8

Comfort

8.1 Introduction

It is possible to distinguish two aspects of wear comfort of clothing:

1 Thermophysiological wear comfort which concerns the heat and moisture transport properties of clothing and the way that clothing helps to maintain the heat balance of the body during various levels of activity.
2 Skin sensational wear comfort which concerns the mechanical contact of the fabric with the skin, its softness and pliability in movement and its lack of prickle, irritation and cling when damp.

8.2 Thermal comfort

8.2.1 Heat balance

The human body tries to maintain a constant core temperature of about 37 °C. The actual value varies slightly from person to person but the temperature of any one person is maintained within narrow limits. In most climates body temperature is above that of the external environment so that there has to be an internal source of heat in order to maintain the temperature difference. The required heat comes from the body's metabolism, that is the necessary burning of calories to provide power to the muscles and other internal functions. However, the body must be kept in thermal balance: the metabolic heat generated together with the heat received from external sources must be matched by the loss from the body of an equivalent amount of heat. If the heat gain and the heat loss are not in balance then the body temperature will either rise or fall, leading to a serious threat to life.

The efficiency of the human organism is such that of the energy taken in as food only 15–30% is converted into useful work with the remaining 70–85% of the energy being wasted as heat. Any level of physical activity

Table 8.1 Energy costs of activities [1]

Activity	Energy cost (watts)
Sleeping	70
Resting	90
Walking 1.6 km/h (1 mph)	140–175
Walking 4.8 km/h (3 mph)	280–350
Cycling 16 km/h (10 mph)	420–490
Hard physical work	445–545
Running 8 km/h (5 mph)	700–770
Sprinting	1400–1500

above that needed to maintain body temperature will result in an excess of heat energy which must be dissipated, otherwise the body temperature will rise. A lower level of physical activity will lead to a fall in body temperature if the available heat is not conserved by increased insulation.

The approximate energy costs which are associated with human activity are shown in Table 8.1 and range from a minimum value of about 70 W when sleeping to an absolute maximum of about 1500 W which is only possible in short bursts. A rate of about 500 W (corresponding to hard physical work) can be kept up for a number of hours.

If a person is comfortable (that is, in heat balance) at rest then a burst of hard exercise will mean that there is a large amount of excess heat and also perspiration to be dissipated. On the other hand if the person is in heat balance during strenuous exercise then he or she will feel cold when resting owing to the large reduction of heat generation.

8.2.2 Heat loss

There are four mechanisms that allow the body to lose heat to the environment in order to maintain its thermal balance. The way the heat loss is divided between the mechanisms depends on the external environment.

1. **Conduction**. In this process heat loss is accomplished through direct contact with another substance. The rate of exchange is determined by the temperature difference between the two substances and by their thermal conductivities. For example the body loses heat in this manner when submerged in cold water.
2. **Convection**. This is a process in which heat is transferred by a moving fluid (liquid or gas). For example, air in contact with the body is heated by conduction and is then carried away from the body by convection.
3. **Radiation**. This is the process of heat transfer by way of electromagnetic waves. The waves can pass through air without imparting much heat to

it; however, when they strike an object their energy is largely transformed into heat. Radiation can largely be ignored as a mechanism of losing heat as it is very dependent on the temperature of an object (varying as T^4) so that it is more important as a means of heat gain from very hot bodies such as the sun, radiant heaters or fires. Heat radiation and absorption by an object are both influenced by its colour. Black is both the best absorber and radiator of heat. White and polished metals are poor absorbers and radiators as most of the energy is reflected. Clothing acts to reduce radiation loss by reducing the temperature differences between the body and its immediate surroundings as the clothing effectively becomes the immediate surroundings.

4 **Evaporation**. Changing liquid water into vapour requires large amounts of heat energy. One calorie will raise the temperature of one gram of water one degree Celsius; however, it takes 2424 J (580 calories) to evaporate one gram of water at body temperature. If the water is evaporated from the skin surface then the energy required is removed from the skin, thus cooling it. When environmental temperatures approach skin temperature (35 °C seated to 30 °C heavy physical work), heat loss through convection and radiation gradually come to an end so that at environmental temperatures above skin temperature the only means for the body to lose heat is through evaporation of sweat. Sweating itself is not effective as it is the conversion of the liquid to vapour that removes the heat. This mechanism works well in a hot dry environment but evaporation of sweat becomes a problem in hot humid climates.

The requirements for heat balance vary with the climate; in hot climates the problem is one of heat dissipation whereas in cold climates it is one of heat conservation.

Clothing has a large part to play in the maintenance of heat balance as it modifies the heat loss from the skin surface and at the same time has the secondary effect of altering the moisture loss from the skin. However, no one clothing system is suitable for all occasions: a clothing system that is suitable for one climate is usually completely unsuitable for another.

The main fabric properties that are of importance for maintaining thermal comfort are:

- insulation,
- windproofing,
- moisture vapour permeability,
- waterproofing.

These properties are closely interrelated in that changes in one property can cause changes to the other three properties.

Insulation

An air temperature of 28–29 °C would be required for a person to be able to sit in comfort without wearing any clothes. At air temperatures lower than this, therefore, the body will lose heat without the added insulation given by clothing.

If losses by convection can be prevented, the air itself offers a very high resistance to heat conduction having a value of thermal resistance which is only slightly less than that of a vacuum. Convection losses arise because the body loses heat to the air in contact with it. This heated air is then immediately replaced with cooler air either through natural convection or through air currents. The air currents can be caused by either body movement or by external air flow such as in windy conditions. Convection losses can therefore be reduced by keeping the air surrounding the body at rest. Air tends to 'cling' to solid surfaces so that material with a large exposed surface area, such as a mass of fine fibres, acts as a good restrictor of air movement. In clothing the majority of the bulk is composed of air, for example a worsted suiting fabric is made up of 25% fibre and 75% air whereas knitted underwear and quilted fabrics filled with fibre battings or down and feathers may contain 10% or less actual fibre, with the rest consisting of air.

The heat flow through a fabric is due to a combination of conduction and radiation the convection within a fabric being negligible [2]. The conduction loss is determined by the thickness of the fabric and its thermal conductivity. The thermal conductivity is itself a combination of the conductivity of air k_A and that of the fibre k_F:

$$\text{Fabric conductivity } k = (1 - f)k_A + fk_F$$

where f is the fraction by volume of the fabric taken up by fibre. The conductivity of air is 0.025 W/m K and that of fibres is 0.1 W/m K, therefore in fabrics of fibre contents below 10% the conductivity is effectively that of air.

The heat flow due to radiation is more complex as it is governed by the temperature difference between the heat emitter and the heat absorber. The infra-red radiation only travels a few millimetres into a fabric as it is either scattered or absorbed by the fibres. These fibres in turn emit radiation which travels a further short distance to the next fibres and so on until it reaches the far surface. Therefore the radiative heat transfer between the body and the external environment is indirect and depends on the absorption and emission properties of the fibres.

In order to predict the heat flow due to radiation through a fabric it is necessary to know the temperature profile. The simplest assumption is a linear change in temperature with distance through the fabric which is true of conduction heat flow. At the edges of a fabric the situation is more complex than this, but in the centre of a thick specimen the conductivity due to radiation can be simplified to [2]:

$$\text{Radiative conductivity} = \frac{8\sigma T^3 R}{f\varepsilon}$$

where σ = Stefan–Boltzmann constant ($5.67 \times 10^{-8}\,\mathrm{W/m^2K^4}$),
ε = thermal emissivity,
R = radius of fibres,
T = mean temperature between heat source and sink (K),
f = fractional fibre volume.

This means that the heat loss from radiation is higher at low fibre volumes (less than 5%) but is reduced by the use of fine fibres and higher fibre volumes [2].

The insulation value of clothing when it is worn is not just dependent on the insulation value of each individual garment but on the whole outfit as the air gaps between the layers of clothing can add considerably to the total insulation value. This assumes that the gaps are not so large that air movement can take place within them, leading to heat loss by convection. Because of this limitation the closeness of fit of a garment has a great influence on its insulation value as well as the fabric from which it is constructed.

The insulation value of a fabric is in fact mainly dependent on its thickness and it can be estimated from the relationship:

$$\text{clo} = 1.6 \times \text{thickness in cm}$$

where clo is a measure of thermal resistance (see below).

Unfortunately any increase in the thickness of clothing in order to increase its insulation value also increases its surface area and bulk and thus decreases its rate of water vapour transmission.

The insulation value of clothing is generally measured by its thermal resistance which is the reciprocal of thermal conductivity. The advantage of using thermal resistance rather than conductivity is that the values of the different layers of clothing can then be added together to give the overall resistance value of the outfit. The thickness of the material is not taken into consideration in the units of thermal resistance used. The SI unit of thermal resistance is degrees Kelvin square metre per watt (1 unit = $1\,\mathrm{K\,m^2/W}$). Two different units are in use in the clothing field:

Clo unit

This is an American unit which was adopted for the simplicity of presentation to a layperson. Clothing having a thermal resistance of one clo unit approximates the normal indoor clothing worn by sedentary workers, i.e. suit, shirt and underwear.

The complete definition is the insulation required to maintain a resting man producing heat at 50 Kcal/m^2/h indefinitely comfortable in an atmosphere at 21 °C less than 50% RH and air movement of 10 cm/s. Its value is equivalent to 0.155 °C m^2/W.

