11
Waterproofing and breathability of fabrics and garments

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Abstract: This chapter discusses the different ways in which breathable waterproof fabrics and garments can be constructed and produced, including the use of microporous and hydrophilic membranes and coatings. The measurement of breathability and waterproofing is covered, as well as the specifications and standards applicable to such fabrics and garments.

Key words: breathable fabrics, breathability, waterproof fabrics, waterproofing, hydrophilic membranes and coatings, microporous membranes and coatings.

11.1 Introduction

Consumers, particularly those regularly involved in outdoor activities (e.g. sport or leisure) or subjected to extreme conditions such as snow, rain, heat, wind and cold, are increasingly seeking multifunctional clothing to maintain their comfort under such conditions (see also Chapter 8). This is illustrated, for example, by the fact that the global market for waterproof breathable textiles is growing by some 8% annually. Ideally, such clothing should keep the wearer dry and comfortable under hot, cold, windy or wet (rain) conditions, even under the extremes of such conditions, for example, driving rain and/or extreme temperatures and/or physical activity. In order to effectively do so, the fabric and garment need to be:

- Breathable (water vapour permeable)
- Waterproof.

In addition, they should also have good heat insulation properties, a good handle, and preferably be lightweight, the water vapour permeability of a fabric depending on both the water vapour diffusion and thermal resistance of the fabric.[1] The main driving force for moisture from the body to the outside is the difference in partial pressure of the water vapour between the two areas.[2]

Although waterproofing and breathability are entirely different concepts, today they are commonly combined, in that the term 'breathability' is used to imply both 'waterproofing and breathability'. For the purpose of this chapter, 'breathability' is taken to mean[3] 'the ability of a textile fabric to allow water vapour (molecules smaller than $\approx 0.0004\ \mu m$ in diameter) to pass through it (i.e. from the body surface to the outside) while not allowing liquid water (molecules $\approx 100\ \mu m$ in diameter) from the outside to pass through it'. Later in this chapter, the difference between waterproof, water repellent and water resistant will be defined. In recent years, the term 'moisture management' has been used to describe the ability of a garment to transport moisture vapour and liquid water (perspiration) away from the skin through the fabric to the outside in a controlled manner, and this has increasingly involved advanced technologies, such as 'body mapping'.

During physical and other activities, and under certain conditions, the body cools itself partly through insensible perspiration, which needs to evaporate, absorbing energy (heat) in the process, thereby causing cooling. For example, during intensive training, an athlete's clothing has to transport around 1.5 to 2.5 litres of moisture per hour.[4] The human body is a very inefficient converter of stored energy into work or physical motion, most of the energy being turned into heat.[5] For the body to maintain its 'core temperature' of 37°C, the heat produced needs to be removed by conduction, radiation and convection from the skin, and also by evaporation of water released from sweat glands. The first three are adequate for low levels of activity, whereas the fourth predominates at high levels of activity.[5] To accommodate the latter, the garment must allow moisture to be easily carried away from the point where it is generated, i.e. the skin, so as not to cause the moisture to remain on the skin or to condense on the inside of the garment. This is a critical requirement to maintain acceptable temperature and comfort (see also Chapter 8), particularly under either very hot or high activity conditions, or various levels and combinations of such conditions.

Historically, different garments, or layers of garments, each designed with a specific function in mind, were worn to provide the required functionality. Thus, for example, a heavy coat would be worn over clothing to offer protection against cold, and if waterproof, also against rain. If only protection against rain is required then a waterproof coat, a raincoat, sometimes also termed a Macintosh, was generally worn over outerwear. One of the first, if not the first, such raincoat was produced in 1823[6] by Charles Macintosh, who coated a fabric with crude rubber. Such garments did not 'breathe' and did not allow perspiration and water vapour to escape, therefore often resulting in the wearer becoming wet with perspiration and highly uncomfortable. In fact, the question of breathability only surfaces when the garment is expected to provide those protective functions mentioned above, mostly protection against rain, since by their very nature most conventional garments are breathable, but not waterproof.

Ideally, a fabric layer against the skin should remove (wick) liquid perspiration as quickly as possible away from the skin, without becoming or feeling wet, since a wet fabric is very effective in removing heat from the body and feels uncomfortably clammy.[7] The challenge, therefore, is to engineer the fabric (and entire garment) in such a way that the fabric or layers of fabric, and ultimately the garment, allow air, water vapour and perspiration to pass easily from the inside to the outside of the fabric or garment, while at the same time providing a barrier to liquid water (as opposed to water vapour) from the outside. In the extreme case, this is in essence a conflicting requirement, and there generally needs to be a compromise. Another important consideration is that the handle and overall comfort properties of the fabric not be adversely affected by any multifunctional finish or property added.

This chapter will discuss ways in which these requirements can be 'engineered' into a fabric or garment and can be measured.

11.2 Definitions

It is first of all important to define some of the terms relevant to this chapter:

- *Breathability* is defined as the ability of a fabric to allow perspiration, evaporated by the body, to escape (diffuse) to the outside (termed moisture vapour transmission), thereby allowing complete comfort. Breathability can therefore be defined as the ability of clothing (and fabric) to allow the transmission or diffusion of moisture vapour, and therefore facilitate evaporative cooling.[8,9]
- *Water repellency* generally refers to the ability of a fabric to resist wetting.[10] *Water repellent* (also referred to as 'shower resistant') fabrics (e.g. light fashion rainwear) will provide some protection against intermittent rain but are not suitable to be worn in a downpour, as they will then become wet through and dampen the wearer. Water will bead and run off the surface[11] of water repellent fabrics but under sufficient pressure it will come through. The amount of pressure required to do so is a measure of *water resistance*.
- *Water (or rain) resistant* fabrics will resist wetting by water and also not allow water to penetrate or pass through the fabric under most pressures, thereby keeping the wearer dry in moderate to heavy rain.[12]
- *Waterproof* is the extreme case of water resistance, implying complete resistance to water. The fabric will not allow water – even wind driven rain – through, since water cannot penetrate the fabric surface,[6,11] and

such fabrics and garments should keep the wearer dry in prolonged moderate to heavy rain.[12]

- *Windproof* means that air cannot pass through the fabric.

