weight which achieved the greatest liquid increase. In the case of the rubbed sample this may be due to the surface being covered in small 'pills', small balls of matted fibres caused by the agitation of rubbing. Because of this pilling effect good surface to surface fabric contact may be hindered by these matted fibres and the optimum size channels created by good inter-fabric surface contact may not be achieved. An increase in the compressive weight will press the fibres closer together creating smaller more acceptable channels /capillaries for wicking.

The brushed samples were not covered in small pills, but were covered in a layer of raised surface fibres. Less weight was therefore required to compress these fibres to create more acceptable wicking channels. Matsudaira and Hong[83] studied the effect of compressional weight on fabric structure and surface properties of a small group of woven and knitted fabrics. Figure 122 shows a model of the effect of weight increase on a fabric matrix. Figure 123 shows the appearance of the weft knitted cotton with a rubbed surface. The pills are clearly visible with a series of matted fibres occurring over the surface of the fabric.

Table 55

COMPARISON OF COTTON SURFACES
Comparison under different weights

(ON SKIN SIM ONLY)
SPEED = NO
MOTION

WEIGHT APPLIED	RUBBED SURFACE WATER CONTENT (%)						
	0	5	10	15	20	25	30
3.0g/cm^2	0	220.9	227.6	235.3	240.9	244.9	248.8
1.0g/cm^2	0	201.4	215.8	222.6	227.3	230.8	233.4
0.68g/cm^2	0	203.6	215.4	221.6	225.2	228.4	230.8

	t / Δω v t (Time) min						
	0	5	10	15	20	25	30
0.68g/cm^2	0	2.37	4.48	6.52	8.57	1056	12.54
1.0g/cm^2	0	2.40	4.38	6.37	8.32	10.25	12.16
3.0g/cm^2	0	2.17	4.15	6.02	7.84	9.64	11.38

Fig. 118 **Cotton weft knit interlock fabric sample**

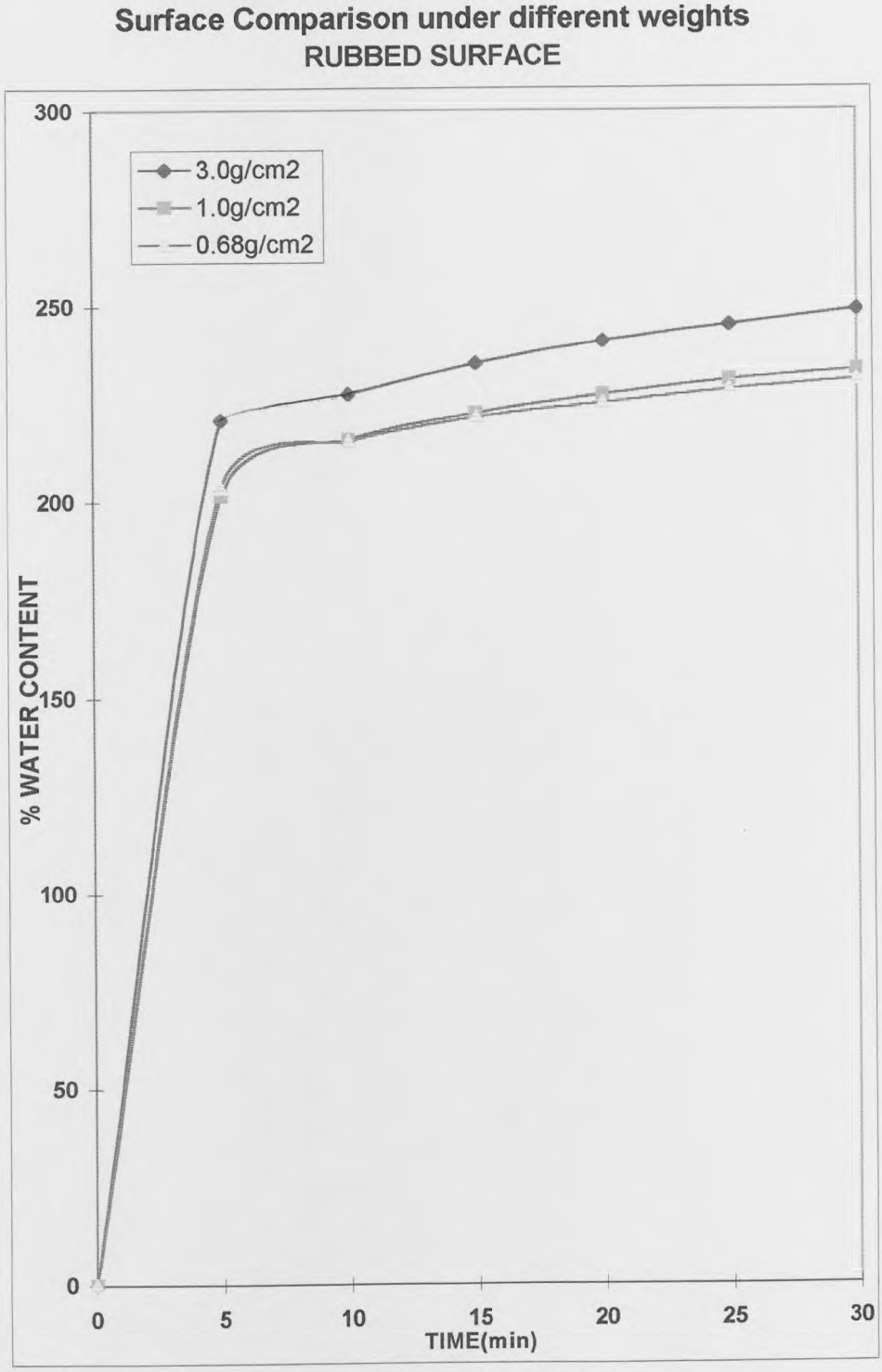


Fig. 119 Cotton weft knit interlock fabric sample

Surface Comparison under different weights
RUBBED SURFACE

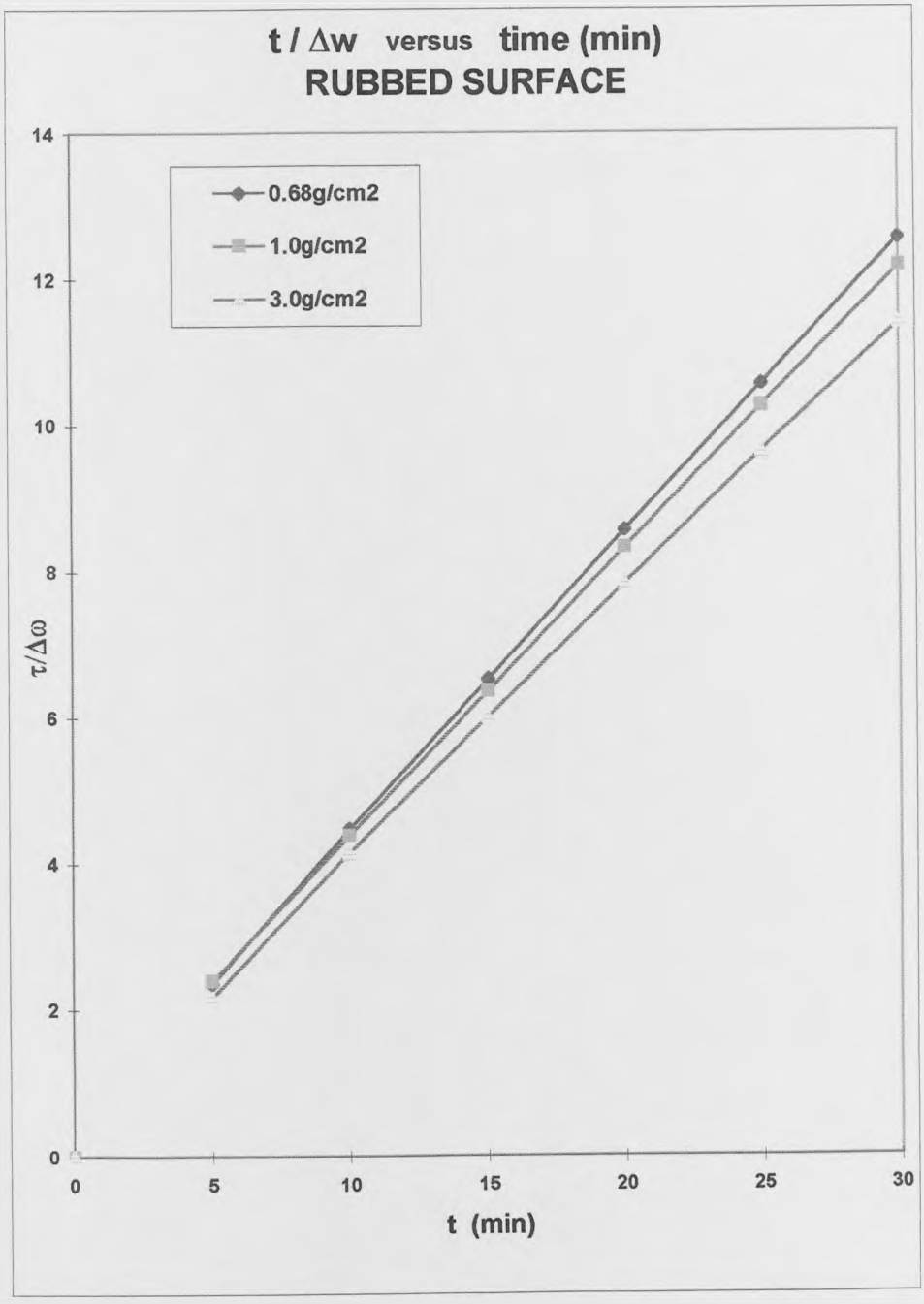


Table 56

COMPARISON OF COTTON SURFACES
Comparison under different weights

(ON SKIN SIM ONLY)
SPEED = NO MOTION

WEIGHT APPLIED	BRUSHED SURFACE WATER CONTENT (%)						
	0	5	10	15	20	25	30
3.0g/cm^2	0	203.4	221.8	228.3	233.6	237.9	240.4
1.0g/cm^2	0	186.6	213.1	220.1	225.2	228.8	231.6
0.68g/cm^2	0	150.4	187.3	199.3	207.0	211.6	214.4

	t / Δω v t (Time) min						
	0	5	10	15	20	25	30
0.68g/cm^2	0	3.23	5.19	7.32	9.39	11.50	13.62
1.0g/cm^2	0	2.61	4.57	6.63	8.64	10.63	12.60
3.0g/cm^2	0	2.39	4.37	6.37	8.31	10.19	12.11