Tog unit

This is a British unit which was proposed by workers at the Shirley Institute and it is related to the international units for thermal resistance used for building materials but converted to larger units to make them easier to use:

$$1\text{ tog} = 0.1\,^\circ\mathrm{C\,m^2/W}$$
$$10\text{ togs} = 1\,\mathrm{K\,m^2/W} = 1\,^\circ\mathrm{C\,m^2/W}$$
$$1\text{ clo} = 1.55\text{ tog}$$

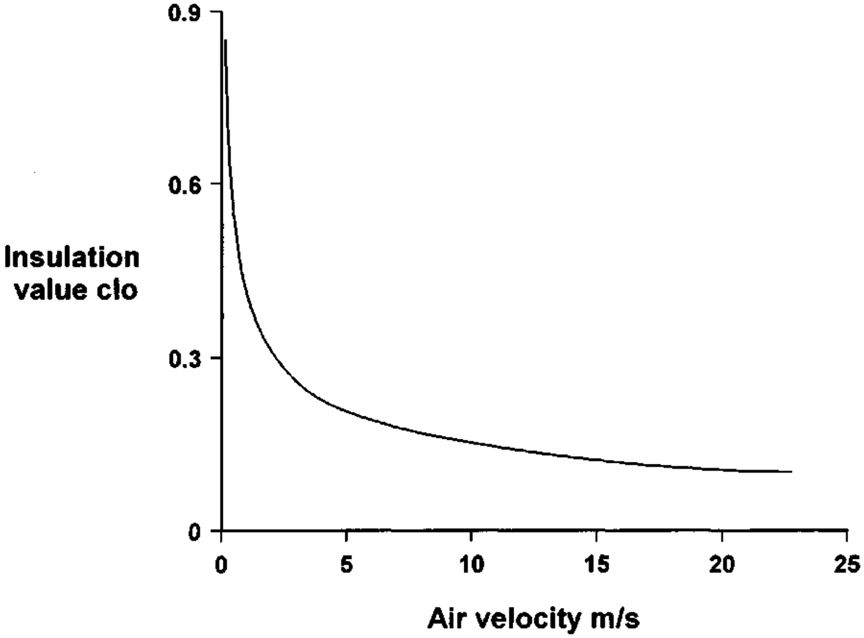
Windproofing

Air tends to cling to surfaces and thus form an insulating layer. The value of this can be as high as 0.85 clo at a windspeed of 0.15 m/s [3] even on an uncovered surface. This is the reason that the comfort temperature for the unclothed body is lower than the skin temperature. However, the air layer is easily disturbed by air movements; Fig. 8.1 shows the fall in its insulation value with increasing windspeed which is governed by the following equation [3]:

$$\text{Insulation of surface layer} = \frac{1}{0.61 + 0.19V^{1/2}}\text{ clo}$$

where V = air velocity cm/s.

Wind has two other major effects on clothing: firstly it causes compression of the underlying fabrics and therefore reduces their insulation value by reducing their thickness. Secondly it disturbs the trapped air in the clothing system by both the movement of the fabric and by penetration through the fabric, thus increasing the convection heat losses. At low windspeeds (less than 8 km/h) these effects are negligible [1] but at windspeeds of 32–48 km/h they can become significant depending on the air permeability of the outer layer of the clothing. For example an impermeable cover fabric worn over a pile insulating layer showed an 18% loss in insulation at a windspeed of 48 km/h due to compression. With the use of permeable outer fabrics the convection losses were:



8.1 The insulation values of air.

10%	4.5 oz (125 g) downproof sateen
43%	5.5 oz (155 g) cotton gabardine
73%	3 oz (85 g) poplin shirting

A fabric can easily be made windproof by coating it with an impermeable coating or by using a tight weave. However, coated fabrics have low rate of moisture vapour transmission.

Moisture vapour permeability

Perspiration is an important mechanism which the body uses to lose heat when its temperature starts to rise. Heat is taken from the body in order to supply the latent heat needed to evaporate the moisture from the skin.

There are two forms of perspiration:

1 Insensible – in this form the perspiration is transported as a vapour and it passes through the air gaps between yarns in a fabric.
2 Liquid – this form occurs at higher sweating rates and it wets the clothing which is in contact with the skin.

The two forms of perspiration raise separate problems: one is the ability of water vapour to pass through the fabric, particularly the outer layer; and the other is the ability of the fabric in contact with the skin of absorbing or otherwise dealing with the liquid sweat.

The ability of a fabric to allow perspiration in its vapour form to pass through it is measured by its moisture vapour permeability in grams of water vapour per square metre per 24 hours. A fabric of low moisture vapour permeability is unable to pass sufficient perspiration and this leads to sweat accumulation in the clothing and hence discomfort. The fabrics most likely to have a low permeability are the ones that have been coated to make them waterproof. The coatings used to keep out liquid water will also block the transport of water vapour.

The overall moisture vapour permeability of clothing is rather like the thermal insulation value in that it depends on the whole clothing system. The resistance of each clothing item together with air gaps adds to the total resistance of the system. If the production of perspiration is greater than the amount the clothing system will allow to escape, moisture will accumulate at some point in the clothing system. If the outer layer is the most impermeable, moisture will accumulate in the inner layers. When excess moisture accumulates it causes a reduction in thermal insulation of the clothing and eventually condensation and wetting. The level of perspiration production is very dependent on the level of activity: clothing that may be comfortable at low levels of activity may be unable to pass sufficient moisture vapour during vigorous activity. However, when activity ceases, freezing can occur because the clothing is now damp and body heat production has been reduced, leading to after-exercise chill and, if the temperature is low enough, frostbite. This factor is particularly important in Arctic conditions where excessive sweating must be avoided at all costs. The overall combination of wind, wetting and disturbance of entrapped air can reduce the nominal insulation value of a clothing system by as much as 90%.

Waterproof breathable fabrics

The existence of the problem of the lack of water vapour permeability in waterproof fabrics has led to the development of waterproof breathable fabrics. One approach to producing such a fabric is to use membranes attached to the fabric or coatings on the fabric which are waterproof but which will allow moisture vapour to pass through. It is possible to achieve this because of the enormous difference in size between a water droplet and a water vapour molecule. A water droplet has a size of around 100 μm whereas a water vapour molecule has a size of around 0.0004 μm. If, therefore, a membrane or fabric can be produced with pore sizes between these two limits it will then have the desired properties.

Another approach is to use a coating or membrane made from a hydrophilic film without any pores. The moisture is absorbed by the membrane and then transported across it by diffusion, evaporating when it reaches the outer surface. The driving force for the diffusion is provided by the body temperature which ensures that the water passes out even when it is raining.

A third approach is to use a tightly woven fabric. One of the original waterproof breathable fabrics, Ventile, was produced in this way by using tightly woven special cotton yarns which swelled when wet thus closing any gaps in the fabric. The production of fine microfibres has allowed the production of fabrics that are woven sufficiently tightly to keep liquid water out.

Lightweight polyurethane-coated nylon fabrics typically have moisture permeability values of the order of 200 g/m^2/24 h, whereas the requirement when walking at 5 km/h is that the fabric should pass between 2800 and 7000 g/m^2/24 h (average surface area of human body 1.7–1.8 m^2). Cotton ventile fabrics have moisture permeability values of about 4900 g/m^2/24 h whereas modern membrane materials have quoted values of between 4000 g/m^2/24 h and 2500 g/m^2/24 h [4]; the comparability of these figures depends on the way the values have been measured.

Overall there is a trade-off between the degree of waterproofing of a fabric and its moisture vapour transmission.

Waterproofing

Waterproofing is very important for the outer layer of a clothing system designed to be worn outdoors. This property is particularly important in cold weather activities for keeping the insulation of any clothing system dry. Waterlogging of fabrics fills up the air spaces with water and hence reduces their insulation value considerably as shown in Table 8.2. If the water penetrates to the skin it can also remove a large amount of heat by the same mechanism as that which makes perspiration effective.

The waterproofing of fabrics can readily be achieved by the use of synthetic polymer coatings; however, the use of simple coatings bring with it the penalty of excess build-up of moisture vapour above certain levels of activity. The design of clothing for comfort and protection in adverse weather conditions is therefore a matter of compromise between the competing requirements. No one fabric or clothing item can fulfil all the requirements, the clothing system as a whole has to be considered.

8.2.3 Air permeability

The air permeability of a fabric is a measure of how well it allows the passage of air through it. The ease or otherwise of passage of air is of importance for a number of fabric end uses such as industrial filters, tents,

Table 8.2 Effect of moisture on insulation values [5]

	Thermal insulation (togs)		
	Staple polyester	Continuous filament polyester	50/50 down/feather
Dry	4.7	6.8	6.6
15% moisture	2.4	3.6	2.8
50% moisture	1.8	2.4	1.5
100% moisture	1.7	2.3	1.3

sailcloths, parachutes, raincoat materials, shirtings, downproof fabrics and airbags.