Water resistant fabrics therefore provide better protection than *water repellent* fabrics against rain, snow and sleet, particularly driving rain. Nevertheless, both will eventually become saturated with water and allow water to leak through.[13] Thus, if a fabric or garment needs to keep a person completely dry under virtually all, including prolonged, conditions of rain and weather, it has to be *waterproof*. In essence, this means that a person wearing a waterproof garment will not become wet even if exposed to driving rain or snow for extended periods. For a garment to offer such protection, the fabric, seams, zips, etc. all need to be waterproof and the garment must be so designed that there are no 'openings' through which water can penetrate (see Section 11.6). Therefore, a 'waterproof breathable' garment needs to satisfy the above waterproof requirements, as well as being able to 'breathe', i.e. allow water vapour to escape so as to maintain a comfortable 'micro-climate' between the skin of the wearer and the garment. The term *weatherproof* is used to stand for both 'waterproof' and/or 'windproof' technologies.[14]

11.3 Measurement of waterproofing and breathability

As the title of this chapter implies, two distinct concepts are involved, namely waterproofing and breathability, and both need to be measured if a fabric or garment is to be categorised as waterproof and breathable. Traditionally, and also still largely today, two different types of tests are carried out: one to measure the breathability (i.e. water vapour transmission) of the fabric and the other to measure the waterproofing of the fabric. In the case of garments, it is also essential to test the waterproofing of the seams, joins, etc. of the garment. It should be noted, however, that different test methods and testing conditions[15] can produce widely different values for the water vapour resistance of waterproof fabrics, for example those coated with hydrophilic coatings,[16] where the resistance to water vapour diffusion decreases with increasing relative humidity.[16] Furthermore, the different test methods can be differently affected by changing the conditions of testing. Holmes[15] and Overington and Croskell[17] have reviewed the various test methods and standards.

Testing for breathability (Water vapour permeability or moisture vapour transport rate – MVTR) is covered under Chapter 8 and will not be dealt with here. The various methods have also been reviewed and compared in other publications,[15,17–19] including the forces that drive MVTR, namely gradients of water vapour concentration, the temperature and, in the case of forced convection, pressure gradient.[20] Overington and Croskell[17] have presented an excellent table summarising the various test methods for water vapour permeability.

11.3.1 Air permeability (wind resistance)

For certain applications and conditions, a fabric/garment is required to be windproof (i.e. resistant to wind). This is normally assessed by measuring air permeability.

The air permeability of a fabric also has some bearing on its water vapour permeability, but the two are by no means identical. Air permeability can be measured using the following test methods:

- EN ISO 9237: Textiles: Determination of the Permeability of Fabrics to Air.
- ASTM D737-96: Standard Test Method for Air Permeability of Textile Fabrics.

Çay *et al.*[21] developed an artificial neural network model to predict the air permeability and water content after vacuum drying of woven fabrics, based upon the fabric structural parameters.

11.3.2 Testing for water repellency/resistance/proofing

Water repellency and resistance (shower and rain resistance)

Water repellency is essentially taken[22] to be the ability of a fibre, yarn or fabric to resist wetting, one of the oldest tests being the 'spray test' in which water is sprayed against the taut surface of the test specimen.[22] *Water resistance* (rain test) measures the resistance to the penetration of water by impact, providing a measure of the resistance to rain penetration of a fabric.[22] A blotter underneath the fabric is weighed before and after the test to provide a measure of water penetration. The Tumble Jar Dynamic Absorption Test, for example, measures water (rain) repellency and absorption of fabrics.[22] *Water resistance* (Hydrostatic Pressure Test) measures the resistance of a fabric to the penetration of water under hydrostatic pressure.[22]

The following test methods can be used to measure water/shower/rain repellency and resistance:[12,23]

- AATCC TM42: Water Repellency, rain test.
- AATCC TM22: Water Repellency, spray test.
- EN ISO 4920: Textiles – Determination of resistance to surface wetting (spray test) of fabrics.
- AATCC TM35: Water Repellency: Impact penetration test.

- EN ISO 9865: Textiles – Determination of Water Repellency of Fabrics by the Bundesmann Rain-shower Test (5 mm diameter water drops fall from a height of 150 cm onto the fabric, and water penetrations is measured after 60 mins).
- AATCC Test Method 42-2000: Water Resistance: Impact Penetration Test, where 500 ml of water is sprayed from a height of 2 feet (61 cm) onto the surface of the test specimen, at 45° angle to the flow, backed by a pre-weighed blotter.[23] The increase in the weight of the blotter provides a measure of water penetration through the fabric. Water repellency is measured in a similar manner, except that the fabric is clamped in a hoop and the water is sprayed from a distance of 6 inches (15.2 cm).
- BS 5066: Method of Test for the Resistance of Fabrics to an Artificial Shower (WIRA SHOWER).
- DIN 53886.
- J.I.S. Z – 0208.

Waterproofing and rainproofing[22]

The following test methods are used to test the water/rainproofing of fabrics:

- AATCC 127: Water Repellency: Hydrostatic pressure test.
- ISO 811: Textile fabrics – Determination of resistance to water penetration, hydrostatic pressure test.

General

EMPA has developed new test methods to assess the water and rain resistance of materials and garments,[24] concluding that water resistance should be measured dynamically to obtain a more realistic assessment,[24] the hydrostatic head test not always being a true reflection of what occurs in practice. Benltoufa *et al.*[25] have developed an experimental device for measuring the water permeability of fabrics, while Butz and Elzer[26] have described a test method that differentiates between nano-structured and conventional water repellent textiles.

11.3.3 Specifications

The Hohenstein Institute has developed a 'wear comfort quality label' grading system,[4] from 1 (excellent) to 6 (inadequate) for waterproof breathable garments. According to European standards,[27] for a fabric to be classified waterproof it must withstand a hydrostatic head pressure of 1500 mm, with most such outerwear fabrics exceeding 10 000 mm.