Fig. 120 **Cotton weft knit interlock fabric sample**

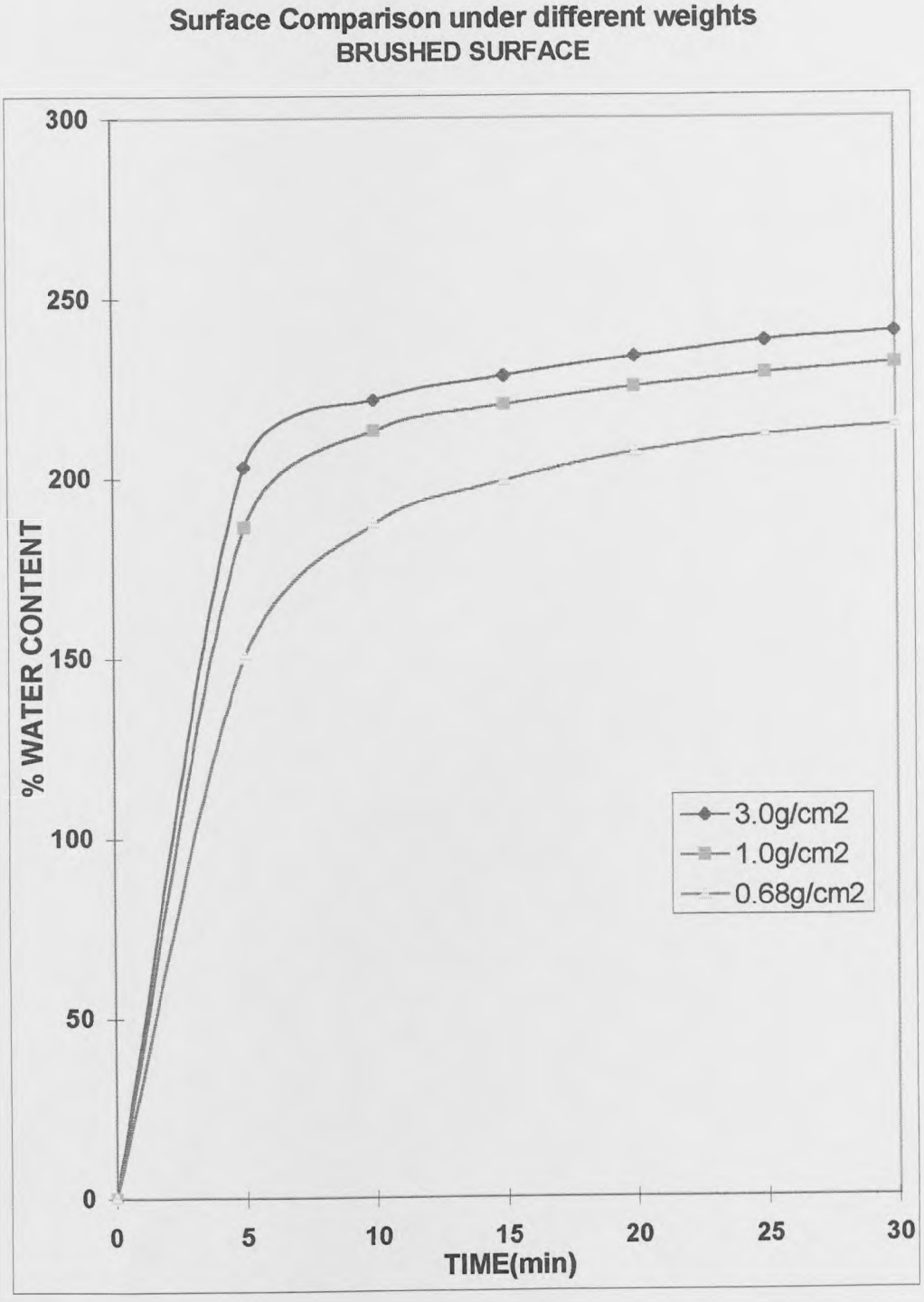


Fig. 121 Cotton weft knit interlock fabric sample

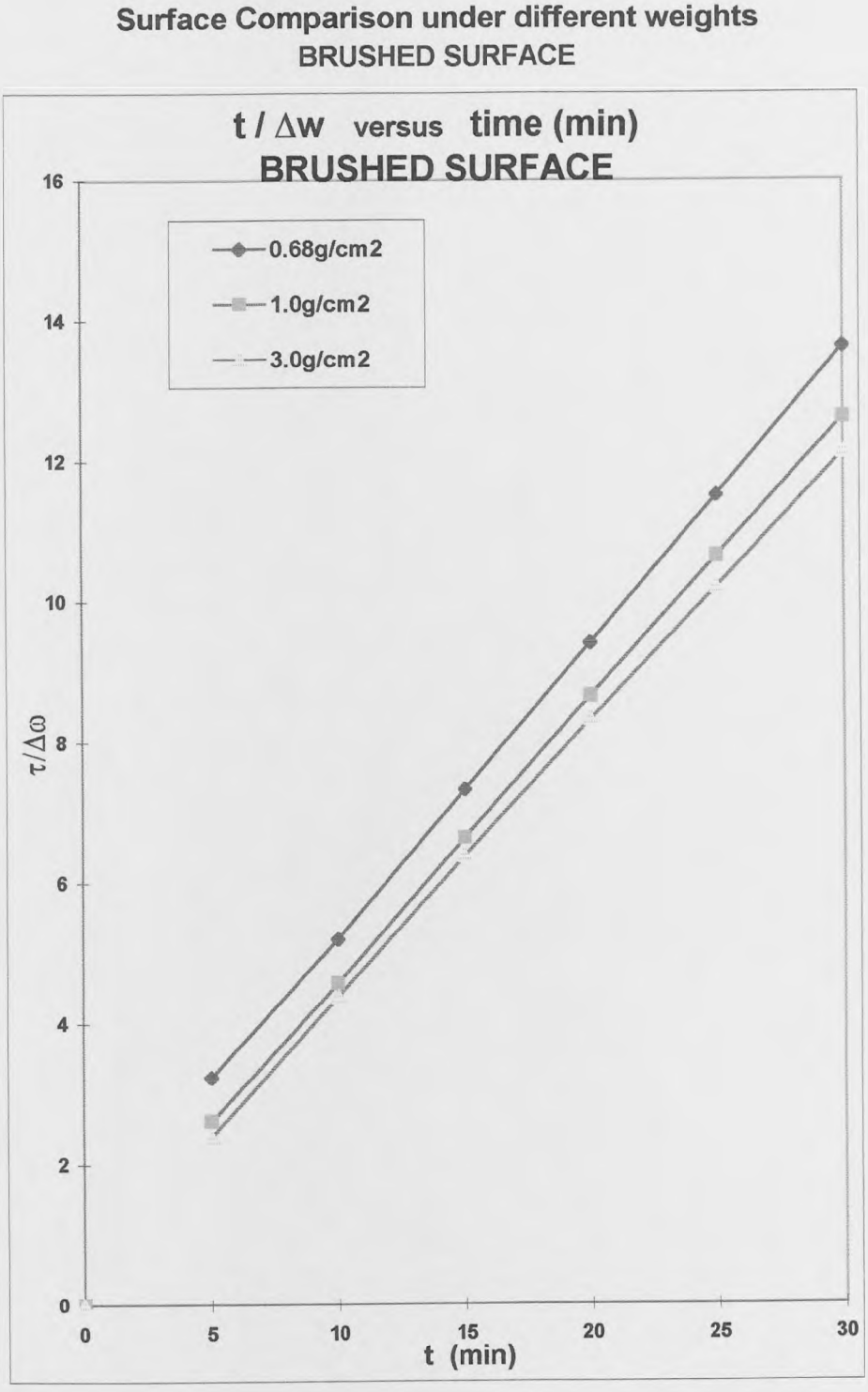
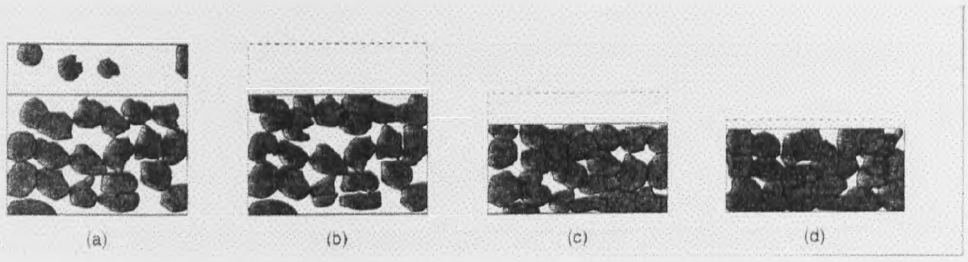
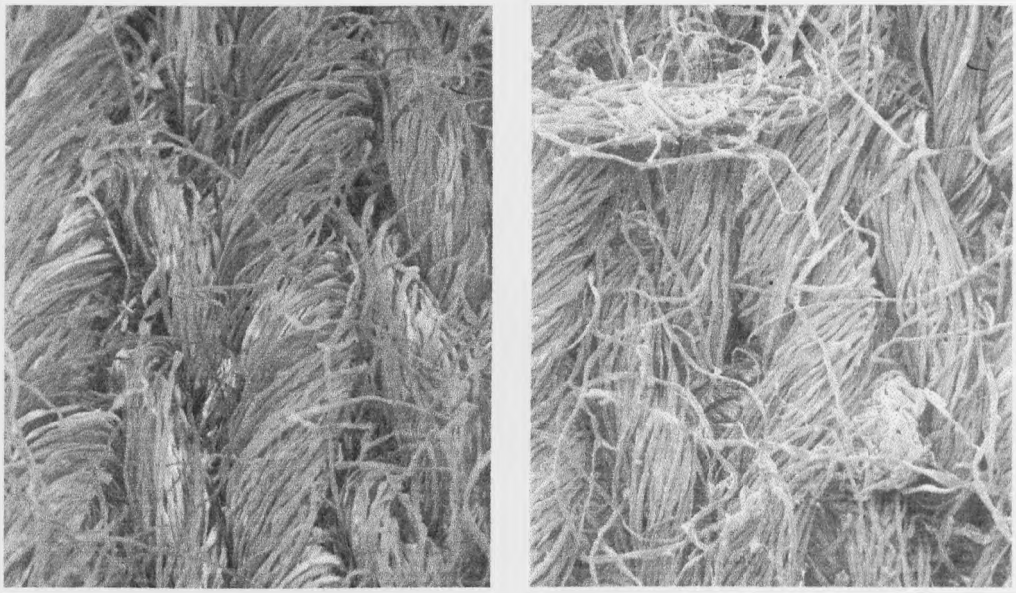


Fig. 122 **Cross-section Model of Fabric[83]**



With increases in pressure surface hairs are compressed, see Fig. 122.

Fig. 123 **Knitted Cotton sample with Normal surface and Rubbed surface**



NORMAL SURFACE RUBBED SURFACE

The capillary pressure theory shows that smaller channels or pores produce high capillary pressure, and therefore a high wicking rate, see equation :

$$P = \frac{F_{wi}}{\pi r_i^2} = \frac{2\pi r_i \gamma \cos\theta}{\pi r_i^2} = \frac{2\gamma \cos\theta}{r_i} \qquad \text{----------[25]}$$

p = capillary pressure F_{wi} = the internal wetting force πr_i^2 = capillary area

θ = liquid-solid contact angle γ = liquid surface tension (dyne/cm)

ri = radius inside the capillary (cm)

Smaller channels or pores enhance the liquid spreading distance, therefore liquid movement can be assisted by decreasing the pore size. The ability of a fabric to retain liquid is not only determined by its pore sizes but also by the overall porosity of the fabric, or the overall number of these types of channels or pores, and these in turn are influenced by the properties of the fibre (i.e. cross-section shape). The distance travelled by the liquid is greater in small capillaries because of the higher capillary pressure, however the liquid mass retained is small. Large pores will retain more water, but the distance travelled is less, therefore fast liquid uptake is facilitated by small evenly distributed interconnected pores, and liquid retention by large numbers of these types of interconnected pores. (i.e. for cotton – the irregularity of the fibre cross-sectional shapes contribute to a high liquid retention)

Further analysis of the graphical representation of the different fabric surfaces were carried out. The shape of the curves in the figures representing the percentage water content versus time appears to conform to an empirical hyperbolic equation of the form [87,88] :

$$\Delta\omega = \frac{t}{a + b\,t} \qquad \text{---------- [26]}$$

where $\Delta\omega$ = water content (%)

t = time (minutes)

and 'a' and 'b' are empirical constants.