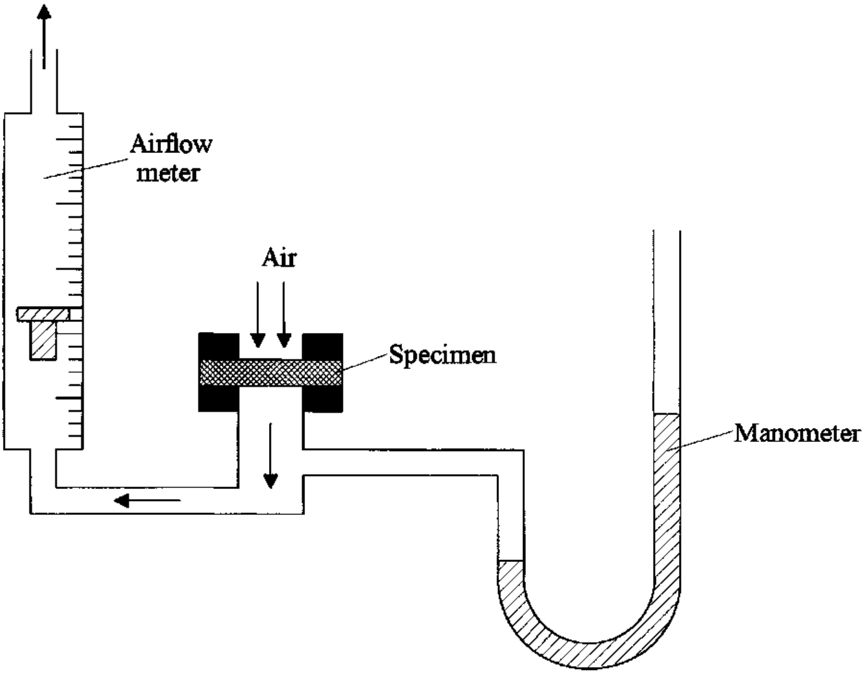
Air permeability is defined as the volume of air in millilitres which is passed in one second through 100s mm^2 of the fabric at a pressure difference of 10 mm head of water.

In the British Standard test [6] the airflow through a given area of fabric is measured at a constant pressure drop across the fabric of 10 mm head of water. The specimen is clamped over the air inlet of the apparatus with the use of rubber gaskets and air is sucked through it by means of a pump as shown in Fig. 8.2. The air valve is adjusted to give a pressure drop across the fabric of 10 mm head of water and the air flow is then measured using a flowmeter.

Five specimens are used each with a test area of 508 mm^2 (25.4 mm diameter) and the mean air flow in ml per second is calculated from the five results. From this the air permeability can be calculated in ml per 100 mm^2 per second.

The reciprocal of air permeability, air resistance, can be defined as the time in seconds for 1 ml of air to pass through 100s mm^2 of fabric under a pressure head of 10 mm of water. The advantage of using air resistance instead of air permeability to characterise a fabric is that in an assembly of a number of fabrics, the total air resistance is then the sum of the individual air resistances.

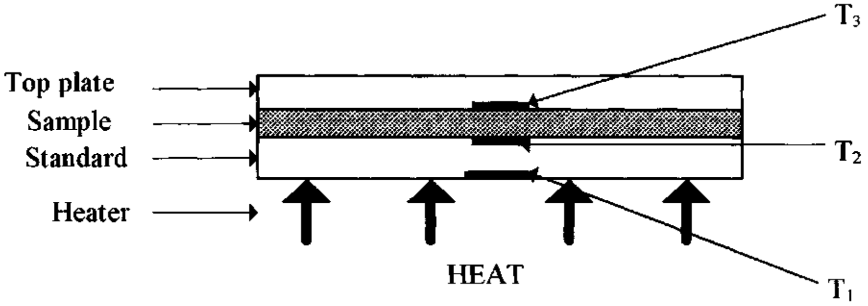
To obtain accurate results in the test, edge leakage around the specimen has to be prevented by using a guard ring or similar device (for example, efficient clamping). The pressure drop across the guard ring is measured by a separate pressure gauge. Air that is drawn through the guard ring does not pass through the flowmeter. The pressure drops across the guard ring and test area are equalised in order that no air can pass either way through the edge of the specimen. A guard ring of three times the size of the test area is considered sufficient.



8.2 The air permeability test.

8.2.4 Measurement of thermal conductivity

The transmission of heat through a fabric occurs both by conduction through the fibre and the entrapped air and by radiation. Practical methods of test for thermal conductivity measure the total heat transmitted by both mechanisms. The insulation value of a fabric is measured by its thermal resistance which is the reciprocal of thermal conductivity (transmittance) and it is defined as the ratio of the temperature difference between the two faces of the fabric to the rate of flow of heat per unit area normal to the faces. As can be seen from this definition it is necessary to know the rate of heat flow through a fabric in order to be able to measure its thermal resistance. In practice the measurement of the rate of heat flow in a particular direction is difficult as a heater, even when supplied with a known amount of power, dissipates its heat in all directions. Two different methods are in use to overcome this problem: one is to compare thermal resistance of the sample with that of a known standard and the other is to eliminate any loss in heat other than that which passes through the fabric being tested. It is important that any measurements of thermal resistance are made at temperatures close to those that are likely to be encountered in use as the thermal conductivity of materials varies with the temperature. This is due



8.3 Togmeter: two plate method.

to the variation in thermal conductivity of the air with temperature and also the dependence of the heat loss through radiation on temperature.

Togmeter

The togmeter [7] avoids the problem of measuring heat flow by placing a material of known thermal resistance in series with the material under test so that the heat flow is the same through both materials. The thermal resistance of the test fabric can then be calculated by comparing the temperature drop across it with the temperature drop across the standard material.

Apparatus

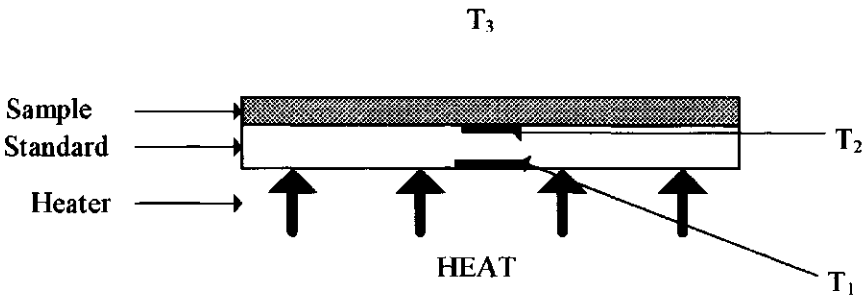
The togmeter consists of a thermostatically controlled heating plate which is covered with a layer of insulating board of known thermal resistance. The temperature is measured at both faces of this standard. The heater is adjusted so that the temperature of the upper face of the standard is at skin temperature (31–35 °C). A small airflow is maintained over the apparatus.

There are two methods of test that can be used with the togmeter:

1 **Two plate method**. In this method the specimen under test is placed between the heated lower plate and an insulated top plate as shown in Fig. 8.3. The top plate has a low mass so that it does not compress the fabric. The temperature is measured at the heater (T_1), between the standard and the test fabric (T_2) and between the fabric and the top plate (T_3).

2 **Single plate method**. In this method the specimen under test is placed on the heated lower plate as above but it is left uncovered as shown in Fig. 8.4, the top plate being used to measure the air temperature (T_3).

The air above the test specimen has a considerable thermal resistance itself so that the method is in fact measuring the sum of the specimen



8.4 Togmeter: single plate method.

thermal resistance and the air thermal resistance. A separate experiment is therefore performed without the specimen (i.e. a bare-plate test) to measure the resistance of the air R_{air}.

To determine the air resistance

The heater and the fan are switched on and the apparatus is allowed to reach thermal equilibrium with no specimen present. The top plate is placed underneath the apparatus shielded from radiation by a foil-covered plate, in order to measure the air temperature. The temperature should remain steady at each thermocouple for 30 mins. It may take some time for an equilibrium to be reached. Thermal resistance of air:

$$R_{\text{air}} = R_{\text{stand}} \times \frac{T_2 - T_3}{T_1 - T_2}$$

where R_{stand} is the thermal resistance of the standard.

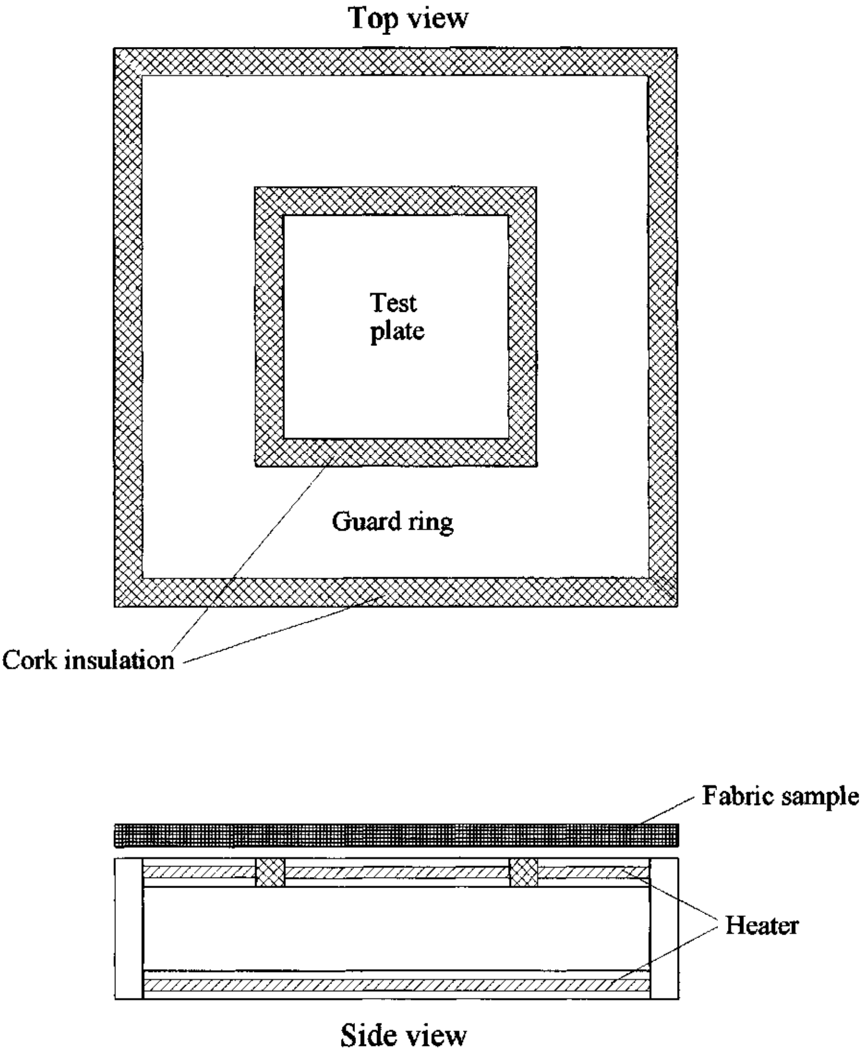
To determine the sample resistance

The above experiment is repeated with the test sample placed on the bottom plate and the apparatus again allowed to reach thermal equilibrium. Thermal resistance of sample:

$$R_{\text{sample}} = R_{\text{stand}} \times \frac{T_2 - T_3}{T_1 - T_2} - R_{\text{air}}$$

