

Smart, Waterproof, Breathable Sportswear – A Review

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ABSTRACT

This paper reviews the various works done in the development of waterproof, breathable sportswear. The moisture transport properties and various factors affecting it, in the sportswear fabrics are also discussed. More on that, the limitations of conventional waterproof breathable fabrics are overcome by redesigning the textile material surface, operating at a microscopic level using stimuli-responsive polymers (SRPs), phase change materials (PCMs), Shape Memory Polymers (SMPs) etc., in the form of smart technology that facilitates active comfort to the wearer is also discussed. Special functionality imparted in sportswear by incorporating smart material in the form of smart coatings is also presented.

Keywords: Moisture transport, Stimuli-responsive polymers, Phase change materials, Shape Memory Polymers, Comfort, Smart Coating, Sportswear

I. INTRODUCTION

Waterproof breathable fabrics are designed for use in garments that provide protection from the environmental factors such as wind, rain and loss of body heat. Waterproof fabric completely prevents the penetration and absorption of liquid water. The term breathable implies that the fabric is actively ventilated. Breathable fabrics passively allow water vapour to diffuse through them and prevent the penetration of liquid water. High functional fabrics support active sportswear with importance placed on high functions as well as comfort.

Waterproofing is a required functionality of sportswear in many sports like mountaineering, skiing, diving, rafting, cycling, and golfing. Human body core temperature should be well maintained within its narrow limits and inclusion of water or wind reduces the thermal insulation of a clothing system and may lead to drastic temperature fall. So sportswear must protect athletes against wind and rain and maintain the body core temperature. Long ago, rubber coating and PVC coating are used, but these coatings also make the fabric impermeable to water vapor. These rubber coatings completely fill the fabric pores and make the fabric unbreathable and uncomfortable to wear. This led to development of waterproof & breathable coatings.

Smart coatings can be defined as those that enable the textile material to sense and respond to any external stimuli, like change in temperature, moisture, strain, etc. This response either could be direct and evidently visible, like change in shape, color, or size, or it could be indirect, like change in molecular configuration, electrical response, etc., [1] Phase change materials PCMs respond to any temperature change by changing their physical state. Shape memory materials, SMPs, change their shape in response to external stimuli like heat, moisture, light, and electricity. Shape change at the macro level is visible to the naked eye like shrinking and curling of fibers, whereas shape change at the micro level is not physically visible but may change material porosity.

To assist the human body in automated thermoregulation, especially in extreme situations of sudden temperature change, novel concepts of smart clothing are constantly being explored. Current systems for adaptive comfort regulation are based on various smart coating technologies which involve the application of PCMs, SMPs, and SRPs. This especially concerns their transition temperature (at which shape memory effects are triggered), which has to be lowered to meet the needs of human body regular temperature.

II. FUNCTIONAL REQUIREMENTS OF SPORTSWEAR

Functional requirements of sportswear depend on many factors such as the nature and duration of sports, amount of physical activity involved, and atmospheric conditions. All sportswear should provide basic functions like comfort, protection, stretchability, light weight, and dimensional stability. According to the nature of sport, sportswear may provide some special functions such as low aerodynamic and hydrodynamic drag force, compression, and also having waterproof, windproof, and health-monitoring capabilities, etc. One of the basic functional requirements for all types of sportswear is the wear comfort. Wear comfort is important for players as it may enhance performance by providing suitable physiological conditions in all climatic extremities. Wear comfort [2] is comprised of

- Thermophysiological comfort,
- Skin sensorial comfort,
- Ergonomic comfort, and
- Psychological comfort

Thermophysiological comfort depends on moisture and heat transmission through textile fabric. It determines the microclimatic condition of the player during the course of a game and also after the completion of the game. In active sports like soccer, tennis, and rugby, sweat rate is extremely high. Therefore, the moisture transmission aspect of thermophysiological comfort becomes a most important functional requirement [3]. In cold climate sports like skiing, snowboarding, and mountaineering, temperatures may fall to subzero conditions. To maintain the body temperature in these conditions, thermal insulation becomes one of the functional requirements for fabric. More physical activity is performed in these sports, so high moisture vapor transmission is also required to avoid sweat condensation at the skin.