Thus rearranging the equation [26], we obtain :

$$\frac{t}{\Delta\omega} = a + b\,t \qquad \text{----------[27]}$$

Thus a plot of $t/\Delta\omega$ versus t (time) should be linear (see figures 109, 111, 113, 115, 117, 119, and 121).

Dividing both sides of equation [27] by 't' (time) we obtain :

$$\frac{t}{\Delta\omega} = \frac{a}{t} + b \qquad \text{---------- [28]}$$

Therefore under conditions where the wicking is very large, (i.e. approaching infinite time ' t_∞'), the following equation can be used :

$$\frac{t}{\Delta\omega_\infty} = b \quad \textbf{OR} \quad \Delta\omega_\infty = \frac{1}{b} \qquad \text{---------- [29]}$$

where the value of $\Delta\omega_\infty$ will be the maximum saturation of the fabric by the water.

A best-fit straight line was obtained using the least square method and used to yield the linear plots in figures 109, 111, 113, 115, 117, 119, and 121.

Table 57 shows the values obtained for **a, b, ^{1}/a** –(initial rate of wicking), **^{1}/b ($\Delta\omega_\infty$)** – (maximum water uptake) from the linear graphs.

Table 57

	NORMAL	SINGED	RUBBED	BRUSHED
0.68g/cm^2				
a	0.29	0.30	0.46	1.05
b	0.403	0.407	0.405	0.421
^{1}/a	3.45	3.33	2.17	0.95
^{1}/b(g)	2.481	2.457	2.469	2.375
^{1}/b(%)	241.1	239.5	238.1	220.7
1.0 g/cm^2				
a	0.45	0.45	0.46	0.55
b	0.370	0.378	0.391	0.404
^{1}/a	2.22	2.22	2.17	1.82
^{1}/b(g)	2.703	2.646	2.558	2.475
^{1}/b(%)	265.0	256.9	246.4	240.8
3.0g/cm^2				
a	0.45	0.41	0.37	0.49
b	0.341	0.380	0.366	0.388
^{1}/a	2.22	2.44	2.70	2.04
^{1}/b(g)	2.932	2.632	2.732	2.577
^{1}/b(%)	286.3	255.0	262.4	249.9

From the results represented in table 57 the normal (untreated fabric) surface appears to be the optimum surface for wicking and retaining water, and therefore gave the best results. Even with an increase in applied weight the normal surface sample managed to hold the greater amount of liquid at maximum saturation ($\Delta\omega_\infty$). The singed sample was ranked second in the first two weight classes of 0.68g/cm^2 and 1.0g/cm^2 . However when 3.0g is applied it cannot retain as much water as the rubbed sample., which at lower weights did not retain as much water the singed sample. This may be due to the singed sample having no surface filaments or hairs to create extra inter-fibre channels on the surface of the fabric to collect water. The rubbed sample which has a surface covered in small 'pills' and therefore small interconnected channels, once enough pressure was applied was able to retain water in these spaces.

The brushed surface sample retained the least amount of water at maximum saturation. Although this surface type also increased the amount of liquid retention with an increase in pressure. This may be due to the orientation of the surface hairs of the brushed sample. A brushed sample may lose its 'randomness' of surface hair orientation, and therefore produce larger capillary spaces on the surface. This will produce a slower wicking rate, and larger capillary spaces are affected adversely by gravity over time.

However the only sample which produced a decrease in water retention at the final weight application of 3.0g was the singed sample, and this may be due to the singed surface having no filaments or hairs to support the extra weight, therefore allowing the fine capillary channels created along the surface of this sample to become crushed or collapsed. This would reduce the amount of capillary space available for water retention.

The initial rate (1/a) for each sample was also calculated and produced some unusual results. At the lowest weight applied 0.68g/cm^2, the normal surface fabric produced the highest initial wicking rate. However an increase in weight produced a reduction in the initial wicking rate for the normal fabric surface sample.

In the case of the singed sample, in general an increase in weight also produced a reduction in the initial wicking rate.

However the rubbed and brushed samples both produced an increase in the initial wicking rate with an increase in the weight applied. The increased wicking rate in the rubbed sample, may be due to the compression of the matted balls of fibres at the pilled area, producing more fine capillary channels and therefore inducing rapid wicking. The brushed sample also produced an increase in initial wicking due to a decrease in capillary size with an increase in the weight applied, inducing a higher capillary pressure and therefore rapid wicking.

The hypothesis could therefore be drawn that depending on the type of wear applied to a fabric surface, this could exert adverse affects in varying degrees, and the effect to the wicking properties would depend where in the clothing system the fabric was utilised.

4.2.4 VERTICAL TRANSPLANAR WICKING TECHNIQUE

These results in the following tables and figures are based on the total percentage water content of the whole of each fabric sample.

Table 58

VERTICAL WICKING TESTS

SAMPLE : **ACRYLIC - (Knitted)**

Test pair	Ref.No.	MEAN RESULTS			
		Orig.Wt.(g)	Wt. at END	CONTENT(g)	WATER (%)
1	1	0.743	0.897	0.154	20.7
	2	0.719	0.773	0.054	7.5
2	3	0.760	0.922	0.162	21.3
	4	0.788	0.800	0.012	1.5
3	5	0.619	0.810	0.191	30.8
	6	0.563	0.588	0.025	4.4
4	7	0.628	0.808	0.180	28.6
	8	0.612	0.641	0.029	4.7

Table 59

VERTICAL WICKING TESTS

SAMPLE : **COTTON - (Knitted)**

Test pair	Ref.No.				
		Orig.Wt.(g)	Wt. at END	CONTENT (g)	WATER (%)
1	A	0.530	0.596	0.066	12.6
	D	0.518	0.548	0.030	5.8
2	C	0.435	0.540	0.105	24.0
	H	0.445	0.466	0.021	4.6
3	E	0.491	0.625	0.134	27.2
	F	0.498	0.503	0.006	1.1
4	B	0.483	0.591	0.108	22.4
	10	0.502	0.547	0.045	8.9