Guarded hotplate method

The guarded hotplate [8] is used to measure thermal transmittance which is the reciprocal of the thermal resistance. The apparatus consists of a heated test plate surrounded by a guard ring and with a bottom plate underneath as shown in Fig. 8.5. All three plates consist of heating elements sand-



8.5 The guarded hotplate.

wiched between aluminium sheets. All the plates are maintained at the same constant temperature in the range of human skin temperature (33–36 °C). The guard ring and bottom plate, which are maintained at the same temperature as the test plate, ensure that no heat is lost apart from that which passes upwards through the fabric under test. The whole apparatus is covered by a hood to give still air conditions around the specimen. The whole of the surroundings of the apparatus is maintained at fixed conditions between 4.5 and 21.1 °C and 20 and 80% RH, the exact conditions being specified as part of the test.

With the test fabric in place the apparatus is allowed to reach equilibrium before any readings are taken. This may take some time with thick specimens. The amount of heat passing through the sample in watts per square metre is measured from the power consumption of the test plate heater. The temperature of the test plate and the air 500 mm above the test plate are measured.

The measured thermal transmittance consists of the thermal transmittance of the fabric plus the thermal transmittance of the air layer above the fabric which is not negligible. Therefore the test is repeated without any fabric sample present to give the bare plate transmittance. The transmittance of the air layer above the plate is assumed to be the same as that of the air layer above the sample.

Combined transmittance of specimen and air U_1:

$$U_1 = \frac{P}{A \times (T_p - T_a)} \text{W/m}^2\,\text{K}$$

where: P = power loss from test plate (W),
A = area of test plate (m^2),
T_p = test plate temperature (°C),
T_a = air temperature (°C).

The bare plate transmittance U_{bp} is similarly calculated and then the intrinsic transmittance of the fabric alone, U_2, is calculated from the following equation:

$$\frac{1}{U_2} = \frac{1}{U_1} - \frac{1}{U_{bp}}$$

8.2.5 Measurement of water vapour permeability

The water vapour permeability of fabrics is an important property for those used in clothing systems intended to be worn during vigorous activity. The human body cools itself by sweat production and evaporation during periods of high activity. The clothing must be able to remove this moisture in order to maintain comfort and reduce the degradation of thermal insulation caused by moisture build-up. This is an important factor in cold environments.

The main materials of interest are those fabrics that incorporate a polymer layer that makes the fabric waterproof but which still allows some water vapour to pass through. There are two main types of these materials: those that contain pores through which the moisture vapour can pass and those containing a continuous layer of hydrophilic polymer. The mechanism of water vapour transmission through the second type is quite different from that of the first type. In particular the rate of diffusion through the hydrophilic polymer layer is dependent on the concentration of water vapour in the layer. The higher the concentration, the higher the rate of transfer. In the materials where transmission is via pores the rate is independent of water vapour concentration. This has a bearing on the results obtained from the different methods of testing water vapour permeability from the two types of material which can rank them differently depending on the test method used.

Cup method

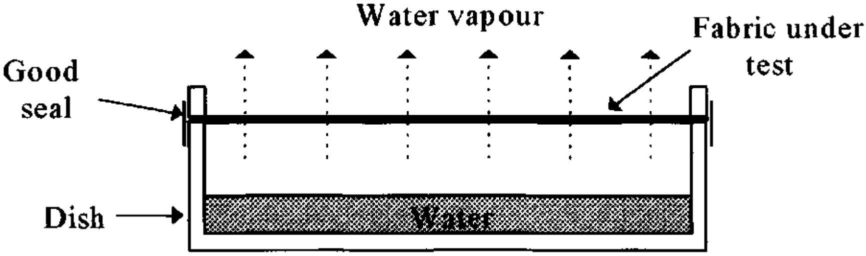
In the British Standard version of this method [9] the specimen under test is sealed over the open mouth of a dish containing water and placed in the standard testing atmosphere. After a period of time to establish equilibrium, successive weighings of the dish are made and the rate of water vapour transfer through the specimen is calculated.

The water vapour permeability index is calculated by expressing the water vapour permeability (WVP) of the fabric as a percentage of the WVP of a reference fabric which is tested alongside the test specimen.

Each dish is filled with sufficient distilled water to give a 10 mm air gap between the water surface and the fabric. A wire sample support is placed on each dish to keep the fabric level. Contact adhesive is applied to the rim of the dish and the specimen, which is 96 mm in diameter, is carefully placed on top with its outside surface uppermost. The cover ring is then placed over the dish and the gap between cover ring and dish sealed with PVC tape as shown in Fig. 8.6.

A dish which is covered with the reference fabric is also set up in the same way. All the dishes are then placed in the standard atmosphere and allowed to stand for at least 1 h to establish equilibrium.

Each dish is then weighed to the nearest 0.001 g and the time noted. After a suitable time for example overnight the dishes are reweighed and the time noted again.



8.6 The water vapour permeability test.

Calculate:

$$\mathrm{WVP} = \frac{24M}{At}\,\mathrm{g/m^2/day}$$

where: M = loss in mass (g),
t = time between weighings (h),
A = internal area of dish (m^2).

$$A = \frac{\pi d^2 \times 10^{-6}}{4}$$

where d = internal diameter of dish (mm).

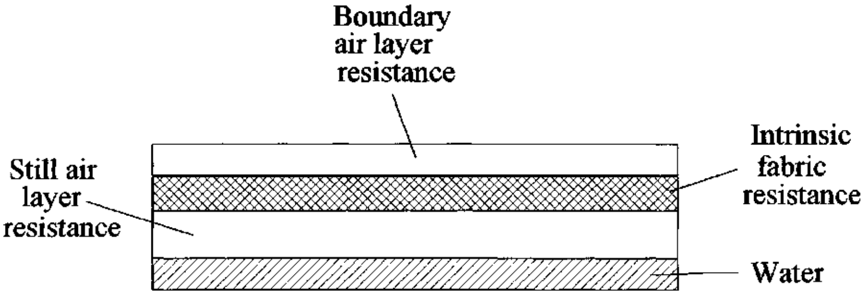
$$\text{Water vapour permeability index} = \frac{(\mathrm{WVP})_f \times 100}{(\mathrm{WVP})_r}$$

where WVP_f is the water vapour permeability of the test fabric and WVP_r is the water vapour permeability of the reference fabric.

The ASTM method E 96–80 [10] procedure B is similar to the above method although the air gap above the water surface is 19 mm (0.75 in) and an air velocity of 2.8 m/s (550 ft/min) is used over the surface of the fabric.

The airgaps above the specimen are important with these tests as the air itself has a high resistance to water vapour permeability [11]. Figure 8.7 shows that the total resistance to water vapour permeability of the experimental set-up depends on three factors.

The experiment is sometimes carried out with the cup inverted so that the water is in contact with the inner surface of the fabric [11]. This form of the test tends to give more favourable results for hydrophilic films.



8.7 The various resistances to water vapour permeability.

Sweating guarded hotplate method

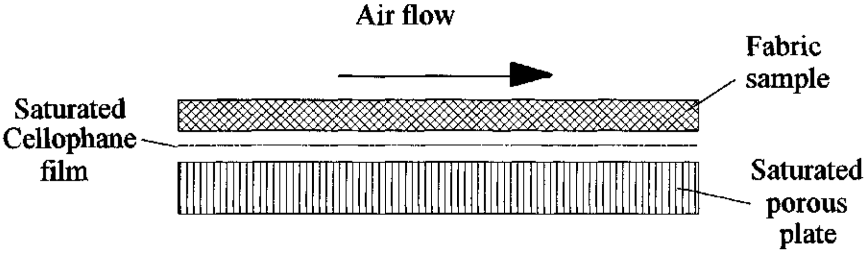
An alternative method to the cup method is to use a plate that is heated to skin temperature and supplied with water in order to simulate sweating. This is much closer to actual conditions of use than the cup method but it requires a more sophisticated experimental procedure. A number of methods have been described that differ in the way of supplying the water to the fabric and in the way of measuring the water vapour passing through it.

The sweating guarded hotplate [11] is similar to the guarded hotplate which is used to measure thermal resistance. In the normal test the power required to maintain the plate at a given temperature is related to the dry thermal resistance of the material. If the plate is saturated with water the power required is then related to the rate at which water evaporates from the surface of the plate and diffuses through the material in addition to the dry thermal resistance.