Skin sensorial comfort depends on surface properties, surface friction, roughness, and softness [4]. It may affect skin abrasion, chafing, and skin injury during the course of a game. Ergonomic comfort depends on the fit and freedom of movement. It may affect the air drag in high-speed games, so it becomes very important in aerodynamic sports like cycling, running, skiing, and swimming [5].

Another required functionality of sportswear is protection against climate extremes like wind, rain, and

snow in sports such as skiing, mountaineering, snowboarding, and alpine running. Protection against ultraviolet (UV) rays also becomes an important functional requirement for someone spending long hours at outdoor sports like golf, cricket, and tennis. In high-speed games, a little reduced drag force may enhance the performance [6] and make a difference in this high competition arena. Motion capturing and health monitoring by textiles during sports training may give accurate and elaborate data for performance enhancement [7].

A. Commercial Classification of Sportswear

As per the market, sportswear can be broadly classified into three categories:

- Performance sportswear,
- Leisurewear and
- Outdoor sportswear.

Performance sportswear enhances the performance of athletes by imparting special functionality like reducing drag resistance as well as providing maximum wear comfort and protection in extreme weather conditions such as rain, snow, extreme cold, and heat. Innovative materials and remarkable technologies are emerging very fast in this area to provide that extra benefit to players for enhanced performance.

B. Traditional Waterproof Breathable Fabrics

Water-resistant and moisture-permeable materials may be divided into three main categories

- ✓ High-density fabrics,
- ✓ Film-laminated materials and
- ✓ Resin-coated materials

Selection can be made according to the finished garment requirements in casual, athletics, ski or outdoor apparel.

1) Densely Woven Waterproof Breathable Fabrics: The densely woven waterproof breathable fabrics consist of cotton or synthetic microfilament yarns with compacted weave structure. One of the famous waterproof breathable fabrics is known as VENTILE, which is manufactured by using long staple cotton with minimum of spaces between the fibres. Usually combed yarns are woven parallel to each other with no pores for water to penetrate and the weave is oxford weave. When fabric surface is wetted by water the cotton fibres swell transversely reducing the size of pores in the fabric and requiring very high pressure to cause penetration. Therefore waterproof is provided without the application of any water repellent finishing treatment.

Densely woven fabrics can also be produced from micro-denier synthetic filament yarns. The individual filaments in these yarns are of less than 10 micron in diameter, so that fabrics with very small pores can be engineered.

2) Laminated waterproof Breathable Fabrics: Laminated waterproof breathable fabrics made by application of membranes into textile product. These are thin membrane made from polymeric materials. They offer high resistance to water penetration but allow water vapour at the same time. The maximum thickness of the membrane is 10 micron. They are of two types:

- Micro porous membranes
- Hydrophilic membranes.

The micro porous membranes have tiny holes on their surface smaller than a rain drops but larger than water vapour molecule. Some of the membranes are made from Polytetrafluoroethylene PTFE polymer , Polyvinylidene fluoride PVDF, etc

The hydrophilic membranes are thin films of chemically modified polyester or polyurethane. These polymers are modified by the incorporation of poly. The poly (ethylene oxide) constitutes the hydrophilic part of the membrane by forming amorphous region in the main polymer system. This amorphous region acts as intermolecular pores allowing water vapour molecules to pass through but preventing the penetration of liquid water due to the solid nature of the membrane.

3) Coated Waterproof Breathable Fabrics: Coated waterproof breathable fabrics consist of polymeric material applied to one surface of fabric. Polyurethane is used as the coating material. The coatings are of two types:

- Micro porous coating
- Hydrophilic coating

Microporous coating contains very fine interconnected channels that are much smaller than finest raindrop but larger than water vapour molecules. Hydrophilic coating is same as hydrophilic membrane. In the microporous coating, water vapour passes through the permanent air-permeable structure whereas in the hydrophilic coating, it transmits vapour through mechanism involving adsorption-diffusion and de-sorption. The desirable attributes of functional sportswear and leisurewear are as follows:

- Optimum heat and moisture regulation
- Good air and water vapour permeability
- Rapid moisture absorption
- Absence of dampness
- Fast drying
- Dimensionally stable even when wet
- Durable
- Easy care
- Lightweight
- Soft and pleasant touch

It is not possible to achieve all of these properties in a simple structure of any single fiber or their blend. The two layer structure has a layer close to skin of the wicking type comprised of synthetic fibers eg. microdenier polyester and the outer layer usually cotton or rayon that absorbs and evaporates. Micro denier polyester is ideal for wicking perspiration away from the skin. The use of superfine or microfibre yarn enables production of dense fabrics leading to capillary action that gives the best wicking properties.