Fig. 124 VERTICAL WICKING TESTS ON ACRYLIC FABRIC

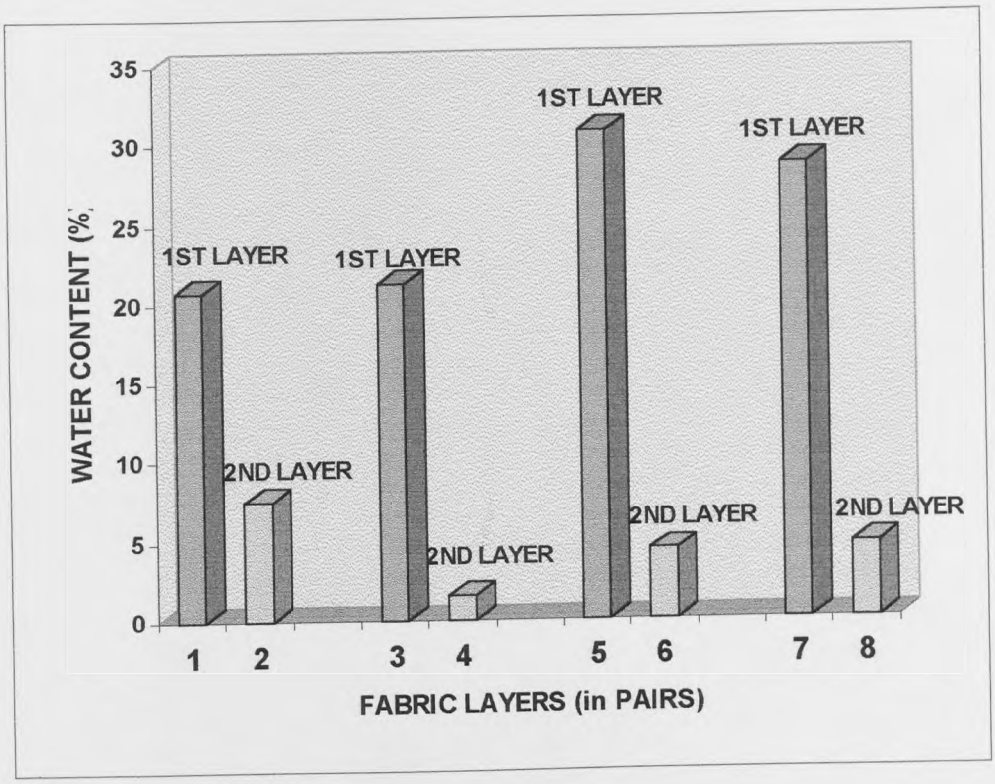


Fig. 125 VERTICAL WICKING TESTS ON COTTON FABRIC

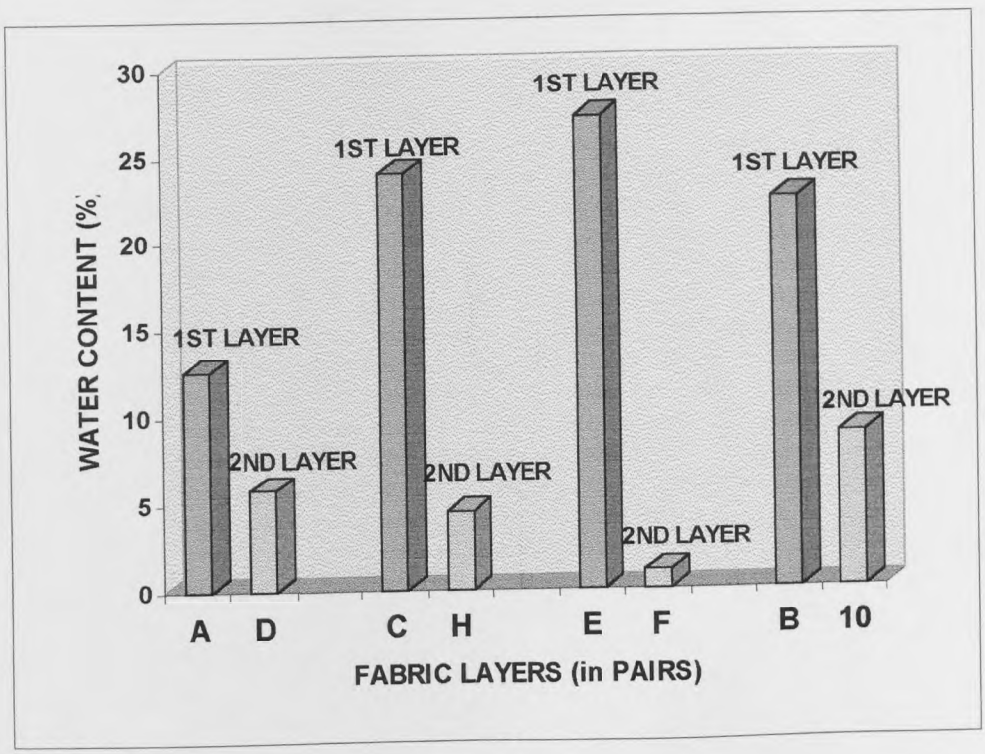


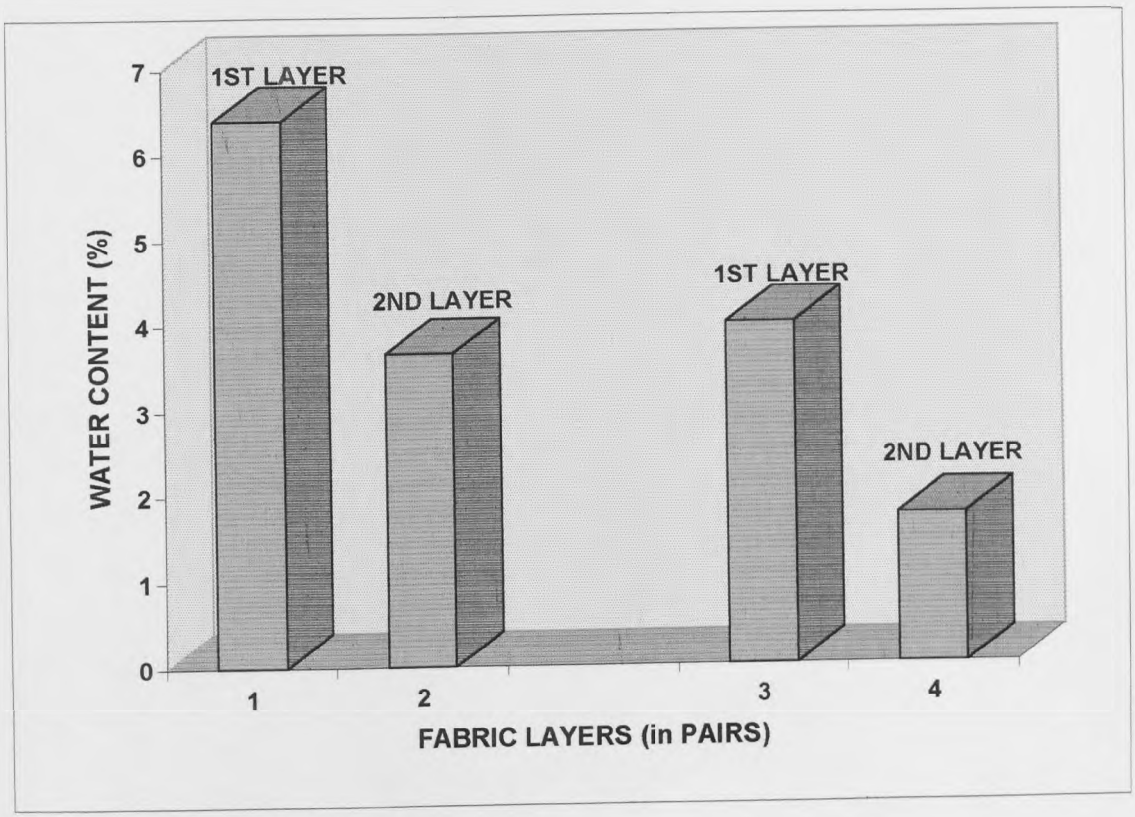
Table 60

VERTICAL WICKING TESTS

SAMPLE : NOMEX - (Knitted)

Test pair	Ref.No.	MEAN RESULTS			
		Orig.Wt.(g)	Wt. at END	CONTENT(g)	WATER (%)
1	1	0.422	0.449	0.027	6.4
	2	0.409	0.424	0.015	3.7
2	3	0.401	0.417	0.016	4.0
	4	0.403	0.410	0.007	1.7

Fig. 126 VERTICAL WICKING TESTS ON NOMEX FABRIC



These next set of results were produced after a modification to the methodology, in order to calculate the water content of the saturated area only of a fabric sample.

Table 61 Water content based on Total fabric sample weight

VERTICAL WICKING TESTS

SAMPLE : COTTON – (Knitted)

Tests	Ref. No.	MEAN RESULTS		
		Orig.Wt (g)	H_2O Content (g)	H_2O Content (%)
1	1	1.946	0.078	4.0
	2	1.918	0.006	0.3
2	1	1.970	0.062	3.2
	2	1.916	0.013	0.7
3	1	2.01	0.077	3.8
	2	1.925	0.006	0.3

Table 62 Water content based on weight of Wet area only of fabric sample weight

VERTICAL WICKING TESTS

SAMPLE : COTTON – (Knitted)

Tests	Ref. No.	MEAN RESULTS		
		Orig.Wt (g)	H_2O Content (g)	H_2O Content (%)
1	1	0.052	0.078	150.0
	2	0.008	0.006	75.0
2	1	0.062	0.062	100.0
	2	0.016	0.013	81.3
3	1	0.065	0.077	118.5
	2	0.011	0.006	54.6

Fig. 127 Water content based on Total sample weight

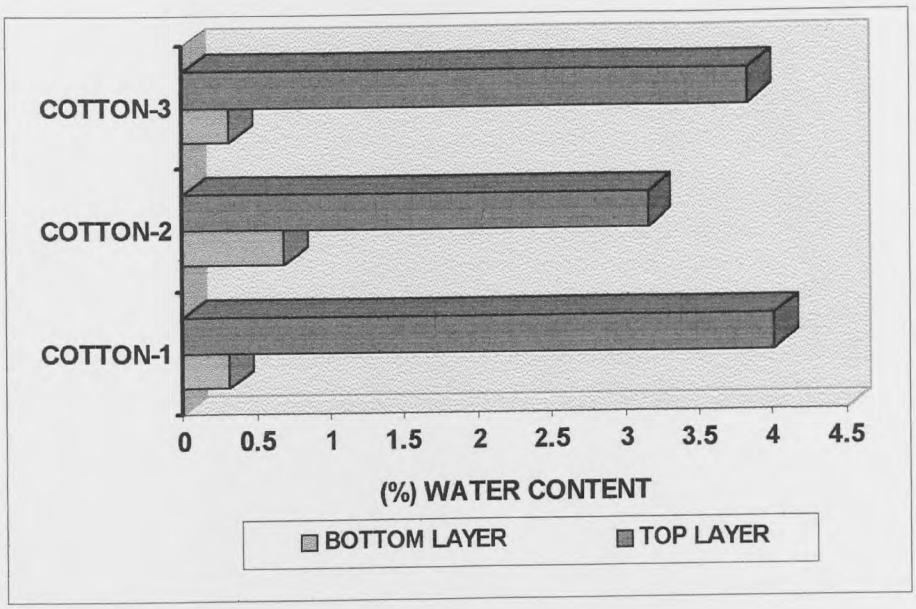


Fig. 128 Water content based on weight of Wet area only

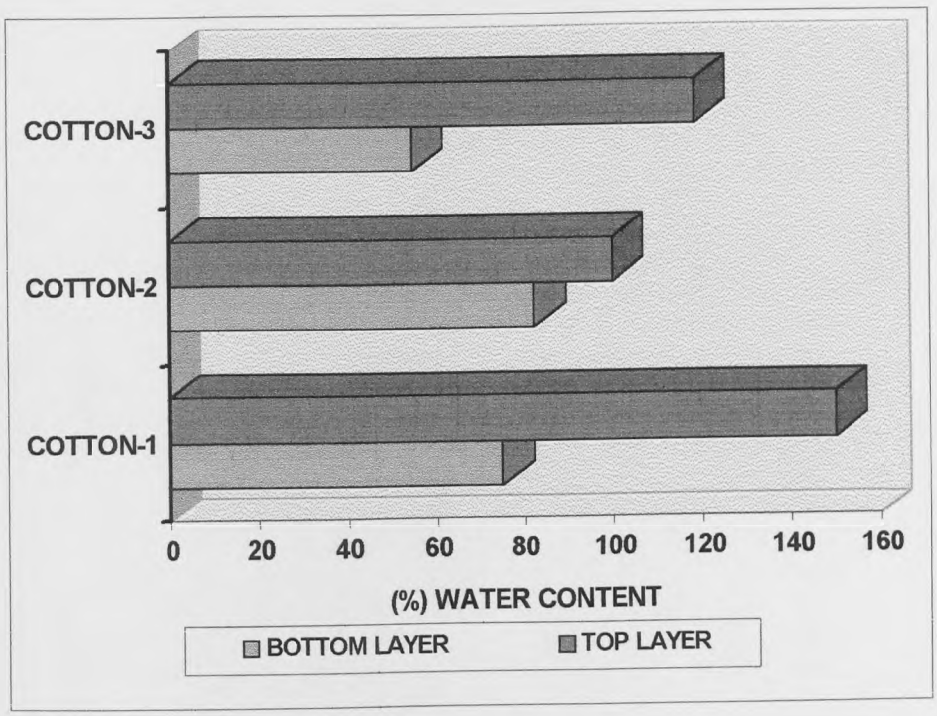


Table 63 Water content based on Total fabric sample weight

VERTICAL WICKING TESTS

SAMPLE : ACRYLIC – (Knitted)

Tests	Ref. No.	MEAN RESULTS		
		Orig.Wt (g)	H_2O Content (g)	H_2O Content (%)
1	1	2.544	0.117	4.6
	2	2.523	0.005	0.2
2	1	2.543	0.076	3.0
	2	2.525	0.023	0.9
3	1	2.543	0.326	12.8
	2	2.582	0.005	0.2

Table 64 Water content based on weight of Wet area only of fabric sample weight

VERTICAL WICKING TESTS

SAMPLE : ACRYLIC – (Knitted)

Tests	Ref. No.	MEAN RESULTS		
		Orig.Wt (g)	H_2O Content (g)	H_2O Content (%)
1	1	0.287	0.117	40.8
	2	0.012	0.005	41.7
2	1	0.202	0.076	37.6
	2	0.015	0.023	153.3
3	1	0.336	0.326	97.0
	2	0.014	0.005	35.7