In order to measure the water vapour permeability of a material, therefore, it is first necessary to measure the dry thermal transmittance U_1 as described in section 8.2.2 on measuring thermal conductivity. The measurement is then repeated with the plate supplied with moisture. This is achieved by using a saturated porous plate covered with a Cellophane film, as shown in Fig. 8.8, which allows moisture to pass through but not in sufficient quantity to wick into the fabric. A moisture vapour permeability index i_m is calculated from the following formula:

$$i_m = \frac{\left[\dfrac{PR_{tot}}{A}\right] - (T_p - T_a)}{S(p_s - \phi p_a)}$$

where: $R_{tot} = 1/U_1$ = resistance of the fabric plus boundary air layer (m^2K/W),
A = surface area (m^2),
T_p = temperature of the saturated plate surface,



8.8 The sweating hotplate.

T_a = temperature of the ambient air,
P = power required to maintain a constant saturated plate surface temperature (W),
S = Lewis relation between evaporative mass transfer coefficient and convective heat transfer coefficient (1.65×10^{-2} K/Pa),
p_s = saturated water vapour pressure at the plate surface (Pa),
p_a = saturated water vapour pressure of the ambient air (Pa),
ϕ = relative humidity of the ambient air.

The i_m value is a relative measure which should vary between 0 for completely impermeable materials and 1 for completely permeable materials.

The moisture permeability index i_m can be combined with the dry thermal resistance R_{tot} to give i_m/R_{tot} which is a measure of both evaporative heat flow and other forms of heat flow. The higher the value for i_m/R_{tot}, the better the material is at dissipating heat by all mechanisms.

The moisture vapour transmission rate (MVTR) for the sweating guarded hotplate is:

$$\mathrm{MVTR}_{\mathrm{plate}} = 1.04 \times 10^3\left(\frac{i_m}{R_{tot}}\right)\mathrm{g/m^2/24\,h}$$

8.3 Moisture transport

In order to keep the wearer dry and hence comfortable, clothing that is worn during vigorous activity, such as sports clothing, has to be able to deal with the perspiration produced by such activity. There are two main properties of clothing, that affect the handling of moisture. Firstly there is the ease with which clothing allows the perspiration to be evaporated from the skin surface during the activity. Secondly after the activity has ceased, there is a need for the moisture that is contained in the clothing layer next to the skin to dry out quickly. This ensures that the wearer does not lose heat unnecessarily through having a wet skin. Some workers [12] also consider that the extent to which the wet fabric clings to the skin is also important to the comfort of a garment.

Moisture is transmitted through fabrics in two ways:

1 By diffusion of water vapour through the fabric. This appears to be independent of fibre type but is governed by the fabric structure. The measurement of air flow through the fabric provides a good guide to its ability to pass water vapour in large quantities.
2 By the wicking of liquid water away from the skin using the mechanism of capillary transport. The ability of a fabric to do this is dependent on the surface properties of the constituent fibres and their total surface

area. The size and number of the capillary paths through the fabric are also very important but these are governed by factors such as the fibre size, the yarn structure and the fabric structure. The capillary network of the fabric is dependent on the direction under consideration so that the wicking properties through the thickness of the fabric may be different from those in the plane of the fabric. Also the rate of wicking may be different along the warp (wale) direction than along the weft (course) direction.

8.3.1 Wetting

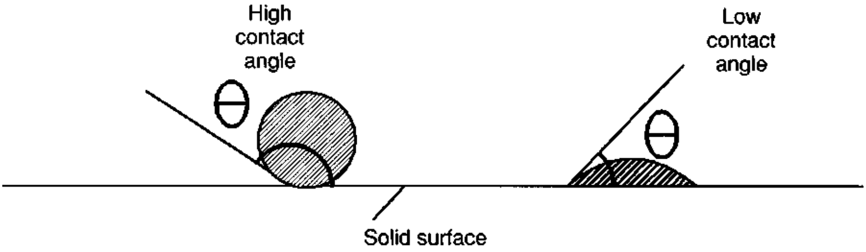
For wicking to take place the fibre has first to be wet by the liquid. In fact it is the balance of forces involved in wetting the fibre surface that drives the wicking process. When a fibre is wetted by a liquid the existing fibre–air interface is displaced by a new fibre–liquid interface. The forces involved in the equilibrium that exists when a liquid is in contact with a solid and a vapour at the same time are given by the following equation:

$$\gamma_{SV} - \gamma_{SL} = \gamma_{LV} \cos\theta$$

where γ represents the interfacial tensions that exist between the various combinations of solid; liquid and vapour; the subscripts S, L and V standing for solid, liquid and vapour,

θ = equilibrium contact angle,
γ_{LV} = the surface tension of the liquid.

The contact angle is defined as the angle between the solid surface and the tangent to the water surface as it approaches the solid; the angle is shown as θ in Fig. 8.9. The angle is determined by the three interfacial tensions: if γ_{SV} is larger than γ_{SL} then $\cos\theta$ is positive and the contact angle must be between 0° and 90°. If γ_{SV} is smaller than γ_{SL} then the contact angle must be between 90° and 180°. A high contact angle for water with the surface means that water will run off it, a low contact angle means that



8.9 Contact angle.

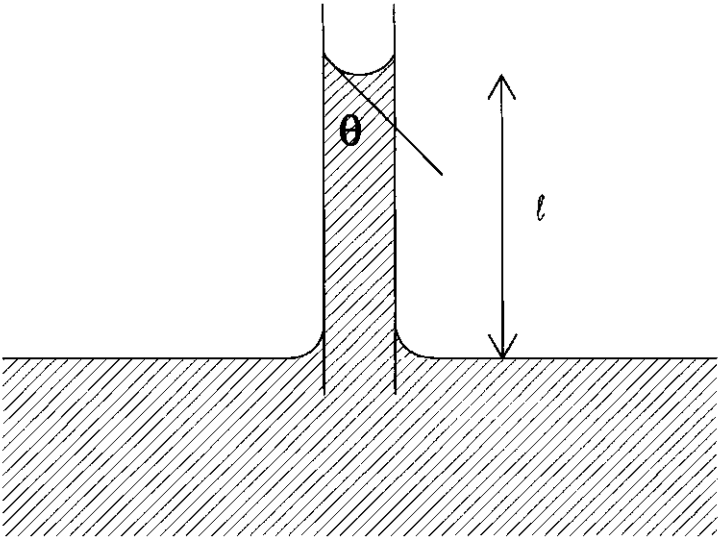
water will wet the material. Water repellent materials exhibit a high contact angle. A contact angle of less than 90° also means that water will wick into the material by capillary action. A contact angle of 90° or more means that water will not rise by capillary action. The measured (apparent) contact angle shows hysteresis in that the contact angle for a liquid that is advancing is usually higher than that for a liquid that is receding. The advancing contact angle is usually used in wicking calculations.

8.3.2 Wicking

In the absence of external forces the transport of liquids into fibrous assemblies is driven by capillary forces that arise from the wetting of the fibre surfaces described above. If the liquid does not wet the fibres it will not wick into the fibrous assembly. In the case of contact angles above 90°, liquid in a capillary is depressed below the surface instead of rising above it. In order for the wicking process to take place spontaneously, the balance of energy has to be such that energy is gained as the liquid advances into the material, therefore γ_{SV} must be greater than γ_{SL}:

$$\text{Work of penetration, } W_p = \gamma_{SV} - \gamma_{SL} = \gamma_{LV}\cos\theta$$

The wicking rate is dependent on the capillary dimensions of the fibrous assembly and the viscosity of the liquid. For a simple capillary of radius r the rate of progress of the liquid front shown diagrammatically in Fig. 8.10 is given by:



8.10 Capillary rise.

$$\frac{\mathrm{d}l}{\mathrm{d}t} = \frac{r\gamma_{\mathrm{LV}}\cos\theta_{\mathrm{A}}}{4\eta l}$$

where θ_{A} = advancing contact angle,
η = viscosity of liquid,
l = length of liquid front.

The wetting of fibres is purely dependent on their surface properties, in particular in the case of wetting with water, whether the surface is hydrophobic or hydrophilic. Therefore the wetting and wicking properties of fibres can be modified by surface finishes and experimental studies can also be affected by the remains of processing oils and finishes. Wetting is also affected by the presence of surfactants in the liquid which alter its interfacial tensions.

When wicking takes place in a material whose fibres can absorb liquid the fibres may swell as the liquid is taken up, so reducing the capillary spaces between fibres, potentially altering the rate of wicking.