The wicking behaviour of the fabric is mainly depending on its base fibres moisture properties. The smaller the diameter or the greater the surface energy, is the greater the tendency of a liquid to move up the capillary. In textile structures, the spaces between the fibres effectively form capillaries. The narrower the spaces between these fibres, is the greater the ability of the textile to wick moisture. Fabric constructions, which effectively form narrow capillaries, pick up moisture easily. Such constructions include fabrics made from micro fibres, which are packed closely together. However, capillary action ceases when all parts of a garment are equally wet. The surface energy in a textile structure is determined largely by the chemical structure of the exposed surface of the fibre.

Hydrophilic fibres have a high surface energy. Consequently, they pick up moisture more readily than hydrophobic fibres. For Hydrophobic fibres, by contrast, have low surface energy and repel moisture. Special finishing processes can be used to increase the difference in surface energy between the face of a fabric and the back of the fabric to enhance its ability to wick.

C. Moisture Vapor Transmission

he mechanism in which moisture is transported in textiles is similar to the wicking of a liquid in capillaries.

Capillary action is determined by two fundamental properties

- Its diameter; and
- Surface energy of its inside face.

Moisture vapour transmission relies on the existence of a temperature/pressure gradient between inside and outside of the garment. In other words, the fabric works by equalising the pressure and heat between the inside and outside of the garment. Once body moisture reaches the inner face of the garment, it must pass through the fabric and then evaporate on the surface. If it cannot pass through the fabric, or if the rate of transmission is slower than the arrival of extra vapour, then the vapour condenses on the inside face.

It is for this reason that breathable products work best when the air inside is humid and warm, the air outside cold and dry to evaporate the excess moisture. When the weather produces warm and humid conditions on the outside of the garment, transmission rates is lower.

1) **Moisture Management Hydrophilic Coatings on Sportswear:** In active sports, the sweat generation rate is very high, so moisture management becomes a very important functional requirement of high active sportswear. Moisture transmission takes place via three processes: absorption, wicking, and evaporation. For active sportswear, higher wicking and faster evaporation are required to enhance comfort and performance [3]. Moisture management mainly depends on the surface energy of the material, which further depends on the chemical structure of the surface. Chemical finishes change the surface chemistry, hence change the surface energy. Special finishes can create different surface energy on either side of the fabric to promote rapid moisture transmission along the fabric. Functional sportswear with distinct hydrophilicity was developed by graft polymerization process [8,9].

Polyester fabric, with a hydrophobic inner side and hydrophilic outer side, is created with graft polymerization of acrylic acid on its surface. This type of structure is reported to have superior moisture management with effective dispersion of sweat along the fabric thickness. Active carbon-coated polyester fabric has been found to have improved moisture comfort due to absorption of sweat impulses by carbon particles [10]. Modified polyester fabric became highly hydrophilic with improved wettability [11,12]. Micro

denier polyester fabric treated with moisture management finish (MMF), composed of a combination of hydrophilic polymer and amino silicon polyether copolymer, is reported to show better wicking, absorbency, and quicker absorption as compared to untreated fabric [13-15].

2) **Factors Affecting Moisture Transport:** There are several factors, which affect moisture transport in a fabric. The most important are

- Fibre type
- Cloth construction or weave
- Weight or thickness of the material and
- Chemical treatment

Synthetic fibres can have either hydrophilic (wetting) surfaces or hydrophobic (non-wetting) surfaces. Synthetic fabrics are generally considered to be the best choice for garments worn as a base layer, because, they are able to provide a good combination of moisture management, softness and insulation. While most fabrics, both natural and synthetic, have the ability to wick moisture away from the skin, not all of these are fast-drying and air permeable, which have direct influence on cooling and perceived comfort. High-tech synthetic fabrics are lightweight, are capable of transporting moisture efficiently, and dry relatively quickly.

It is generally agreed that fabrics with moisture wicking properties can regulate body temperature, improve muscle performance and delay exhaustion. While natural fibres such as cotton may be suitable for clothing worn for low levels of activity, synthetic fabrics made of nylon or polyester are better suited for high levels of activity. They absorb much less water than cotton, but can still wick moisture rapidly through the fabric.