Fig. 129 Water content based on Total sample weight

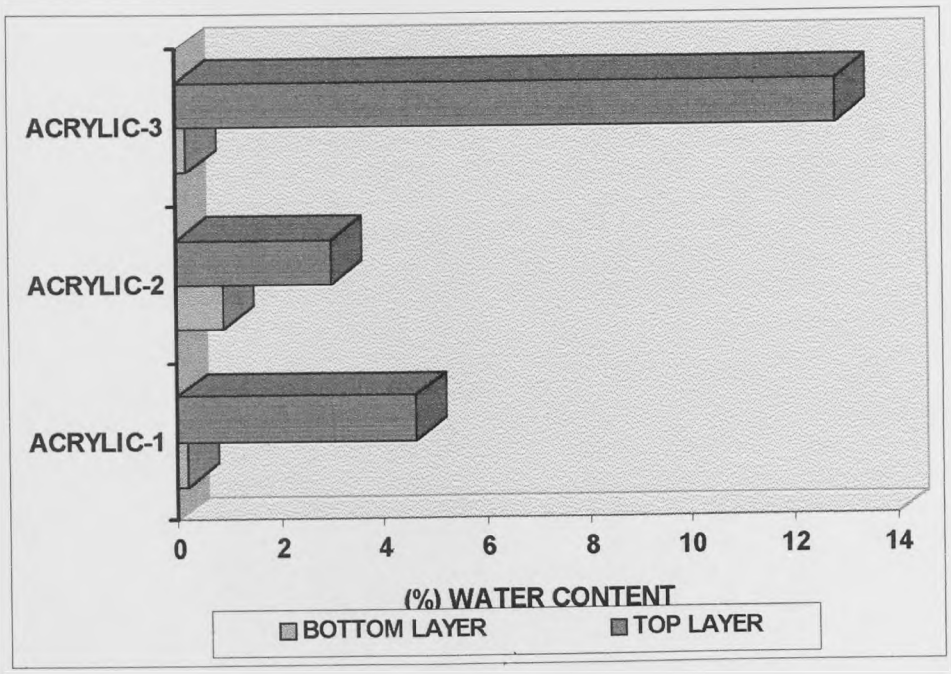


Fig. 130 Water content based on weight of Wet area only

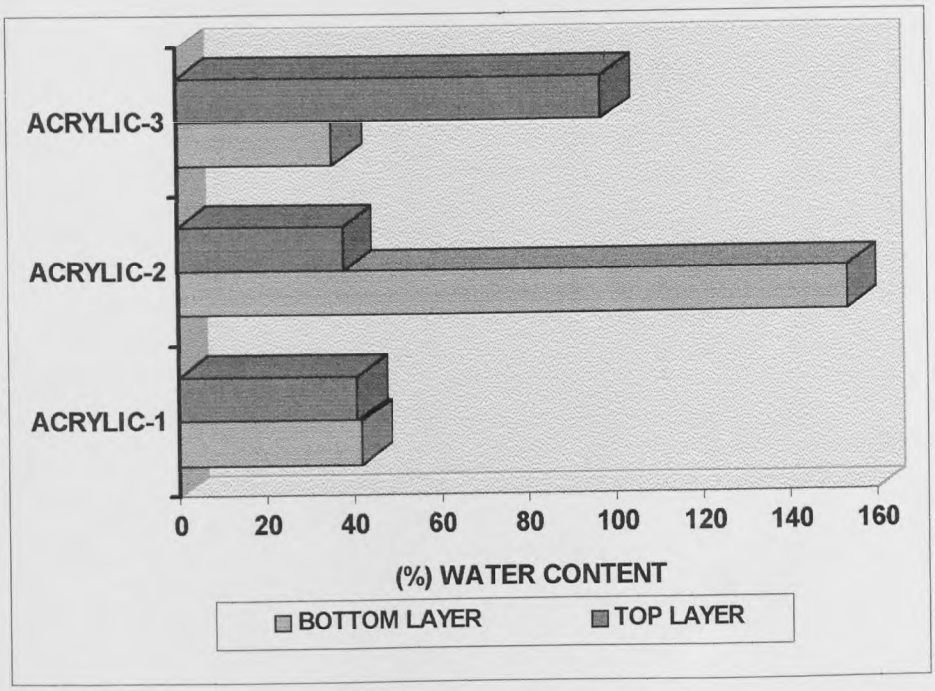


Table 65 Water content based on Total fabric sample weight

VERTICAL WICKING TESTS

SAMPLE : NOMEX – (Knitted)

Tests	Ref. No.	MEAN RESULTS		
		Orig.Wt (g)	H_2O Content (g)	H_2O Content (%)
1	1	1.378	0.044	3.2
	2	1.416	0.017	1.2
2	1	1.378	0.017	1.2
	2	1.415	0.009	0.6

Table 66. Water content based on weight of Wet area only of fabric sample weight

VERTICAL WICKING TESTS

SAMPLE : NOMEX – (Knitted)

Tests	Ref. No.	MEAN RESULTS		
		Orig.Wt (g)	H_2O Content (g)	H_2O Content (%)
1	1	0.052	0.044	84.6
	2	0.008	0.017	212.5
2	1	0.015	0.017	113.3
	2	0.005	0.009	180.0

Fig. 131 Water content based on Total sample weight

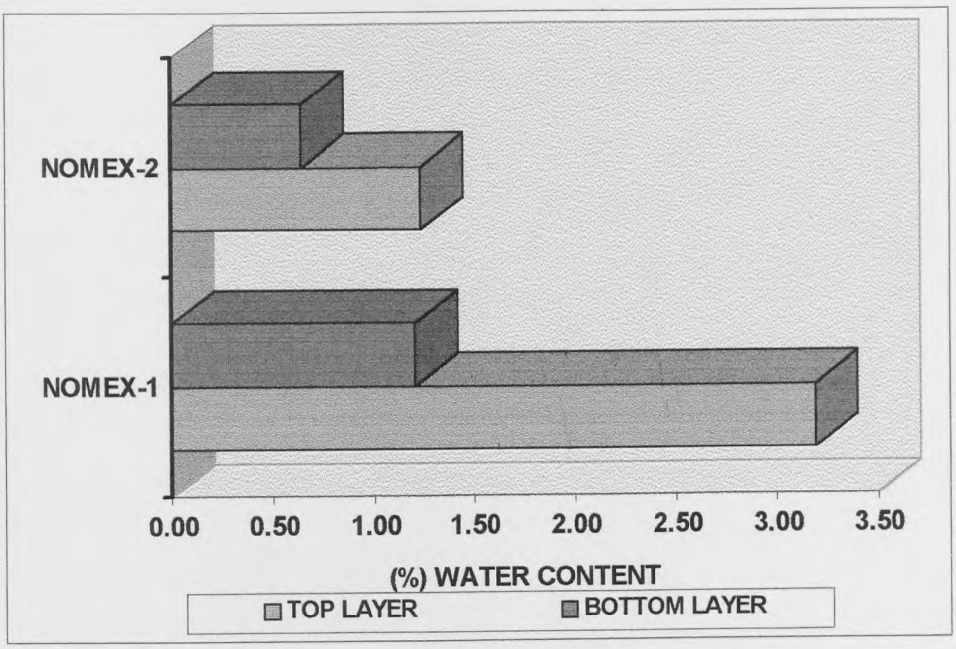
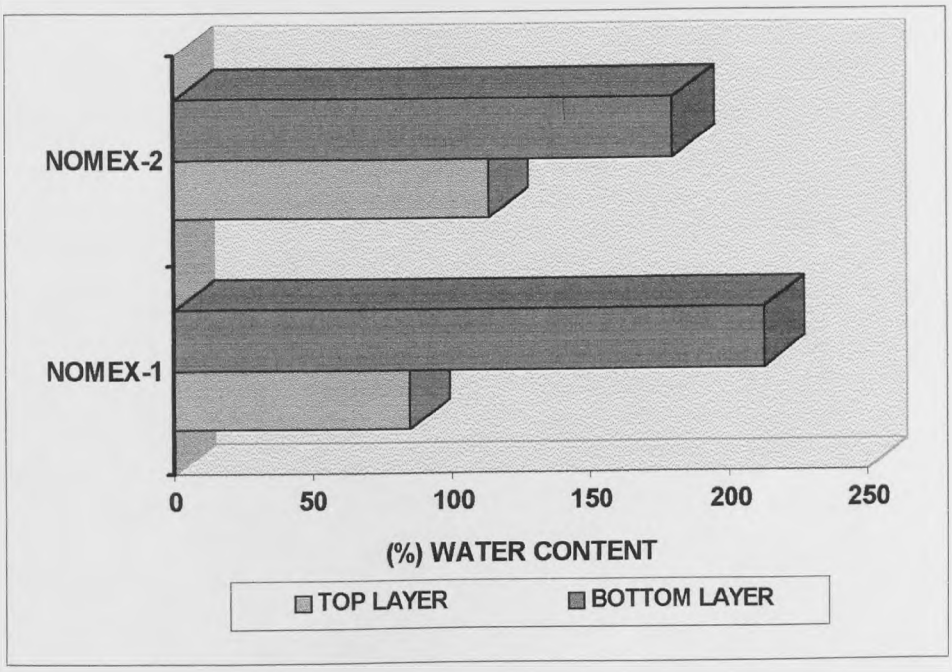


Fig. 132 Water content based on weight of Wet area only



Just as in the horizontal transplanar wicking tests, the vertical transplanar wicking tests showed that vertical transplanar wicking occurs in isolated pockets of saturation. In the vertical transplanar wicking tests double layer fabric assemblies were used. Initial contact with the water is in essence very similar to the spot or drop test[22]. Water was introduced to the fabric samples by a syringe, and a drop of liquid is placed in contact with the fabric surface via this method. Once the first drop has wicked into the fabric layer and is no longer visible on the fabric surface another drop is introduced, and so forth, until breakthrough is observed on the underside of the second layer.

This technique was originally devised to see if it was possible to observe transplanar wicking in the vertical state., and to determine whether a set quantity of water was necessary in the first layer before transplanar wicking would take place to the second layer in the vertical state.

The top layer (layer 1) was always the layer nearest the water source, and the bottom layer (layer 2) the layer furthest from the water supply.

Tables 61 and 62, and figures 127 and 128 represent the results from the knitted interlock cotton fabric. The results revealed that a high water content was present in the top layer when liquid was transported to the next layer.

However in the case of the acrylic interlock fabrics (table 63 and 64, figures 129 and 130) not only was less water taken up by the top layer before breakthrough occurred , but the test produced much more variable results.

In general it could be said that more water was taken into the bottom layer with the acrylic interlock fabric at the end of the test in contrast to the cotton interlock fabric in which the inverse applied.

In a horizontal state water collecting in the inter-yarn spaces (knitted loops) would be slowed by the influence of gravity, with a wide area to act upon, but in the vertical state the inter-yarn space is turned on its side, with gravity acting on the top of the loop. Good inter-fabric contact points are much harder to create, and capillary pressure must be harder to maintain.

However the results could not be said to be conclusive, no matter how many tests were performed the variability with this fabric could not be eliminated.

The Nomex 1x1 rib fabric samples (tables 65 and 66, figures 131 and 132) produced more unusual results ; these samples took on more water in the bottom layer(layer 2) than in the top layer(layer 1), i.e. the layer next to the water source. This may be due to vertical planar wicking being the more dominant process, which occurs more rapidly than transplanar wicking with the aid of gravity.

In comparison with the acrylic and Nomex fabrics, cotton has a greater wetting capacity than the other two fabrics. In this test the wetting ability of any fabric tested is of great importance. With the polypropylene fabric this test technique could not be utilised on this fabric as initial wetting would not occur quickly enough for this test.

Of all three fabrics, cotton has the greater wetting property, and was able to take on water almost continually. This may explain the higher water content in the top layer (1 later), as this layer was able to keep up with the demand for water from the bottom layer.(layer 2) The Nomex and acrylic samples were much slower at wetting, with Nomex the slowest, which may be responsible for the increased amount of water in the bottom , because water was not forced into the fabric layers but introduced a drop at a time. The better the wetting property the quicker water was absorbed into the fabric matrix. The rate at which the second layer took on water was governed independently, and not by the rate that the first layer took on water. Therefore the bottom layer was taking on water at a more rapid rate than the top layer in the Nomex and acrylic fabric samples.

CHAPTER 5

5.0 INTRODUCTION

As mentioned in Chapter 1 the right combination of fabric layers could help in the transmission of liquid through a fabric assembly and in turn help in the reduction of heat stress, through the use of heat and flame protective garments such as those used by firefighters.

The equipment developed and described in chapter 3 was used to study the wicking mechanisms and properties of individual fabric layers within multi-layer fabric systems, with a view to understanding the effects of mixed fibre types within a multi-layer fabric assembly. This in turn would help in establishing the ideal fabric combinations.