8.3.3 Longitudinal wicking

The distance l travelled along a capillary by a liquid in time t is given by:

$$l = \left(\frac{rt\gamma_{\mathrm{LV}}\cos\theta_{\mathrm{A}}}{2\eta}\right)^{0.5}$$

If the material is vertical the height to which the liquid wicks is limited by gravitational forces and ceases when the capillary forces are balanced by the weight of liquid:

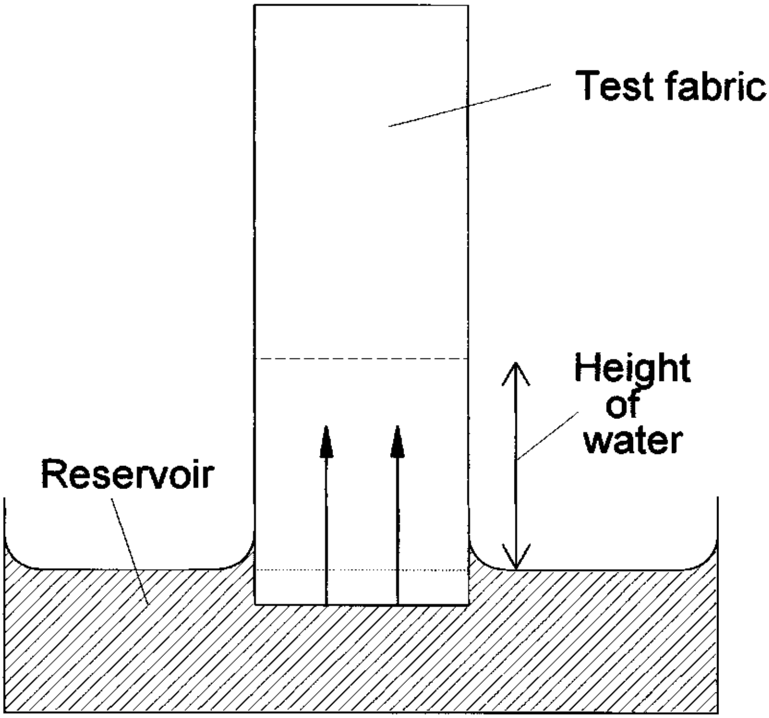
$$\text{Equilibrium height } l = \frac{2\gamma_{\mathrm{LV}}\cos\theta_{\mathrm{A}}}{rg\rho}$$

where ρ = liquid density,
g = gravitational acceleration.

8.3.4 Wicking test

In this test [13] a strip of fabric is suspended vertically with its lower edge in a reservoir of distilled water as shown in Fig. 8.11. The rate of rise of the leading edge of the water is then monitored. To detect the position of the water line a dye can be added to the water or, in the case of dark coloured fabrics, the conductivity of the water may be used to complete an electrical circuit. The measured height of rise in a given time is taken as a direct indication of the wickability of the test fabric.

The simple form of the test does not take into account the mass of the water that is taken up. This will depend on the height the water has risen



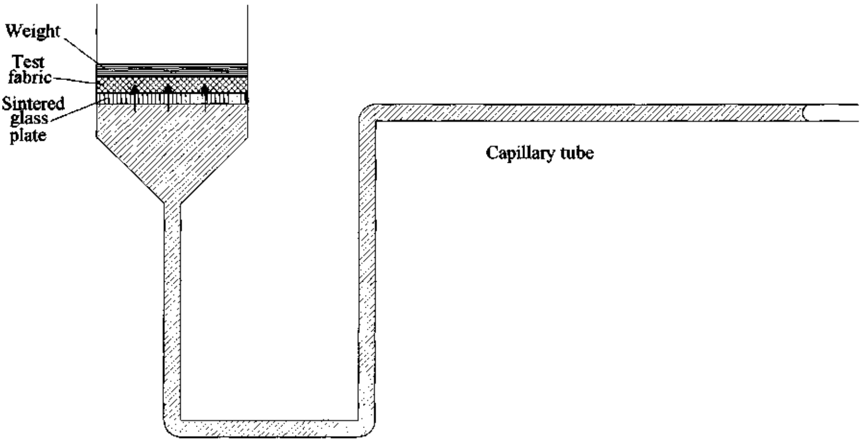
8.11 Wicking test.

to, the thickness of the fabric and the water-holding power of the fabric structure. One way of allowing for this is to weigh the fabric at the end of the test and hence obtain the mass of the water taken up by the fabric. The mass can then be expressed as a percentage of the mass of the length of dry fabric which is equivalent to the measured height of water rise.

8.3.5 Transverse wicking

Transverse wicking is the transmission of water through the thickness of a fabric, that is, perpendicular to the plane of the fabric. It is perhaps of more importance than longitudinal wicking because the mechanism of removal of liquid perspiration from the skin involves its movement through the fabric thickness. Transverse wicking is more difficult to measure than longitudinal wicking as the distances involved are very small and hence the time taken to traverse the thickness of the fabric is short.

One test is the plate test which consists of a horizontal sintered glass plate kept moist by a water supply whose height can be adjusted so as to keep the water level precisely at the upper surface of the plate. A fabric placed



8.12 The plate test.

on top of this glass plate as shown in Fig. 8.12 can then draw water from the glass plate at a rate which depends on its wicking power. It is important that the water level is adjusted to touch the underside of the fabric but not to flood it. The rate of uptake of water is measured by timing the movement of the meniscus along the long horizontal capillary tube. The equipment is arranged so that the head of water supplying the glass plate does not change during the experiment. Given the diameter of the capillary tube, the mass of water taken up by the fabric in a given time can be calculated. A problem encountered with this method is that a load has to be placed on top of the fabric to ensure contact with the sintered glass plate. Unfortunately when a fabric is compressed its structural elements are moved closer to one another which can potentially change its absorption characteristics. A contact pressure of 0.098 kPa has been used by Harnett and Mehta [13].

8.4 Sensorial comfort

Sensorial comfort is concerned with how a fabric or garment feels when it is worn next to the skin. It has been found that when subjects wore various fabrics next to the skin they could not detect differences in fabric structure, drape or fabric finish but could detect differences in fabric hairiness [14]. Some of the separate factors contributing to sensorial comfort which have been identified [14] are:

1 **Tickle** caused by fabric hairiness.
2 **Prickle** caused by coarse and therefore stiff fibres protruding from fabric surface. Matsudaira *et al.* [15] found that the stiffness of protruding fibres

is the dominant factor in causing prickle sensations. This is affected by both fibre diameter and to a lesser extent fibre length. For a fibre of a given diameter the end of a long fibre is more easily deflected a fixed amount than the end of a short fibre so it appears less prickly. For a fibre of a given length a larger diameter is much stiffer depending on the fourth power of the diameter and hence is more likely to prick.

3 **Wet cling** which is associated with sweating and is caused by damp and sticky sweat residues on skin. A factor influencing cling is the actual area of fabric in contact with skin which in turn is influenced by fabric structure.

4 **Warmth to touch**: when a garment is first picked up or put on it is usually at a lower temperature than the skin and thus there will be a loss of heat from the body to the garment until the temperatures of the surfaces in contact equalise. The faster this heat transfer occurs, the greater is the cold feel of the fabric. The differences in cold feel between fabrics is mainly determined by their surface structure rather than by the fibre type.

For example a cotton sheet feels cool whereas a flannelette sheet, which is produced by raising the surface of a cotton fabric, feels comparatively warm. The raised surface gives a lower contact area and hence a slower rate of change of temperature. Ironing a cotton sheet has the effect of increasing the cold feel by compacting the surface structure.

8.5 Water absorption

Some textile end uses such as towels, tea towels, cleaning cloths, nappies (diapers) and incontinence pads require the material to absorb water. There are two facets to the absorption of water: one is the total amount that can be absorbed regardless of time and the other is the speed of uptake of the water. These two properties are not necessarily related as fabrics of similar structures but with different rates of uptake may ultimately hold similar amounts of water if enough time is allowed for them to reach equilibrium. Alternatively soaking the fabrics in water so that they take up their maximum load may mask any differences in rate of uptake.

8.5.1 Static immersion

The static immersion test [16] is a method for measuring the total amount of water that a fabric will absorb. Sufficient time is allowed in the test for the fabric to reach its equilibrium absorption.

In the test weighed samples of the fabric are immersed in water for a given length of time, taken out and the excess water removed by shaking.

They are then weighed again and the weight of water absorbed is calculated as a percentage of the dry weight of the fabric.

Four specimens each 80mm × 80mm are cut at 45° to the warp direction. The first step is to condition the samples and weigh them. They are then immersed in distilled water at a temperature of 20 ± 1 °C to a depth of 10cm. A wire sinker is used to hold the specimens at the required depth. The samples are left in this position for 20min. After the specimens are taken from the water the surface water is removed immediately from them by shaking them ten times in a mechanical shaker. They are then transferred directly to preweighed airtight containers and then reweighed:

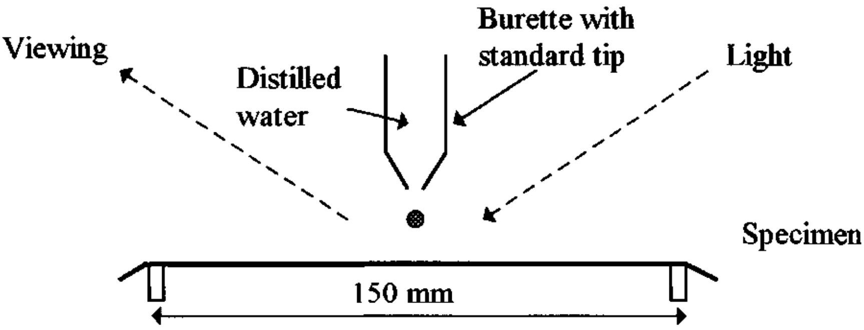
$$\text{Absorption} = \frac{\text{mass of water absorbed}}{\text{original mass}} \times 100\%$$

The mean percentage absorption is calculated.

8.5.2 Wettability of textile fabrics

This is a test [17] for fabrics containing hydrophilic fibres. **Wettability** is defined as the time in seconds for a drop of water or 50% sugar solution to sink into the fabric. Fabrics that give times exceeding 200s are considered unwettable.