It has been stated that fabric for active sportswear should support at least a 450 mm water column,[28] and if a fabric can withstand a hydrostatic head (pressure) of 100 g/cm^2 (1.41 psi) or higher, then it will be impermeable to rain.[29] Most specifications require a hydrostatic head (pressure) of 2000 mm; above 1500 mm the fabric is impenetrable to raindrops. According to ISO 811, materials with a hydrostatic head of 1500 mm and more may be designated as rainproof.[24]

11.4 Engineering fabric and garment breathability

11.4.1 Introduction

As mentioned and defined previously, breathability encompasses two different requirements, namely, breathability and waterproofing. Therefore, when engineering breathability into a fabric or garment, both these characteristics need to be considered and designed into the fabric or garment. This generally involves some compromise between the two extreme cases of total waterproofing and complete breathability. Frequently, the precise balance of properties required for breathable fabrics depends upon the end-use of the fabric and the specific level and balance appropriate to that particular end-use. Moisture diffuses readily through air, whereas fibres present a barrier to such diffusion. Therefore, the resistance of a traditional textile fabric/garment to moisture vapour diffusion will *largely* depend upon the fabric construction, notably density (compactness or tightness) and thickness, and to a lesser extent on the fibre properties, notably hydrophilic and hygroscopic properties, such as moisture absorption. Nevertheless, fabrics mostly have a high ratio of air to fibre volume and only in extreme cases do differences in the fabric construction (i.e. density and thickness) *per se* play a major role in changing moisture vapour diffusion for conventional or traditional fabrics.

The subject of engineering breathable fabrics has been reviewed.[15,30,31] In broad terms, the main ways of achieving waterproof breathable fabrics, in practice, are (i) using tightly woven constructions (usually involving cotton or micro-fibres), (ii) using micro-porous or hydrophilic membranes (a thin polymer film laminated to the fabric) and (iii) using coatings (polymer, usually polyurethane, applied directly to the fabric).

There are various types of breathable fabrics and ways in which breathability can be engineered into a fabric, including the following categories:[30]

- Closely woven fabrics
- Micro-porous membranes and coatings
- Hydrophilic membranes and coatings

- Combination of both micro-porous and hydrophilic membranes and coatings
- Smart breathable fabrics
- Fabrics based on bio-mimetics.

11.4.2 Effect of fibre and yarn properties

Except in the case of very closely or tightly woven fabrics, fibre and yarn properties generally play only a secondary role in achieving the required standards for waterproof breathable fabrics. In view of this, only brief reference will be made to the effects of the fibre and yarn properties *per se* on breathability. Essentially, the most important fibre properties within the context of closely woven fabrics are fibre fineness (the finer the fibre the better) and the ability of the fibre to swell with increasing moisture content (the greater the swelling the better), with intrinsic fibre moisture absorption and water repellency characteristics of lesser importance. Similar considerations apply to the yarn, with yarn twist factor, compactness and smoothness having some effect.

11.4.3 Effect of fabric and laminate structure and properties

Tightly woven fabrics

Breathable waterproof fabrics can be achieved by appropriate selection of the fabric structure and tightness (e.g. dense Oxford structure), together with the appropriate fibre (e.g. cotton or micro-fibres/filaments), yarn composition and properties, and water repellent fabric finish (e.g. silicone or fluoro-chemical). The foremost requirement for tightly woven breathable fabrics is that the pore structure is such that water droplets cannot permeate into and through the fabric from the outside. The first showerproof (rather than waterproof) breathable fabric, called Ventile, which was developed by the Shirley Institute (UK) in the 1940s, was made from low twist mercerised (generally combed and plied) yarns containing fine Egyptian cotton, and woven in a very dense Oxford fabric construction. This construction was ideal for this purpose, providing good fabric abrasion resistance, packing density and flexibility. Although the fabric is not showerproof to start with, when it comes into contact with water, the cotton fibres swell, thereby reducing the size of the inter-yarn pores (from about 10 μm to 3–4 μm) and hence the ability of water to penetrate the fabric. A water repellent finish is essential, but must not restrict the ability of the cotton to absorb moisture and then swell.

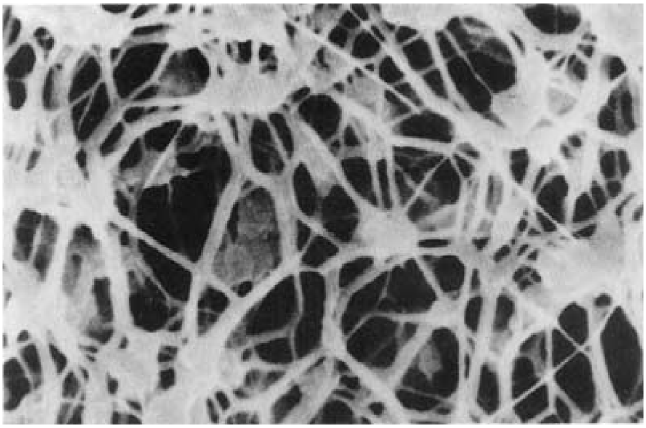
More recently, tightly woven fabrics have been woven from man-made micro-fibres/filaments, such as polyester, polyamide, viscose and acrylic fibres (conventional and bi-component), which produce sufficiently small pores, even when dry. Very fine filaments and micro-fibres (e.g. 1 dtex, 10 μm or less) can be woven into tight constructions (e.g. 4800 × 7680 filaments/cm) to produce pores small enough to prevent water molecules from penetrating, but large enough to allow water vapour to pass through. They can be laminated to a highly absorbent outer fabric (e.g. viscose or cotton), wicking perspiration to the outer fabric which absorbs it and allows it to evaporate to the outside.[28] Alternatively, they can be used on their own, but with a water repellent or other coating (finish), such as silicone or fluoro-carbon, which can increase water repellency and reduce water penetration. An example of a fabric in this category is Hoechst Trevira Finesse, which will support a 500 mm water column,[28] also after 5 washes. In the Bundesmann Water Repellency Test (DIN 5388), in which the fabric is exposed to artificial rain, it will remain dry for 5 hours, even after five washes. These fabrics are softer and more water repellent than the original Ventile fabric. They have a narrow pore size distribution, within the sub-micron range.[32]

Yoon and Buckley[33] showed that air permeability and water vapour transmission rate are mainly dependent on the fabric geometrical properties (thickness and porosity), whereas liquid water transport is strongly dependent on the fibre properties, although geometrical factors also play an important role here.