5.1 SUMMARY AND CONCLUSIONS

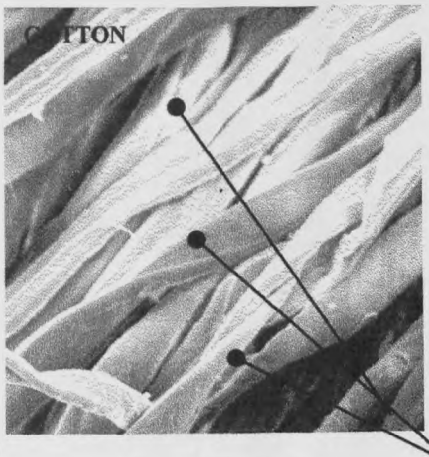
5.1.1 Mechanism of Horizontal Transplanar wicking

Overall observation at the time of testing, and from all the horizontal transplanar wicking test results have produced the following hypothesis for horizontal transplanar wicking in fabric layers :

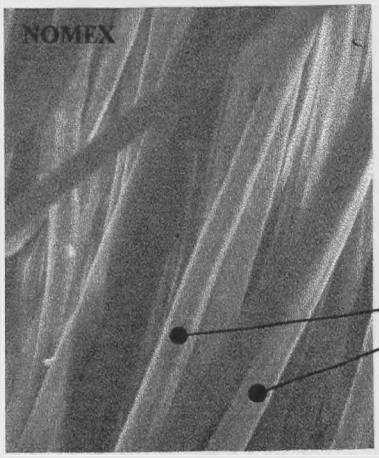
- Fabric pores/channels present in the test fabrics, are determined by the porosity of the fabric, this in turn is determined by the fabric structure ; fibre type ; pressure applied ; inter-fabric alignment.
- Wicking will occur in the horizontal planar direction, and it is also the amount of planar wicking needed which will determine the speed of water transmission through multi-layer fabric systems.
- Horizontal transplanar wicking occurs initially at specific inter-fabric contact points, which are determined by the fabric structure ; pressure applied ; inter-fabric alignment and fabric geometry.
- The horizontal transplanar wicking process occurs by water travelling along the long arms of the knitted loops (in the inter-fibre channels)[78,80] until it reaches a transfer point (inter-fabric contact point), where the transfer point will most likely be the top of a loop head , (see figures 134 and 135).

- The rate of initial wicking is determined by the number of small inter-fibre channels present in the yarn. Small inter-fibre channels create a higher capillary pressure than inter-yarn channels thereby inducing more rapid wicking. It is considered that the size and shape of the inter-fibre capillaries are determined by the fibre cross-sectional shape, and the degree of fibre packing within the yarn bundle, (see figure 133).
- The amount of retained liquid and the rate of horizontal transplanar wicking is determined by the number and size of the inter-yarn channels. Above a certain loop size the inter-yarn spaces are affected adversely by gravity[80] and the rate of wicking is reduced.
- The speed at which water will wick transplanarly from one layer to the next is determined by the inter-fabric contact points on each layer in the assembly, and relies upon the fabrics being aligned in the most conducive sequence to allow transplanar wicking to occur from one layer to the next.
- The transmission path in horizontal transplanar wicking will vary with combinations of knitted and woven fabrics ; woven and woven fabrics ; knitted and knitted fabrics, and these are represented in Figures 136 and 137.

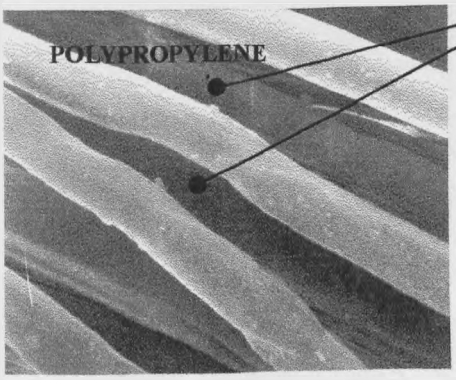
Fig. 133 Indications of Inter-fibre spaces or channels comparing basic cross-sectional shapes



X-sectional shape = collapsed tube



X-sectional shape = dog-bone



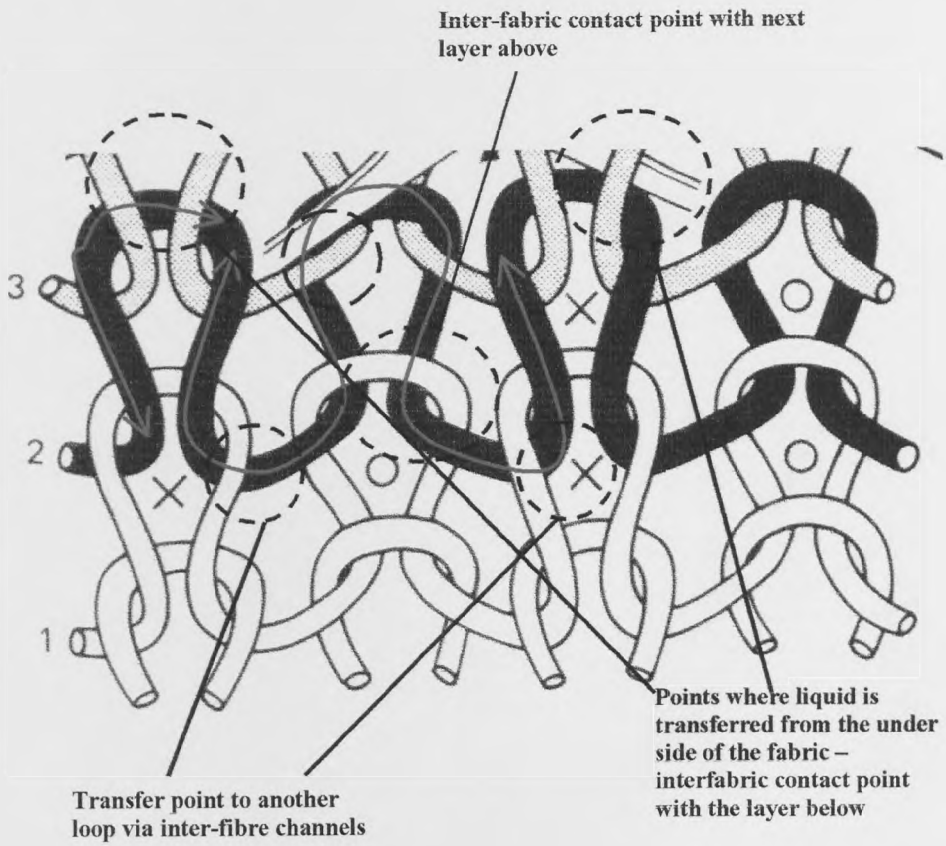
X-sectional shape = round

THESE ARE TYPICAL INTERFIBRE SPACES OR CHANNELS AVAILABLE WHERE WICKING MAY TAKE PLACE EITHER IN THE TRANSPLANAR OR PLANAR DIRECTION -

The more irregular the fibre cross-sectional shape the more water can be collected in the interconnected channels formed by the indentations formed along the fibre length.

E.g. cotton test samples will always have a greater retaining power and wicking rate compared to that of polypropylene samples due to the cross-sectional shape of the fibres used in the samples.

Fig. 134 Areas of inter-fabric contact, and possible water transmission paths within a 1x1 rib fabric



- Figure 134 and 135 highlight the areas where inter-fabric contact points may occur and also the water transport path by horizontal planar wicking within a 1x1 rib fabric and an interlock fabric, using the inter-fibre channels. The inter-yarn channels(loop spaces) become filled with water at a later stage.
- Inter-yarn spaces are formed in the loop spaces, creating larger inter-yarn capillary channels. The capillary pressure in these channels is lower, and therefore wicking is slower in these spaces. The sizes of these channels or pores are also susceptible to gravity.
- In intermittent contact within a fabric system these inter-fabric contact points will vary with each subsequent contact. A new set of contact points may be created, and therefore a new liquid transport path will be generated. This makes exact reproducibility of these paths extremely difficult. Hence high CV% during transplanar wicking tests.

Fig. 135 Areas of inter-fabric contact, and possible water transmission paths within an Interlock fabric

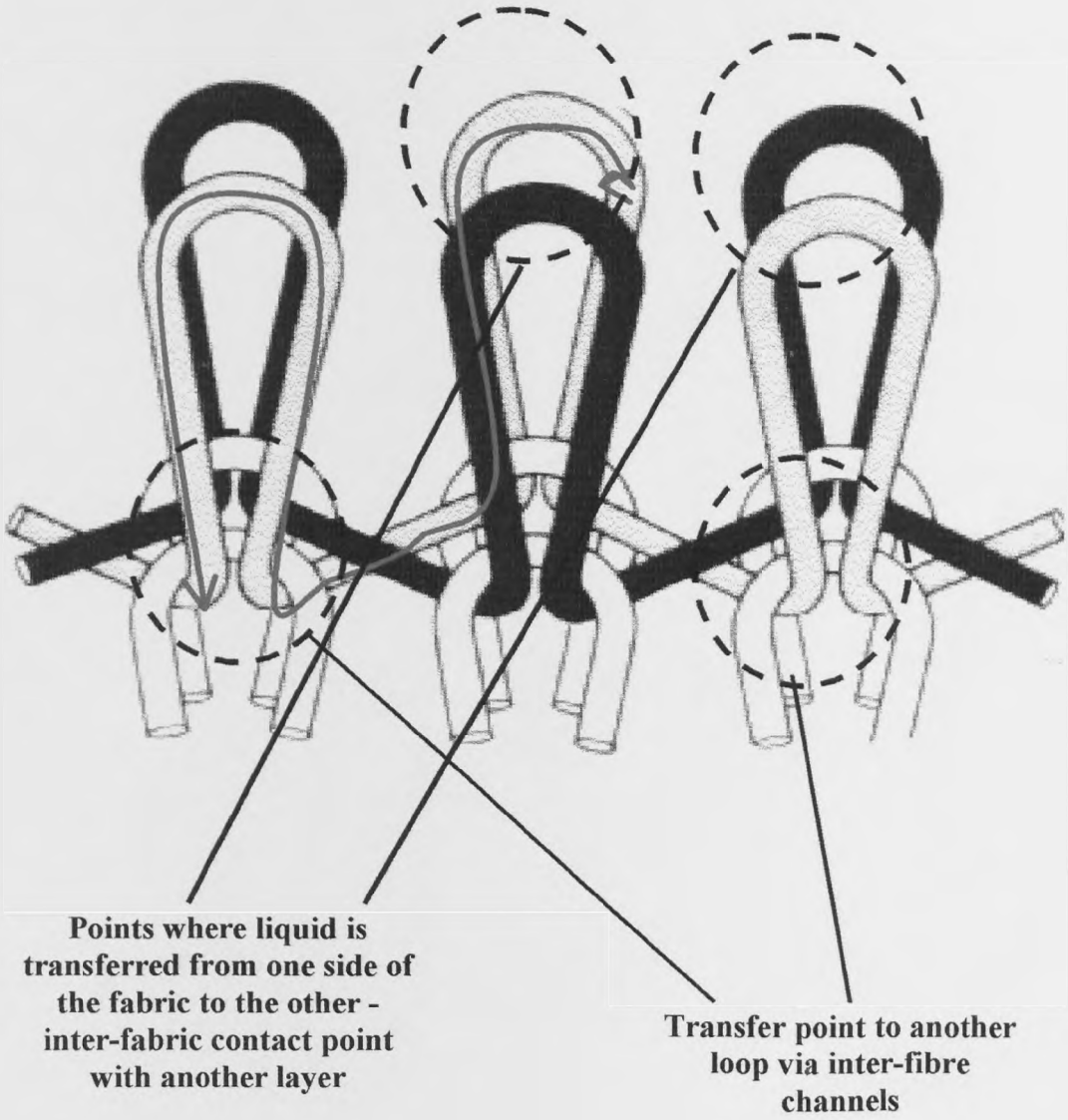


Fig. 136 Cross-sectional representation of multi-layer fabric systems – woven to woven ; knitted to woven.