In the test the specimen is clamped onto an embroidery frame 150mm in diameter so that it is held taut and away from any surface. A burette with a standard tip size (specified in the standard) is clamped 6mm above the horizontal surface of the sample as shown in Fig. 8.13. The fabric is illuminated at an angle of 45° and is viewed at 45° from the opposite direction so that any water on the surface reflects the light to the viewer. At the start of a test a drop of liquid is allowed to fall from the burette and the timer started. When the diffuse reflection from the liquid vanishes and the liquid



8.13 Wettability.

is no longer visible, the timing is stopped. If the time recorded is less than 2 s, the burette is changed to one containing 50% sugar solution.

Five areas on each specimen are tested, three samples in all, to give a total of 15 measurements.

8.5.3 Sinking time

This is a simple test for highly absorbent materials in which a 25 mm × 25 mm piece of fabric or a 50 mm length of yarn taken from the fabric is dropped onto the surface of distilled water and the length of time it takes to sink is measured. If the sample does not sink within 1 min it is considered as having floated.

8.6 Water repellency

A number of fabric end uses, particularly those where fabric is used out of doors, require the material to be more or less impermeable to rain. These include outerwear such as anoraks, cagoules and raincoats and also industrial fabrics such as tents and tarpaulins. Broadly two main categories of resistance to water penetration are recognised, based mainly on the treatment that has been used on the fabric:

1 *Waterproof.* A waterproof fabric is one that is coated or impregnated to form a continuous barrier to the passage of water using for example rubber, polyurethane, PVC or wax coatings. In such fabrics the gaps between the yarns are filled in by the coating which gives rise to two main drawbacks. Firstly the fabric will no longer allow water vapour to pass through it, making it uncomfortable to wear when sweating. Secondly the binding together of the yarns by the coating reduces the ability of the fabric to shear and thus to mould to the body contours.

2 *Showerproof.* Showerproof fabrics are ones that have been treated in a such a way as to delay the absorption and penetration of water. Showerproofing of fabrics is often achieved by coating them with a thin film of a hydrophobic compound such as a silicone. The film covers the surface of the individual fibres making them water repellent. When a fabric has been treated in this way a drop of water on the surface does not spread. The process leaves the gaps in the fabric weave untouched so keeping it quite permeable to air and water vapour. The process also leaves the handle of the fabric largely unaffected unlike fabrics with a waterproof coating. However, water can penetrate the fabric if it strikes it with sufficient force as in heavy rain; alternatively, the flexing of the fabric during wear can cause the gaps in the weave to open and close so allowing the water to penetrate.

A showerproof fabric can also be produced by a correct choice of yarn and fabric construction to give a very tight weave which physically keeps the water out; an example of this is the gabardine construction used in coats.

8.6.1 Spray rating

The spray rating test [18] is one used to measure the resistance of a fabric to surface wetting but not to penetration of water. It is therefore a test which is particularly used on showerproof finishes. It is often the case that waterproof coatings are applied to the inner surface of a material and a water repellent finish is then applied to the outer fabric surface to stop it absorbing water as it would otherwise become waterlogged. In such cases the test is used on the outer layer of fabrics which are otherwise considered waterproof.

In the test three specimens are tested, each one 180 mm square. Each specimen in turn is held taut over a 150 mm diameter embroidery hoop which is mounted at 45° to the horizontal. A funnel which is fitted with a standard nozzle containing 19 holes of a specified diameter is held 150 mm above the fabric surface as shown in Fig. 8.14. Into the funnel is poured 250 ml of distilled water at 20 °C to give a continuous shower onto the fabric. After the water spray has finished the hoop and specimen are removed and tapped twice smartly against a solid object on opposite points of the frame, the fabric being kept horizontal. This removes any large drops of water. The fabric is then assigned a spray rating either using the written grading shown in Table 8.3 or from photographic standards (American Association of Textile Chemists and Colorists scale).

8.6.2 Bundesmann water repellency test

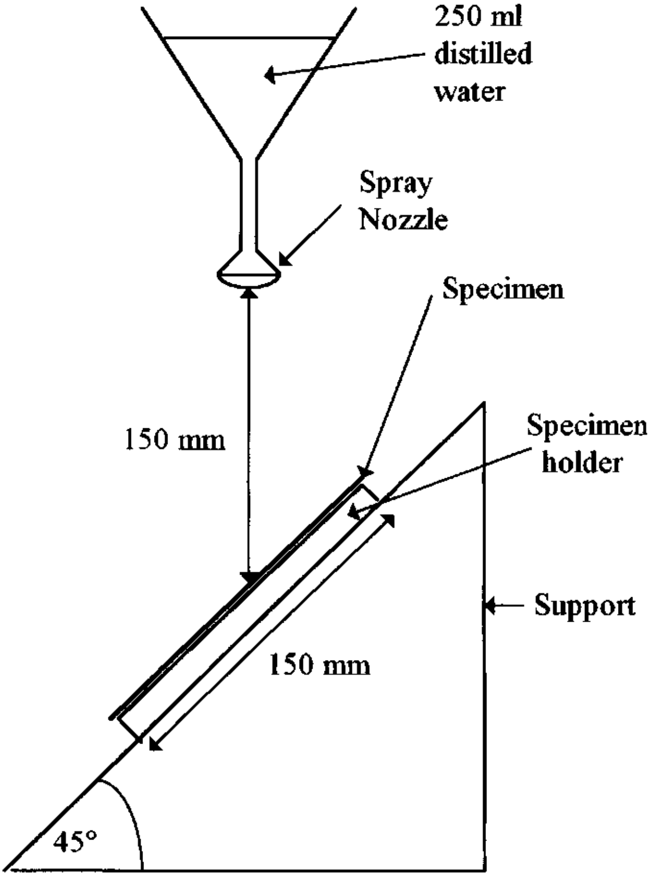
The Bundesmann test aims to produce the effect of a rainstorm on a fabric in the laboratory. In the test shown in Fig. 8.15 the fabric is subjected to a shower of water from a head fitted with a large number of standard nozzles. During the shower the back of the fabric is rubbed by a special mechanism which is intended to simulate the flexing effect which takes place when the fabric is worn.

The method is not currently a British standard because considerable variation has been found between different machines, although when tests are carried out on the same machine the variability can be reduced to acceptable levels.

In the test four specimens are mounted over cups in which a spring loaded wiper rubs the back of the cloth while the whole cup assembly slowly rotates. They are subjected for 10 min to a heavy shower whose rate has been adjusted so as to deliver 65 ml of water per minute to each cup. The

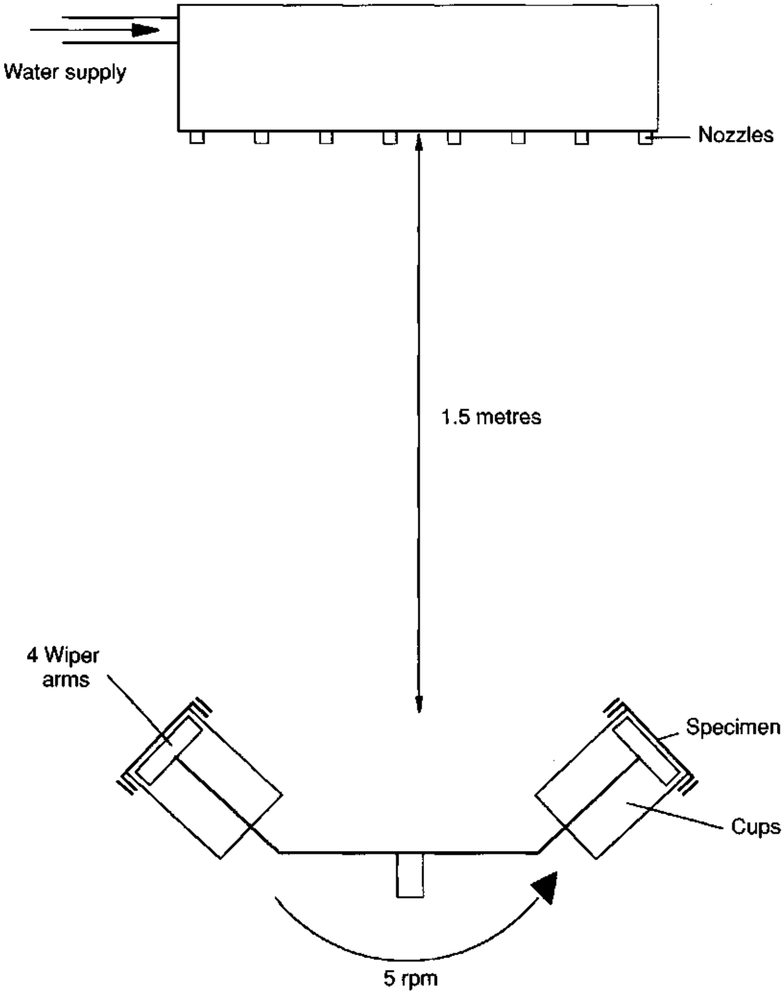
Table 8.3 Spray ratings

Grade	Description
1	Complete wetting of the whole of the sprayed surface
2	Wetting of more than half the sprayed surface
3	Wetting of the sprayed surface only at small discrete areas
4	No wetting of but adherence of small drops to the sprayed surface
5	No wetting of and no adherence of small drops to the sprayed surface



8.14 Spray rating.

water flow is maintained at 20 °C and between pH 6 and 8. Because of the large amount of water consumed the equipment has to be connected to the mains water supply which leads to difficulties in keeping the water temperature constant. The shower is calculated to have a kinetic energy 5.8



8.15 The Bundesmann shower test.

times that of a cloudburst, 90 times that for heavy rain, 480 times that for moderate rain and 21,000 times that for light rain.