Micro-porous membranes and coatings

Micro-porous membranes are generally made from the polymers[27] PTFE, polyurethane (PU), polyolefins, polyamides, polyester, polyether and polyether based copolymers, with the first two mentioned (i.e. PTFE and PU) being the most popular. In most cases they can be cast directly onto the fabric (i.e. coated) or formed into a membrane and then laminated to the fabric.

A micro-porous membrane (or coating) can be defined[34] as a thin-walled structure having an open spongy morphology of precisely controlled pore size, typically ranging from 0.03 μm to 10 μm in diameter. Micro-porous coatings and membranes rely on an interconnected network of tiny holes (pores) introduced by various means into an otherwise impermeable polymeric structure.[35] Sheets of polymers can be produced with common salt incorporated which is washed out afterwards to leave voids/pores. Such holes (or pores) are too small to allow water droplets to pass through, but are large enough to allow water vapour to pass through. Micro-porous structures work, as do tightly woven structures, because of the large



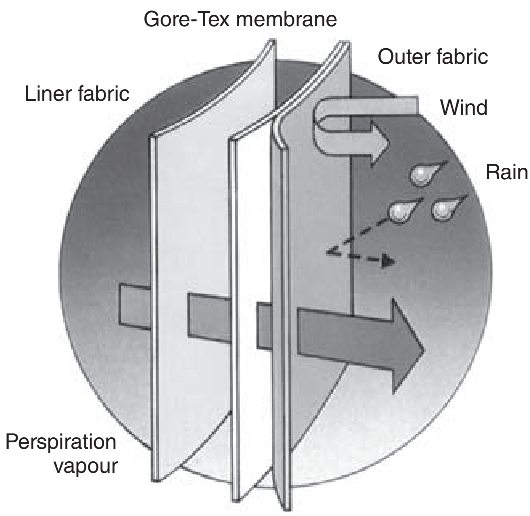
11.1 Gore-Tex® fabric membrane magnified by 40 000. Source: Ody, 1990[36]

difference in size between individual water molecules present in water vapour and water droplets of rain, each of the latter consisting of many millions of water molecules held tightly together by surface tension forces.[35] Micro-porous membranes typically weigh 10–20 g/m^2 and should be durable and resistant to laundering, chemicals and UV degradation.

Micro-porous based breathable fabrics usually have a layer of hydrophilic polyurethane or water repellent finish (fluorocarbon or silicone) so as to ensure consistent performance and to prevent the pores being contaminated.[30]

The first use of a micro-porous membrane to produce a breathable fabric in the 1970s, called Gore-Tex (W.L. Gore; *http://www.gorefabric.com*), represented a major step forward in the achievement of comfortable breathable fabrics and garments. The membrane (thin film) comprises an expanded polytetrafluoroethylene (or Teflon) (ePTFE), having over a billion pores per square centimetre (Fig. 11.1),[36] their size (≈ 0.2 μm in diameter) being orders of magnitude smaller than the smallest water droplet (±100 μm) and several times larger than a water vapour molecule (40×10^{-6} μm),[15] and able to withstand a water pressure of up to 100 psi.[28] Pore size should preferably be below 3 μm[30] for optimum balance between waterproofness and breathability. The PTFE membrane is chemically inert, smooth, UV resistant, water repellent, durable and can withstand high temperatures.

Today, some of the most durable and high-quality breathable fabrics are produced by laminating (sandwiching) a micro-porous membrane between two fabrics: an inner, soft and flexible fabric (e.g. warp knitted) and an outer abrasion resistant fabric (e.g. woven nylon fabric). Such fabrics are popular



11.2 Gore-Tex®, three-component laminated fabric.
Source: Ody, 1990[36]

for military wear, foul weather garments and work-wear. Two-layer laminated fabrics are popularly used for sportswear and fashion leisurewear, often with a loose lining or other insulation material. Drop liners are also used, where the breathable laminate is inside, but separate from, the outer fabric, and therefore in no way affects the handle, drape and constructional characteristics of the outer fabric. The membrane can be laminated to a non-woven or tricot fabric. Generally, the membrane is 'dot' laminated (for example hot melt screen printing using polyurethane adhesive dots) to the outer fabric and frequently also to an inner, fairly open and flexible fabric which provides flexibility and facilitates the passage of perspiration to the outside, the membrane being sandwiched between the two (Fig. 11.2[36]).

Tetratec Corporation also produces a micro-porous PTFE fibre. Donaldson Membranes has a portfolio of Tetratex fabrics, involving expanded micro-porous PTFE (ePTFE) membranes, films and laminates, the membrane being stable from –270° to +260°C. Other such membranes are based on micro-porous polyurethane (e.g. Aquatex, produced by Porvair) or on micro-porous polyvinylidene fluoride (PVDF) cast directly onto the fabric. Honeycombed micro-porous polyurethane coatings (pore sizes 2 to 3 μm) provide waterproof breathable fabrics[28] with, for example, a water vapour transmission of 4000 $g/m^2/24$ hr and a resistance to 2000 mm of water column for the Entrant Fabric of Toray.

Problems that can arise with micro-porous membranes and coatings include contaminants and detergents blocking the pores, stretching the fabric, increasing the size of the pores, and reducing adhesion to the textile substrate.