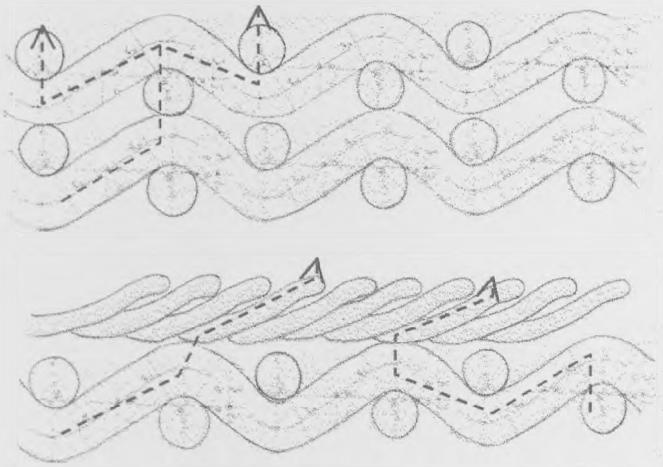
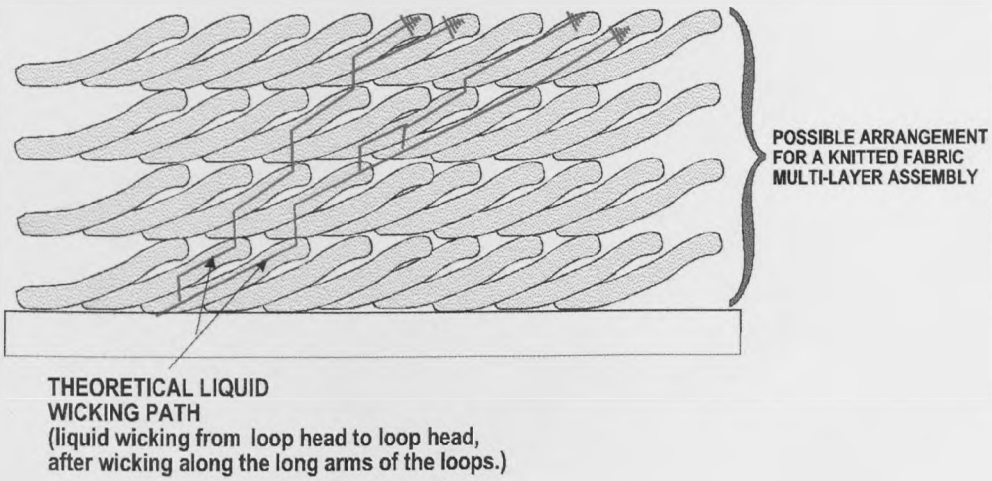


Fig. 137 Theoretical representation of liquid transmission path through multi-layer assemblies (knitted to knitted)



5.1.2 Horizontal Static transplanar wicking

Horizontal static transplanar wicking tests were carried out on various multi-layer assemblies comprising of different fibre combinations.
Of the four core fabrics (cotton, acrylic, Nomex and polypropylene) the cotton and acrylic fabrics had the greater wicking ability, with the Nomex and polypropylene having the poorer wicking properties when tested on their own.
However in mixed combinations these properties could be either hindered or enhanced, see Figures 78 to 97.

In the acrylic/polypropylene combination, with polypropylene nearest the liquid source the liquid uptake of the acrylic layer was severely hindered by the polypropylene, and thus produced an overall mean liquid uptake of less than 1%. The polypropylene took on more liquid than the acrylic by the end of the test period (20 minutes).
Polypropylene tested in combination with the other high wicking fabric (cotton) also had a negative effect on cotton wicking. Although the cotton produced a mean overall liquid uptake of 7.7% in combination with polypropylene, this was a long way below its normal abilities, and when tested in combination with the other fabric, i.e. acrylic.
The low wicking fabrics, polypropylene and Nomex, in combination with each other actually produced greater liquid uptake than in combination with the higher wicking fabrics cotton and acrylic.
In the case of the polypropylene combined with acrylic, and with the polypropylene layer nearest the liquid source (i.e. bottom layer). Polypropylene produced a final mean liquid uptake of 38.4%. However combined with acrylic it could only produce a final mean water content of 0.99%, and with cotton only 0.55%, and in both cases polypropylene was the layer nearest the water source.
The explanation for results obtained from the polypropylene/Nomex may be due to the similarity of the fabric structure. Their similarity in liquid uptake may be the reason for the ability of the Nomex and polypropylene fabrics to take on and retain more water when in combination together.

One possible theory is that the overall rate of liquid uptake of the whole assembly is controlled by the bottom fabric layer, (i.e. the fabric layer nearest the water source). If a slow or low wicking fabric is in the bottom layer the overall wicking process is slowed down, and the liquid uptake is reduced. This becomes more apparent when the fabric combination involves a high (or good) wicking fabric and a low (or poor) wicking fabric.

One unusual aspect appears in the results obtained from the polypropylene fabric samples. With polypropylene as the bottom layer combined with the Nomex fabric, the polypropylene appears to have taken on more water than when it was tested in a single layer state. However polypropylene produced the most variable results and this can be seen in the CV% produced for these tests in Appendix 2 and 3.

The horizontal dynamic transplanar wicking test results yielded similar conclusions to those observed in the horizontal static transplanar wicking.

With the added dimension of fabric movement, the cotton had the greater liquid uptake, but the acrylic, Nomex and polypropylene layers also demonstrated a significant increase in the wicking rate with the introduction of fabric movement.

5.1.3 Horizontal Dynamic transplanar wicking

The introduction of fabric movement produced a very clear overall conclusion on the effect of fabric movement on horizontal transplanar wicking. In all cases liquid uptake was increased with introduction of movement. In some cases a very significant increase, i.e. polypropylene liquid uptake was significantly increased with movement, see Tables 48 and 49.

Most results highlighted the traditional wicking abilities of most of the fabrics. The cotton fabric took on the most water with interfabric motion with itself, and the least amount was obtained from interfabric motion with polypropylene fabric samples.

Once again variability was unavoidable, with the polypropylene and Nomex knitted fabric samples having the highest CV% in general, see Appendix 4.

5.1.4 Comparison of fabric surface types

Observations of the horizontal dynamic wicking test revealed a secondary effect, created by the movement during the tests. The introduction of wear during these tests revealed an effect on the wicking ability of the fabrics being tested.

Four fabrics with 4 different fabric surface wear modifications were observed on one fabric type, the blue weft knitted interlock cotton fabric.

Singed, normal (untreated), rubbed and brushed knitted cotton fabric samples were tested under $0.68g/cm^2$, $1.0g/cm^2$, and $3.0g/cm^2$ compressional weights, using the horizontal dynamic transplanar.

Using an empirical hyperbolic equation to analyse the results, the initial rate of wicking and maximum water uptake could be calculated. Overall analysis indicated that with wear wicking properties could be reduced. The type of wear on a fabric would also determine the amount of reduction in liquid uptake. The amount of pressure applied to each surface type also produced different effects on liquid uptake. However it was determined that the (untreated) Normal surface had the best surface conditions for static horizontal wicking to take place under all three pressures ($0.68g/cm^2$; $1.0g/cm^2$; $3.0g/cm^2$). Under the lightest weight ($0.68g/cm^2$) all four surface types took on fairly similar final water contents. An increase in applied pressure produced an increase in liquid uptake, with the normal and rubbed samples taking on the most water at maximum uptake at infinite time. The singed sample took on the least amount under the lightest pressure.

These observation lead to the belief that wear has a detrimental affect on horizontal transplanar wicking, and is further affected by the area in which a fabric is utilised in a garment, i.e. the shoulder areas of garments, especially heat and flame protective clothing.

With increased wear the horizontal transplanar wicking properties of a garment diminish and the amount of reduction is dependent on the type and amount of wear present.

5.1.5 Vertical Transplanar Wicking

Observation of the vertical transplanar wicking tests revealed that the wetting ability of any fabric is very important in establishing initial transplanar wicking in this test. The poorer the wetting ability of the test fabric the slower transplanar wicking occurred in vertical wicking. In the case of polypropylene this was too slow for these tests to work efficiently, and consequently vertical transplanar wicking tests were abandoned on the polypropylene knitted fabrics.
Reproducibility of this test was extremely difficult to achieve, and consequently was not as good in general as the horizontal transplanar wicking tests. The CV% can be seen in Appendix 5, however with further improvement to this test this may be improved, as this is an important aspect in the overall view of the wicking process occurring within a multi-layer fabric system or garment.

5.1.6 Conclusions

The complexities of wicking within a multi-layer fabric system can be seen clearly, as figure 30 initially demonstrated. It is clear that many factors influence the wicking in both directions within a textile medium, and in many states e.g. horizontal versus vertical, static versus moving samples.
It is particularly difficult to analyse the wicking process in simple terms within knitted fabrics. However the experimental work carried out has determined that horizontal transplanar wicking does occur at inter-fabric contact points, creating isolated pockets of saturation. Transmission occurs along the arms of knitted loops by horizontal planar wicking via inter-fibre channels, connecting with other layers at inter-fabric points, and creating larger inter-yarn channels. These in turn transfer more liquid, and collect and retain liquid within the fabric matrix.
In multi-layer assemblies the ability to transfer liquid from one layer to the next, and thus move liquid from the surface of the skin to the outside layer of a fabric system can be influenced by the mix of fibre types and/or the mix of fabric structures within a fabric assembly.

It is clear from the results that certain combinations of fabrics will either hinder or assist the rate and amount of liquid movement within multi-fabric layer systems. It could therefore be said that the right combination of fabrics within a multi-layer fabric assembly could be of benefit in removing enough liquid away from the skin, in turn increasing evaporation and reducing the amount of heat stored within certain types of multi-layer clothing system, i.e. heat and flame protective clothing assemblies.

5.1.7 Recommendations for future work

1. Further investigation into more fabric structure combinations may yield interesting data.
2. More work should be carried out on vertical transplanar wicking, which has proved to be very difficult to simulate.
3. Image analysis of different fabric constructions could establish more clearly the pattern of inter-fabric contact points and lead to further refinements in the theory of horizontal transplanar wicking.
4. The influence of different fibre cross-sections and different fibre blends and blend ratios on horizontal transplanar fabric wicking should be investigated.
5. The role of fibre lubricants and surface finishes upon the rate and extent of horizontal transplanar fabric wicking should yield interesting results.
6. The effects of pressure and different types of fabric movement upon horizontal transplanar fabric wicking, e.g. the extent of fabric reciprocation or rotary motion should be studied.