Two fabric parameters are determined from the test:

1. Penetration of water through the fabric: the water collected in the cups is measured to the nearest ml.
2. Absorption of water by the fabric: in order to do this the specimen is weighed before the test and then after the shower. To remove excess water the fabric is shaken ten times using a mechanical shaker and then weighed in an airtight container:

$$\text{Absorption} = \frac{\text{mass of water absorbed}}{\text{original mass}} \times 100\%$$

In each case the mean of four values is calculated.

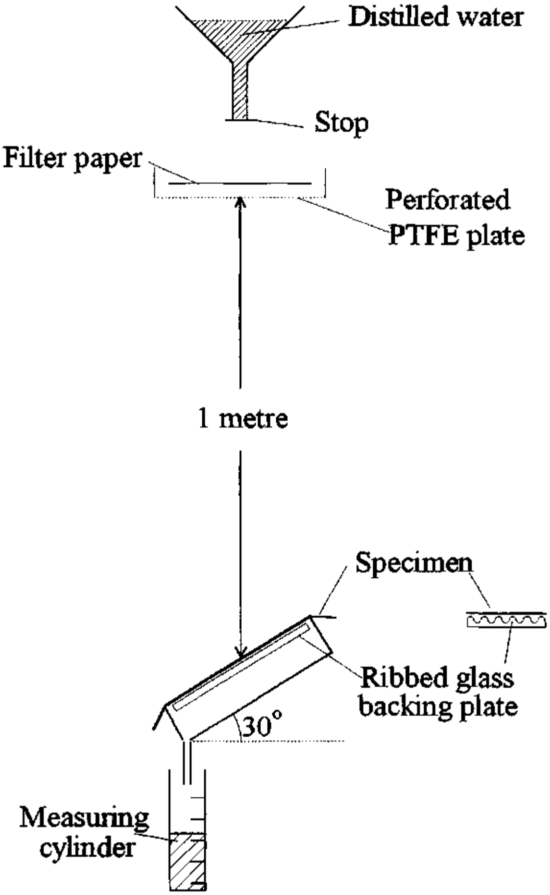
8.6.3 WIRA shower test

The WIRA shower tester [19] also aims to produce the effect of a rainstorm on a fabric in the laboratory. Like the Bundesmann test it measures water absorption and penetration but it is claimed to have certain advantages over the Bundesmann test. These are:

1. It is not dependent on the flow of water through fine holes in plates or capillary tubes.
2. It uses distilled water and the essential parts are non-metallic so avoiding the corrosion and deposition problems which are associated with tap water.
3. Provision is made for detaching and cleaning the backing material. Penetration is often critically dependent on the surface properties of the backing material.
4. The apparatus is free-standing and is not dependent on elaborate plumbing and electrical fittings.

The method, shown diagrammatically in Fig. 8.16, is based on a patented method of drop propagation which produces a sustained and uniform shower of well-separated drops of water. The method consists of a shallow container having at the base a hydrophobic PTFE (poly (tetrafluoroethene)) plate with large holes covered with a filter paper. Water is run into the container at a fixed rate through a capillary tube from a large funnel.

In the test four samples each one 125 mm × 250 mm are tested two at a time. Firstly the ribbed glass backing plates are cleaned thoroughly by the prescribed method and dried. The filter papers, boxes and measuring cylinders have to be wetted out before the test starts. The specimens are conditioned and then weighed and mounted face side up stretched across the ribbed glass plate. The valves are opened simultaneously while the stop-watch is started. During the test the time for the first 10 ml of water to collect in the measuring cylinders is noted. The shower should stop after about 7.5 min. After 8.5 min the interceptor is pulled forward and the specimens removed. These are then given ten drops on the mechanical shaker and weighed in a previously weighed airtight container. The water penetration is measured to the nearest 0.5 ml if under 10 ml or to the nearest 1 ml if over 10 ml.



8.16 The WIRA shower test.

Calculate

$$\text{Percentage absorption} = \frac{\text{final mass} - \text{original mass}}{\text{original mass}} \times 100\%$$

Give:

1 the mean absorption %;
2 the mean water penetration in ml;
3 if appropriate mean time for first 10ml.

This test is not intended for fabrics with marked wicking properties as penetrating water can wick over the edge of the box and so not be recorded. For general rainwear it is suggested that:

- the absorption is not greater than 20%;
- the penetration is not greater than 120 ml;
- the first 10 ml of penetration takes longer than 120 s.

8.6.4 Credit rain simulation tester

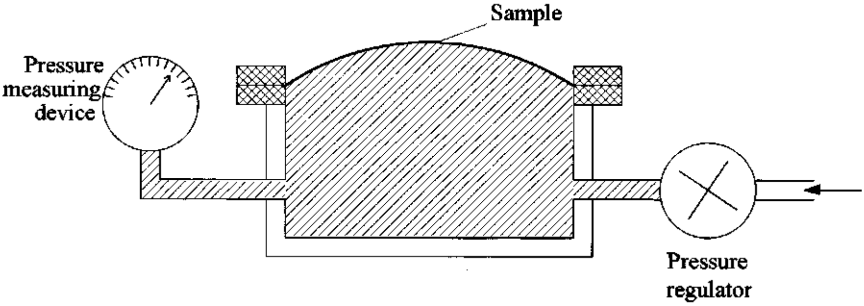
This instrument was produced to simulate natural rain in terms of drop size and distribution. The test subjects a fabric to a simulated shower and records the time taken for the water to penetrate to the back of the fabric.

The shower is produced by dropping water through needles onto a mesh cone which splits the drops to give a distribution of drop sizes similar to natural rain. The fabric is mounted over a printed circuit board which is organised so that penetration of water completes a circuit and shows the area where penetration has taken place. An electronic timer is automatically started when the first drop falls and the timing is stopped when contact is made. The time to penetration is shown and an LED (light-emitting diode) display shows where it has occurred.

8.6.5 Hydrostatic head

The hydrostatic head test [20] is primarily intended for closely woven water repellent fabrics. The hydrostatic head supported by a fabric is a measure of the opposition to the passage of water through the fabric. In the test, shown diagrammatically in Fig. 8.17, one face of the fabric is in contact with water which is subjected to a steadily increasing pressure until it penetrates the fabric. The pressure at which the water penetrates the fabric is noted. The current size of specimen used is 100 cm^2.

The circular specimens are clamped between rubber gaskets over a water-filled chamber and pressure is applied to the water forcing it up against the specimen. The pressure of the water is monitored by a water-



8.17 The hydrostatic head test.

filled manometer which measures the pressure on the specimen in cm of water. The rate of pressure increase of the water is controlled and can be either 10 cm head of water per minute or 60 cm head of water per minute. The results which are obtained at the two rates of increase are not directly comparable.

The pressure is allowed to increase until water appears at three separate places on the surface of the specimen, the pressure being taken at the appearance of the third drop. Five specimens in total are tested and the mean pressure calculated from the results.

The test normally has a maximum of 2 m head of water:

$$1\,\text{cm}\ H_2O = 98.0665\,\text{Pa}$$

A similar test is used for coated fabrics [21] but because the pressures involved are usually higher the requirement for a steady increase in pressure is omitted, otherwise the tests would take a long time. The tests are usually conducted on a pass/fail basis, the pressure being increased to the value laid down in the specification within 1 min from the start of the test.

References

1. Morris J V, 'Performance standards for active wear', *Text Ins Ind*. 1980 **18** 243–245.
2. Farnworth B, 'Mechanisms of heat flow through clothing insulation', *Text Res J*, 1983 **53** 717–725.
3. Fourt L and Hollies N R S, *Clothing Comfort and Function*, Marcel Dekker, New York, 1970.
4. Davies S and Owen P, 'Staying dry and keeping your cool', *Textile Month*, 1989 **Aug** 37.
5. Cooper C, 'Textiles as protection against extreme wintry weather', *Textiles*, 1979 **8** 72.
6. BS 5636 Method of test for the determination of the permeability of fabrics to air.
7. BS 4745 Method for the determination of thermal resistance of textiles.
8. ASTM D 1518 Thermal transmittance of textile materials.
9. BS 7209 Specification for water vapour permeable apparel fabrics.
10. ASTM E 96-80 Standard test methods for water vapor transmission of materials.
11. Gibson P W, 'Factors influencing steady-state heat and water vapour transfer measurements for clothing materials', *Text Res J*, 1993 **63** 749–764.
12. Umbach K H, 'Moisture transport and wear comfort in microfibre fabrics', *Melliand Textilber*, 1993 **74** 174–178.
13. Harnett P R and Mehta P N, 'A survey and comparison of laboratory test methods for measuring wicking', *Text Res J*, 1984 **54** 471.
14. Smith J, 'Comfort in casuals', *Text Horizons*, 1985 **5**(8) 35.
15. Matsudaira M, Watt J D and Carnaby G A, 'Measurement of the surface

prickle of fabrics Part 1: The evaluation of potential objective methods', *J Text Inst*, 1990 **81** 288–299.

16. BS 3449 Testing the resistance of fabrics to water absorption (static immersion test).
17. BS 4554 Method of test for wettability of textile fabrics.
18. BS EN 24920 Textiles. Determination of resistance to surface wetting (spray test) of fabrics.
19. BS 5066 Method of test for the resistance of fabrics to an artificial shower. Method of test for textiles, BS Handbook 11, 1974.
20. BS EN 20811 Textiles. Determination of resistance to water penetration. Hydrostatic pressure test.
21. BS 3424 Testing coated fabrics Part 26 Methods 29A, 29B, 29C and 29D. Methods for determination of resistance to water penetration and surface wetting.