Hydrophilic membranes and coatings

Hydrophilic membranes and coatings are very thin polymer films, generally of chemically modified polyester or polyurethane, containing essentially no holes (pores) as such and sometimes referred to as non-porometric.[15] They combine 'soft' segments (e.g. polyether chains) with 'hard' segments (e.g. polyurethane chains[37]). Hydrophilic coatings 'breathe' by passing water vapour molecules along their chains to the outside, while preventing water molecules from penetrating. Such hydrophilic (non-micro-porous) polymer films (membranes and coatings) can transmit water vapour efficiently by a complex molecular diffusion or chemical adsorption mechanism,[38] with the water vapour molecules reacting with the hydrophilic 'polar' groups (e.g. polyethylene oxide) incorporated into the polymer chain, these regions acting like 'inter-molecular pores' which allow water vapour molecules to pass through, by absorption, diffusion and desorption, but not liquid water. The vapour initially 'dissolves' in the polymer, with the concentration directly proportional to the vapour pressure, after which it migrates to the opposite surface under the concentration gradient.[15] Incorporation of hydrophilic functional groups into conventional coatings achieves the desired water vapour diffusion, the hydrophilic–hydrophobic balance required[30] in the coating being achieved, for example, by the use of segmented copolymers, incorporating polyethylene oxide into the hydrophobic polymer chain.[30] Commercial films are around 10 to 25 μm thick, have a vapour permeability above 2500 $g/m^2/24$ h, with 5% swelling, and can support a hydrostatic head of 1500 mm.

A membrane 0.01 mm thick can have over 584 billion hydrophilic cells/cm^2 which transport moisture.[30] It needs to be flexible, and have good strength and softness. One of the first such coatings developed by the Shirley Institute,[35] was polyurethane based. Coatings are generally less expensive and easier to handle than the membranes. They are up to 50 times more effective in water vapour transmission than conventional polyurethane coatings, and compare favourably with micro-porous structures.[35]

One example of a hydrophilic membrane is Sympatex,[39] by Akzo (Enka AG), which is about 10 μm thick. It consists of a copolymer of 70% polyester and 30% polyether. Polyester is hydrophobic (repels water) and polyether is hydrophilic (allows water vapour through). The direction of travel is influenced by the temperature gradient, always being from high to low.[39] It is claimed to be able to stretch up to 300% and still be impermeable to liquid (water); only water vapour (e.g. evaporated perspiration) can pass through the membrane. It can withstand a water pressure (column) of 10 metres (1 bar[39]). It is windproof and is always laminated to a textile substrate, also sandwiched between the outer fabric and an inner (lining) fabric. Sympatex-containing garments can be dry-cleaned or washed in a washing machine (delicate wash) at a temperature of 40°C, after which the outer fabric has to be reproofed to re-establish its water repellency properties. The outer fabric needs to hydrophobic. It transmits more than 2500 g/m^2/24 hrs of water vapour.[28] Sympatex has recently developed[40] an eco-friendly (100% recyclable) laminate made from polyester–polyether copolymers, a combination of the Sympatex membrane and recycled polyester. Its latest Reflexion III membrane is lightweight, waterproof, windproof and recyclable.

Other examples in this category include Porelle from Porvair. An alternative technology uses a polyether co-block polyamide film (e.g. Peebax from Elf Atochem[37]).

Advantages of hydrophilic films and coatings include:[37]

- Water and solvent resistance
- Strength and toughness
- Windproofness
- Good handle
- High breathability without water leakage
- Pinhole free films.

Disadvantages include:[37]

- Vapour reservoir is required for breathing to commence
- The surface wets out in rain, giving a cold clammy handle
- The film swells when wet, leading to possible 'noise' effects in wet laminates.

Combination of micro-porous and hydrophilic membranes and coatings

Fabrics can also be coated with copolymers (coatings and membranes) combining a non-micro-porous hydrophilic layer with a micro-porous hydrophobic layer, which can offer the following advantages over a pure micro-porous film:[30,37,41]

- Hydrophilic layer seals the micro-porous base, reducing any tendency for water leakage
- Increased strength and toughness
- Reduced stretch
- Greater windproofness and resistance to penetration by some solvents and light mineral oils
- Film swelling is lower
- Lower friction during sewing when making 2-ply laminated fabrics.

Disadvantages include:[30]

- Increased stiffness
- Cost
- Reduced breathability
- Moisture vapour reservoir required to initiate water vapour transmission
- Tends to 'wet out', giving a cold clammy handle.

Smart breathable fabrics

Smart (or intelligent) breathable fabrics, as is the case with smart (intelligent) textiles in general, imply that the fabric can respond to different ambient conditions by changing its properties accordingly. Phase change materials (PCM) for example, are, being used which change the breathability properties of the fabric as the environment (micro-climate) changes. If the moisture-saturated outside air is as warm as the 'micro-climate' between the skin and the membrane, perspiration will no longer be able to be evaporated and transmitted to the outside, and the wearer will feel uncomfortable, as would be the case with no clothing. Products have therefore been developed[42] (for example by Schoeller Textil) which adapt to the climate, by, for example, the hydrophilic membrane opening up with increasing water vapour and body heat, and closing up when the converse occurs. Schoeller's c_change three-layer fabric's hydrophilic membrane changes as the activity and temperature change, allowing moisture to escape more rapidly when the body temperature and the moisture increase, by opening up (and by closing, when the body temperature drops),[43] thereby retaining body heat.

The use of temperature-sensitive polyurethanes (TS-PU) is also being explored,[30] their water vapour transmission increasing with increasing temperature.

Biomimetic-based fabrics

Biomimetic fabrics, which mimic biological mechanisms, have been developed. One example is improving the water vapour permeability of fabric coatings by incorporating an analogue of leaf stomata, which open and close according to water vapour transmission needs.[15] Akzo Nobel markets a product under the name of Stomatex, which is used in conjunction with its Sympatex waterproof breathable membrane.[30]

The Super-Microft fabric developed by Teijin Co., Japan, which emulates the high water repellency of the structure of the lotus leaf, is another example of a biomimetic fabric.[30] Ramaratnam *et al.*[44] reported on a method of mimicking the lotus effect on polyester fabric using silver nano-particles and a non-fluorinated hydrophobic polymer.