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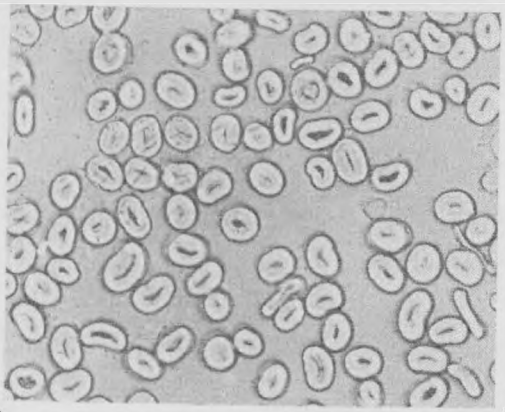
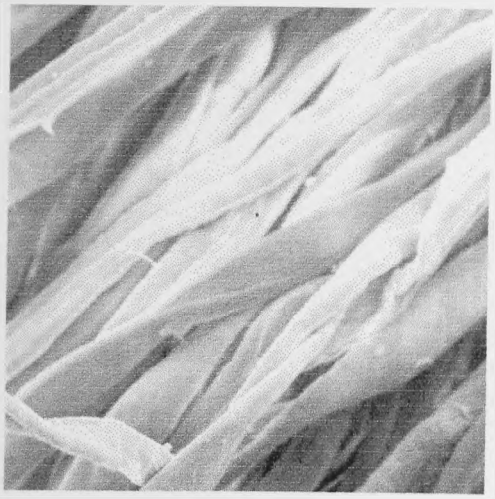
APPENDIX I

Fig. 138 Cotton fibre



a)

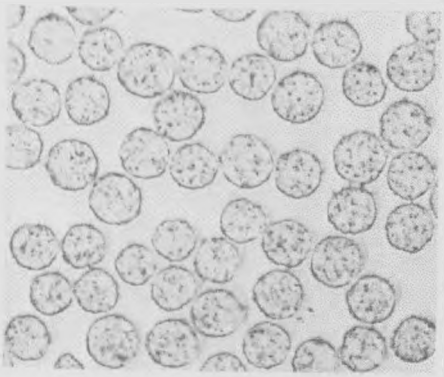


b)

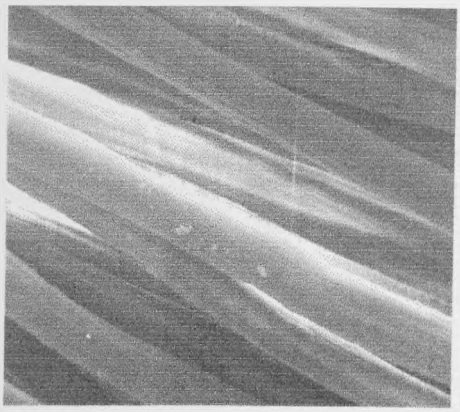
a) cross-section of Cotton fibres[77] fibre

b) longitudinal section of Cotton.L

Fig. 139 Acrylic fibre



a)

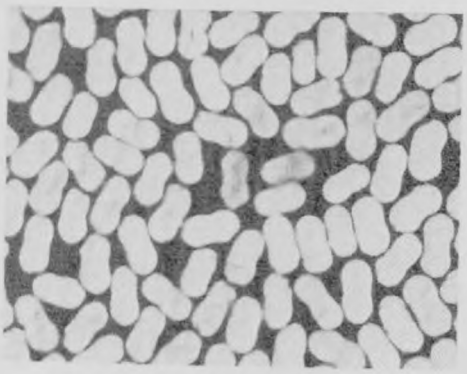


b)

a) cross-section of Acrylic fibres[77] fibre

b) longitudinal section of Acrylic

Fig. 140 Nomex Fibre



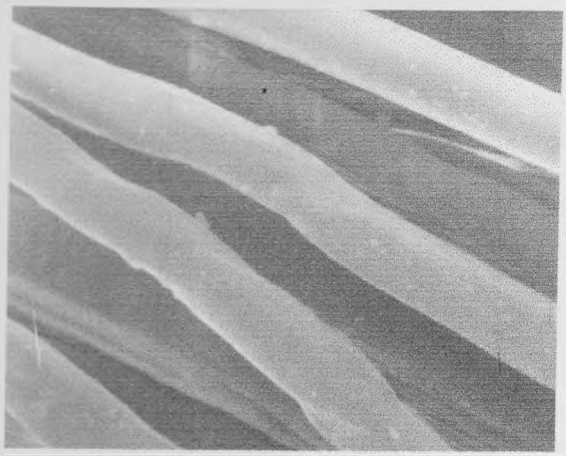
a)

b)

a) cross-section of Nomex fibres[77] fibre

b) longitudinal section of Nomex

Fig. 141 Polypropylene fibre



Longitudinal section of the Polypropylene fibre

APPENDIX II

Horizontal Static transplanar wicking tests

(Mean results based on 5 tests on 5 test samples)

Table 67

COMPARISON OF TEST VARIABILITY BY CV%

	MEAN COEFFICIENT OF VARIATION % Time (min)			
	1	3	10	20
POLYPROPYLENE	0.1	0.1	21.3	37.3
ACRYLIC	50.0	14.9	1.1	0.0

	MEAN COEFFICIENT OF VARIATION % Time (min)			
	1	3	10	20
ACRYLIC	20.6	5.5	2.3	0.7
POLYPROPYLENE	13.7	9.9	17.6	13.3

Table 68

COMPARISON OF TEST VARIABILITY BY CV%

	MEAN COEFFICIENT OF VARIATION % Time (min)			
	1	3	10	20
POLYPROPYLENE	11.5	24.1	14.9	11.9
NOMEX	32.9	25.5	24.5	8.3

	MEAN COEFFICIENT OF VARIATION % Time (min)			
	1	3	10	20
NOMEX	0.4	3.9	12.2	2.2
POLYPROPYLENE	62.0	74.2	69.1	63.8

Table 69

COMPARISON OF TEST VARIABILITY BY CV%

	MEAN COEFFICIENT OF VARIATION % Time (min)			
	1	3	10	20
NOMEX	31.1	0.5	7.2	16.2
ACRYLIC	12.5	20.1	11.0	8.7

	MEAN COEFFICIENT OF VARIATION % Time (min)			
	1	3	10	20
ACRYLIC	20.2	0	15.7	5.4
NOMEX	1.4	4.4	13.2	25.0

Table 70

COMPARISON OF TEST VARIABILITY BY CV%

	MEAN COEFFICIENT OF VARIATION %			
	Time (min)			
	1	3	10	20
COTTON	5.3	2.1	4.3	11.7
POLYPROPYLENE	0.5	8.6	10.6	21.5

	MEAN COEFFICIENT OF VARIATION %			
	Time (min)			
	1	3	10	20
COTTON	40.7	31	12.5	33.7
ACRYLIC	5.3	28.4	23.6	26.7

	MEAN COEFFICIENT OF VARIATION %			
	Time (min)			
	1	3	10	20
COTTON	0.1	0.1	77.6	6.1
NOMEX	31.4	3.4	22.8	1.4

APPENDIX III

A comparison of the variability of test results after a change in the test method as performed on single layer assemblies.

Variability of Tests are represented by the Coefficient of variation (CV%)

(Mean test results based on 5 tests on 5 samples)

Table 71.

	COEFFICIENT OF VARIATION %			
	Time (min)			
NOMEX	1	3	10	20
BEFORE	36.8	35.4	27.3	20.9
AFTER	18.3	21.9	9.4	5.6

Table 72.

	COEFFICIENT OF VARIATION %			
	Time (min)			
ACRYLIC	1	3	10	20
BEFORE	45	24.5	7.4	7.2
AFTER	11.0	12.2	1.8	1.3

Table 73.

	COEFFICIENT OF VARIATION %			
	Time (min)			
POLYPROPYLENE	1	3	10	20
BEFORE	8.7	93.6	91.4	85.8
AFTER	53.5	67.4	48.5	7.1

APPENDIX IV

DYNAMIC DEMAND WETTABILTY - MULTI-LAYER RESULTS
INTER-LAYER MOTION TEST RESULTS

(Mean test results based on 5 samples tested 5 times)

Table 74.

Acrylic on	MEAN COEFFICIENT OF VARIATION % Time (min)					
	5	10	15	20	25	30
NOMEX	3.5	15.1	27.1	30	26.7	25.3
ACRYLIC	16.4	25.2	21.8	13.5	9.3	4.5
POLYPROPYLENE	21.1	16.7	8.2	2.6	4.1	6.8
COTTON	30.6	13.3	5.6	2.7	2.1	1.7

Table 75.

Cotton on	MEAN COEFFICIENT OF VARIATION % Time (min)					
	5	10	15	20	25	30
NOMEX	37.6	23.3	34.9	28.4	24.8	16.8
ACRYLIC	30.6	13.3	5.6	2.7	2.1	1.7
POLYPROPYLENE	50.3	51.6	47.5	41.4	36.7	32.8
COTTON	1.9	1.7	1.7	1.6	1.7	1.9

Table 76

Nomex on	MEAN COEFFICIENT OF VARIATION % Time (min)					
	5	10	15	20	25	30
NOMEX	46.2	18.9	13.5	17.4	17.9	20.9
ACRYLIC	7	23.3	0.1	5.6	7.5	4.3
POLYPROPYLENE	19.4	16.2	19.3	19.4	19.1	17.7
COTTON	11.3	14.3	10.5	9.7	6.2	2.4

Table 77.

Polypropylene on	MEAN COEFFICIENT OF VARIATION % Time (min)					
	5	10	15	20	25	30
NOMEX	28.7	19.1	16.2	5.5	1.2	5.5
ACRYLIC	46.2	18.9	13.5	17.5	17.9	20.9
POLYPROPYLENE	49.8	50.7	55.9	56.2	58.0	56.7
COTTON	5.3	7.1	9.5	9.0	10.6	11.0

APPENDIX V

VERTICAL WICKING TEST RESULTS
Variability of Tests are represented by the Coefficient of variation (CV%)

Table 78.

VERTICAL WICKING TEST RESULTS

SAMPLE : **Acrylic** - Interlock knitted structure

(water content based on total fabric weight)

	% WATER CONTENT	
	Top layer	Bottom layer
	20.7	7.5
	21.3	1.5
	30.8	4.4
	28.6	4.7
Mean	25.4	4.5
Stdev	5.11	2.45
CV%	20.2	54.2

(water content based on wet area of fabric only)

	% WATER CONTENT	
	Top layer	Bottom layer
	40.8	41.7
	37.6	153.3
	97	35.7
Mean	58.5	76.9
Stdev	33.41	66.23
CV%	57.1	86.1

Table 79.

VERTICAL WICKING TEST RESULTS

SAMPLE : **Cotton** - Interlock knitted structure

(water content based on total fabric weight)

	% WATER CONTENT	
	Top layer	Bottom layer
	12.6	5.8
	24.0	4.6
	27.2	1.1
	22.4	8.9
Mean	21.6	5.1
Stdev	6.29	3.22
CV%	29.2	63.2

(water content based on wet area of fabric only)

	% WATER CONTENT	
	Top layer	Bottom layer
	150	75
	100	81.3
	118.5	54.6
Mean	122.8	70.3
Stdev	25.28	13.96
CV%	20.6	19.9

Table 80

VERTICAL WICKING TEST RESULTS

SAMPLE : **Nomex** - 1 x 1 Rib knitted structure

(water content based on total fabric weight)

	% WATER CONTENT	
	Top layer	Bottom layer
	6.4	3.7
	4.0	1.7
Mean	5.2	2.7
Stdev	1.70	1.41
CV%	32.6	52.4

(water content based on wet area of fabric only)

	% WATER CONTENT	
	Top layer	Bottom layer
	84.6	212.5
	113.3	180.0
Mean	99.0	196.3
Stdev	20.29	22.98
CV%	20.5	11.7