11.4.4 Production of coated and laminated breathable fabrics

As previously mentioned, several methods are available for producing waterproof breathable fabrics, including tightly woven fabrics (e.g. using cotton or micro-fibres), membranes (hydrophilic or micro-porous) and coatings (hydrophilic or micro-porous), the latter generally being thicker than the former.[45]

Essentially, the construction of breathable fabrics can be grouped into the following categories:

- Tightly woven fabrics (e.g. cotton, linen and micro-fibres)
- Laminated and coated fabrics, for example:
  - Micro-porous or hydrophilic membrane laminated to a fabric
  - Micro-porous or hydrophilic membrane sandwiched between a high performance outer fabric (e.g. woven) and an inner fabric (e.g. knitted fabric)
  - Micro-porous or hydrophilic polymer coating applied directly to a fabric.

Membranes and coatings need to be joined with at least one textile or other substrate to produce a material with the desired balance of functionality, aesthetics, handle, drape, durability, etc. (see also Section 11.4.3). There are various ways of combining membranes and textile fabrics.[30,37] If the outer fabric and the membrane are laminated it is referred to as an 'outer' laminate, while if the membrane is laminated to an 'inner' fabric (lining), it is referred to as a 'lining fabric' or liner.[46] A three-layer laminate involves three layers (outer fabric, membrane and inner fabric) being bonded. For coatings, a thin plastic film (generally polyurethane) is applied directly to the fabric[46] from a solution, dispersion, or hot-melt.

The lamination process must be such that it does not deleteriously affect breathability, and it must be durable and flexible. The membrane can be laminated to one or more of the following materials:

- Woven (most common for apparel and generally used as the outer fabric)
- Knitted (provides softness/flexibility, often used as the inner fabric)
- Non-wovens that are cost effective (e.g. wound dressings, roofing membranes)
- Foams (e.g. upholstery).

Behera and Singh[27] provided a table (Table 11.1) of commercial breathable fabrics.

Mid-layer fabrics, i.e. between those in contact with the skin and the outer fabric, need to offer good wicking and insulation. An example is the Polartex Power Dry polyester fabrics, with large capillaries on the inside to remove (wick) perspiration quickly, and to spread it on its outer surface by means of small capillaries for maximum evaporation.[7] Sarkar *et al.*[47] have compared the water transport behaviour of different multilayer fabric structures.

11.5 Fabric finishes

Generally, waterproof breathable fabrics require a water repellent finish to be applied to the outer layer which does not adversely affect breathability. Mechanical, chemical and coating treatments are the main methods[10] for imparting water repellency to textiles, the effect also depending upon the fibre type and the fabric structure and tightness (density). Ozcan[10] has compared various water repellent finishes.

Fabrics are generally given a water repellent finish by depositing hydrophobic substances such as fluoro-polymers, fluoro-chemicals, silicones and waxes on the fabrics[10] (applied, for example, by spraying, lick roller or padding). These are based mainly on the reduction of the critical surface tension of the fabric surface to below that of water, which results in a chemical barrier against water penetration.[48]

Initially, wax emulsions, with a maximum surface energy of 30–32 dynes/cm, were used, which was good enough for aqueous fluids but not for many oily substances.[49] Fluoro-chemicals (fluorocarbons) are now popularly used, providing effective repellency against both aqueous and oily based substances (polar and non-polar liquids[48]), generally being applied from an aqueous dispersion. They also provide easy cleanability. The fluoro-chemicals, which are mostly applied by padding, provide both 'repellent' and 'release' properties, preventing wetting and soiling (i.e. repellency) on the one hand, and easy removal (release) of dirt, soil, etc. during cleaning on the other hand. The fabric needs to be properly prepared prior to the application of the fluoro-chemical, it being particularly important that the fabric is free from residual substances, such as silicone de-foamers, residual alkaline, rewetting tensides (detergents, emulsifiers), preparations and sizing residues.[48] Wetting agents are included to enable even wetting and application of the fluoro-chemical. Such wetting agents should preferably volatilise during the subsequent drying or curing processes so as to prevent re-wetting.[48] Various 'supplementary' products can be applied with the fluoro-chemical so as to enhance the performance of the fluoro-chemical and extend the range of properties imparted to the fabric,[48] these including

Table 11.1 Commercially available breathable fabrics. Source: Behera and Singh, 2007[27]

Product brand name	Company	Features of the product
Permatex	DuPont	PU based film, offers 70% MVTR
Microtech	Aigle Inc.	Micro-porous coated fabric
Walotex	Deerfield Co. Ltd (Bayer Group of Cos.)	Monolithic hydrophilic membrane
Crosstech	Gore-Tex Associates Inc.	Bi-component membrane technology
Hydroseal, Vertex, HyVent	The North Face	Micro-porous laminated
Powertex	Salewa	Laminated breathable
Coopertex™	Cooper Fabrics, USA	Membrane based WPB fabrics
Formosa Raintex WPB	Formosa Raintex, Taiwan	Multilayer laminated fabric
Triple Point	Lowe Alpine	Micro-porous coating
Weathertight	Karrimor Inc.	Hydrophilic coating
Gore-Tex (3-Ply)	WL Gore Associates Inc.	Micro-porous PTFE membrane
Aquatex	Aquatex Co. Ltd, Malaysia	Micro-porous laminates
Sympatex	AKZO Nobel	Hydrophilic laminates
Entrant	Toray Coatex Co. Ltd Japan	Superior waterproof, breathable, pore size 2–3 mm Bi-component coating
Gore-Tex	WL Gore Associates Inc.	Bi-component laminates
Tetratex	Tetratec	PU bi-component film
Breathe-Tex Plus® and Stediar 2000®	Aldan Industries Inc.	Monolithic moisture barrier products using polyurethane
Proline	Lainiere de Picardie Inc.	Waterproof, breathable, windproof laminated fabric
Poldura	Modulo M	PU based multilayer fabric for dry suit
Sure-seal	Carlisle coating and WP	Membrane and coating waterproof system
Eclipse Barrier/Tech	BarrierTECH	Monolithic barrier membrane
Paclite	WL Gore Associates Inc.	Lightweight and soft membrane
Aquadry	Aquatex Co. Ltd	Hydrophilic coating
Conduit™	Conduit	Hydrophobic and hydrophilic membrane

'extenders' (e.g. blocked isocyanates), cellulose cross-linkers, softeners, antistatic agents, fungicides and flame-proofing. Care must be taken not to adversely affect other desirable properties of the fabric, notably handle and comfort. Fluoro-chemicals have good fastness to washing and dry-cleaning, although a heating process (ironing or tumble drying) is often necessary after the cleaning process.

Blackwood[50] has compared the different methods of applying silicone coatings to fabrics, silicone finishes generally protecting against water-based soils and liquids only.[51]

An ion-mask plasma treatment has recently been developed,[52] while nano-structured finishes, e.g. nanosols, with particle sizes of less than 100 nm (e.g. self-cleaning) have also been developed.

11.6 Construction of showerproof garments

The first requirement for producing a waterproof breathable garment[53,54] is to use fabric(s) with the required performance characteristics, as discussed in the previous sections of this chapter. Thereafter, the design, seaming and seams of waterproof breathable garments need to be carefully engineered to ensure that water (rain etc.) cannot enter from the outside, either through seams or openings in the garment, while still allowing water vapour to escape from the body to the outside. Seams are commonly sealed with special tapes (e.g. heat bonded to the laminate) which must be durable to both washing and dry cleaning. Cuffs, hems, zippers, hoods, pockets, etc. all have to be specially designed for water proofing. These are normally specified and compulsory when trademarks are to be applied to garments. Seam tapes are thermoplastic adhesive films applied to sewn seams to prevent water from leaking through.[49] Such tapes must be resistant to washing and dry cleaning.

Even the best water-repellent fabrics can be made up into a very disappointing garment unless certain rules are observed.

Lining

First, the lining of the garment has an important influence on its wettability. A wettable lining causes the water to wick through from the outer surface, and transmits it to the clothing underneath. Linings, therefore, as well as the top fabric, should be given a water-repellent finish to delay this happening. Linings are often made from nylon, viscose or acetate, or, for heavier garments, a cotton lining may be used.

Interlinings (i.e. the stiffening fabric inserted between the top and inner layers of the garment)

Without an effective finish, interlinings will also cause wicking of water, and where interlinings are fused to the top fabrics, at cuffs and collars for instance, this can accelerate the penetration of water and produce disastrous effects on the appearance of the garment.

Interfacing

Before fusing any interfacing, the fabric needs to be tested. Some of these fabrics do not respond well to the application of heat; in these cases, a sew-in interfacing will be necessary. Cotton muslin or batiste can be selected, washed to eliminate the possibility of further shrinkage, and cut using the same grainlines as the rainwear fabric. The interfacing can be attached to the rainwear fabric with adhesive dots of glue stick (the school variety glue stick works well). If a fabric will accept a low-heat iron, use the lightest weight fusible, such as So Sheer, and apply without using steam.

Seams, seam finishes, and hems

Seams are particularly vulnerable to penetration by water, and for this reason special attention must be directed to their construction and location when designing a garment. When stitching is visible on the outside of the garment, water is liable to pass through, and seams which lie horizontally are prone to the full impact of rain, for example on the crown of the shoulder, the top of an attached hood, and the top edge of a pocket. To minimise the risk, it is necessary to use proofed sewing threads and the finest needle possible. Resistance to water penetration is further assisted by ensuring that open and not closed seams are used. By opening out the seam of the top fabric on the inside of the garment, the stitching lies protected between two layers of the outer fabric; the initial penetration of water through the seam consequently is delayed from reaching the lining or wearer. Since such concealment of the sewing thread is desirable, it is obvious that stitching in seams should not be superimposed.

The most common method of making seams waterproof is by taping the inside, using an adhesive or a heat-sensitive tape, or welding the layers together.

Stitches should be lengthened slightly for rainwear/coated fabric, to approximately 3.0–3.5 length. Hems are attractive when sewn with a cover-stitch. Any auxiliary needles should be removed from the cover-stitch machine, as pinholes will leave a permanent mark in the fabric. If cover-stitch capabilities are not available, a double row of topstitching can be used for hems. The stitch should be lengthened to 3.5 for such hem-stitching. Seam finishes are not necessary to prevent fraying, as the fabric does not ravel. However, selecting a topstitch for seams may help them to remain flat. If so, the same 3.5 length stitching should be used as for the machine hem. It is advisable to finger press the seam open and stitch on each side of the seam line, or finger press the seam to one side, trim out the inner layer of the seam allowance, and run one row of topstitching to secure the seam in place.

For a creative topstitching, zigzag stitch should be used, set to 2.5 width and 2.5 length. Two strands of construction thread should be put through the machine needle.

Pockets

Patch pockets, with a horizontal edge, are greatly exposed to rain; if they are considered essential to the garment style, then fabric flaps must be used. However, pockets located at a slant are less likely to be a source of penetration. In any event, all linings for pockets should be proofed.

The design of pockets must be aimed at keeping out wind, wind-blown rain, and water that runs off the surface of the garment. Pockets need to be closable, say with a zip, with the opening preferably protected by a flap which itself can be secured in position.

Fastenings, buttons, and zips

Ideally, fastenings, buttons and zips should not be fully exposed to the rain. If the button thread and zip tape are absorbent it will assist penetration. Water-repellent sewing thread and tape should be used, with further protection given by a storm flap. Where buttons are used for decorative features, as with shoulder tabs, the stitching often provides an entry point for rain. Cuffs most of the time need to fit snugly, round the wrist, but they must also be capable of being 'opened' not only for the removal of the garment but to facilitate ventilation. Consequently, cuffs should be designed with adjustable openings. However, if an elasticated construction is used (differing in character from the top fabric), it is essential that it should not wet preferentially.

Design of fastenings, pockets, cuffs, and hoods must be directed to keeping out wind, wind-blown rain, and water which runs off the surface of the garment. A flap used to protect a zip is more effective if, in addition, a press stud, a touch-and-close fastener, e.g. 'Velcro', or other fastening is introduced to hold the flap close to the surface of the garment.

Magnetic closures, metal eyelets/grommets, long-prong snaps and separating zippers all work well with rainwear/coated fabric. Buttons and buttonholes will require additional reinforcement, such as a second layer of interfacing. It is important to avoid the use of heat on this fabric.

Needles and thread

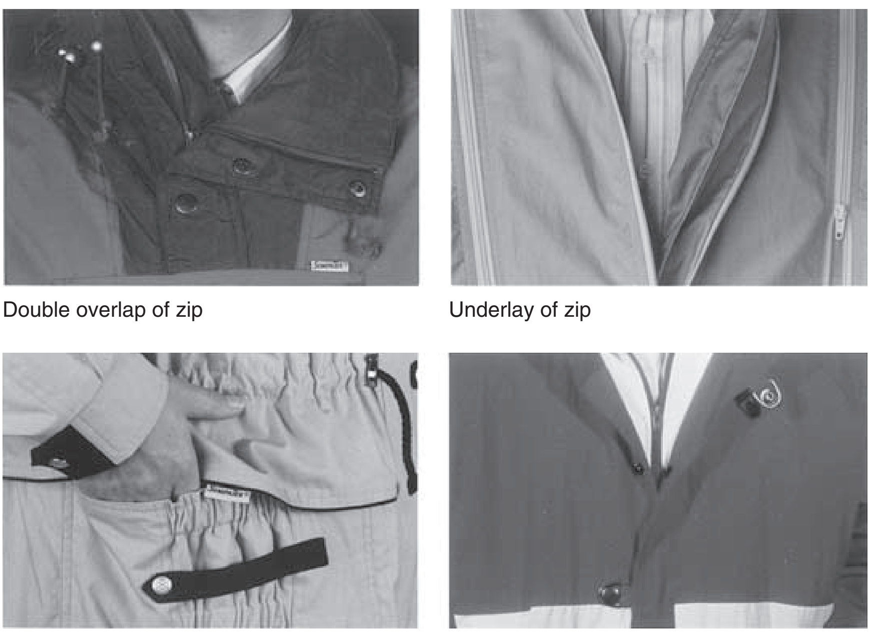
Microtex needles represent a good choice for rainwear fabrics. Select the smallest needle that can be threaded easily, so as to avoid any needle and pin holes. If a Microtex needle is not available, a 75/11 sharp needle (packaged as a 'quilting' needle) should be used along with an all-polyester thread.

Style

Further scope for improvement hinges on the construction and location of seams. For instance, Magyar sleeves would ensure that seams will not occur along the shoulder or along the outer side of the arm. Such a style increases costs because it utilizes more material, and the choice possibly of a more complicated seam construction increases garment manufacturing cost.

Pattern suggestions

Some examples of waterproof garment constructions are given in Fig. 11.3.



Double overlap of zip

Underlay of zip

Overflap on pocket

Overlay of zip

11.3 Examples of Sympatex® (Akzo) waterproof breathable garment constructions.
Source: The Woolmark Company

11.7 Comparative fabric and garment properties

Several researchers[15,55,56] have compared the performance of different types of waterproof breathable fabrics, with Lomax[55] and Saltz[56] giving tables comparing the water vapour transport properties of different fabrics.

Often there has to be a compromise between high breathability and high waterproofing, with cost an important factor. Furthermore, the absolute and relative breathability of fabrics can often differ significantly under different test (and wear) conditions (e.g. steady state, rain, wind, etc.), with water (i.e. rain) generally decreasing breathability while wind increases it. Temperature (particularly sub-zero) and temperature gradient also play a role in the breathability of fabrics.

The following ranking was given[15,36] according to the time taken for breathability to cease under rainy and windy conditions:

- Micro-fibre (worst)
- Cotton Ventile
- Porometric polyurethane laminate
- PTFE laminate
- Polyurethane coated
- Hydrophilic laminate (best).

Based on a slightly modified BS7209 vapour permeability test, Holmes *et al.*[57] ranked the breathability of different types of breathable fabrics in the following order, from highest (best) to lowest:

- Tightly woven fabrics
  - Synthetic filament fabrics
  - Cotton
- Membranes
  - Micro-porous
  - Hydrophilic
- Coatings
  - Hydrophilic.

Various other authors[30,58,59] have compared the performance of different breathable fabrics.

Bartels[60] reported that hydrophilic lining material improved the transport of liquid perspiration through waterproof functional garments, and was superior to hydrophobic lining in this respect.

11.8 Sources of further information and advice

Various workers have reviewed the subject of waterproofing and breathability.[15,27,30,31,61–68]

11.9 Concluding remarks

Considerable research and development is taking place in the field of breathable waterproof fabrics and garments, with cost *vis-à-vis* performance and end-use being important factors. The trend is towards lighter-weight fabrics and garments[69] and towards smart (intelligent) fabrics. Smart fabrics (e.g. phase change materials), nano-technologies, as well as bio-mimetics, are areas which show promise in the development of the next generation of waterproof breathable fabrics. Venting and core comfort mapping represent new trends in making garments breathable and water-proof,[70] garments being engineered in such a way that they even provide for the different functional requirements of the various parts of the human body. There is also a strong move towards eco-friendly treatments (e.g. perfluoro-octanoic acid-free fluoro-chemical finishes) and environmentally friendly and recyclable fabrics and garments. In 2006, the breathable textile market was estimated[71] to comprise 63% PU coating, 20% PTFE laminates, 9% PE laminates, 6% PU laminates and 2% other.

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