D. Developments in Sportswear

A highly fruitful innovation in sportswear garments have come during 1980s. Some reasonably simple micro fibres and coated fabrics were developed and variants of which have met the needs of many sports garments. The innovation of new materials and garments was so successful that in many sports. The fundamental performance requirements have been identified and largely satisfied. Nowadays, from very simple micro fibres to much more complex fabrics are effectively used in active sportswear. The latest textile materials are

much more functional specific for fulfilling specific needs in different sports activities.

E. Sweat Absorption and Fast Drying Property

Moisture handling properties of textiles during intense physical activities have been regarded as major factor for developing active sportswear. Actually the comfort perceptions of clothing are influenced by the wetness or dryness of the fabric and thermal feelings resulting from the interactions of fabric moisture and heat transfer related properties. For the garment that is worn next to skin should have good sweat absorption and sweat releasing property to the atmosphere, fast drying property for getting more tactile comfort. It has been found that frictional force required for fabric to move against sweating skin (resulting from physical activities, high temperature and humidity of surroundings) is much higher than that for movement against dry skin. Which means, the wet fabric, due to its clinging tendency, will give an additional stress to the wearer.

F. Commercial Developments in Sportswear

One of the techniques is using a microporous membrane, in which very fine pores are created in an impermeable membrane. The size of pores is much smaller than a water droplet but large enough for water vapor to pass through. Gore-Tex® is the most revolutionary product in this category, which is made up of stretched polytetrafluoroethylene (PTFE) membrane. This microporous PTFE film has 9 billion pores per square inch, where pore size is 700 times than that of water vapor but 1/20,000 of a water droplet. Gore-Tex® membrane is laminated to the outer side of fabric and makes it impermeable to water and wind but allows perspiration to pass through. The maximum pressure that can sustain without getting wet is of 30 psi. Gore-Tex® fabric is a two-layer construction in which Gore-Tex® membrane is laminated to the outer material and the lining is independently placed under it. This product provides protection and comfort in many sports like, golfing, cycling, running, skiing, and snowboarding [16].

Pro® is a three-layer construction in which membrane is sandwiched between an outer layer and inner lining. This is a very durable product used for sports in extreme conditions like winter climbing, mountaineering, snowboarding, and sailing. Gore-Tex Active® is an ultra lightweight micro denier three-layer system in which lining is integrated as backing to finer and lighter Gore-Tex® membrane which is shown in figure 1. It

provides maximum breathability as compared to two other products with similar protection. It is preferred in active sports like alpine running, endurance running, and fast-ascent mountaineering.

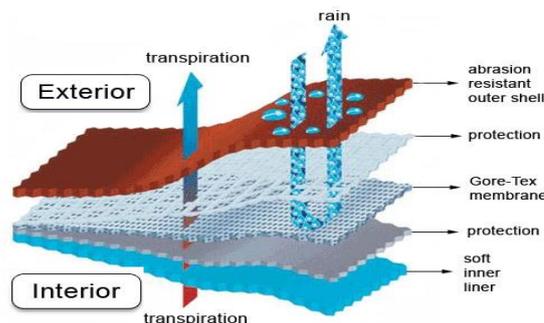


Figure 1: Gore-Tex® construction

Polyurethane (PU) microporous membrane is used in waterproof breathable fabrics. Porelle Dry® is a microporous PU membrane with micropores of less than 1 mm, which help to diffuse water vapor from the skin to the outside environment. It claims to provide a super dry feel even after repeated washing due to hydrophobic nature of PU. It shows high moisture vapor transfer due to larger pores [16]. Dermizax NX® is the latest waterproof breathable PU membrane developed by Toray Industries. It minimises the condensation with double breathability and super stretch than its previous product, Dermizax EV®. Hard segments make the waterproof and soft segment is responsible for water vapor transfer. Temperature and relative humidity difference is the driving force for water vapor transfer. Hydrophilic molecules act as transfer agents and moisture vapor transfer takes place by adsorption, diffusion, and desorption [18-20].

Sympatex is the commercial hydrophilic solid film that is based on the copolymer of polyester and polyether. It has been reported that two-layer micro porous membranes perform better and are more permeable to water vapor as compared to hydrophilic membranes and coatings in isothermal conditions, whereas hydrophilic solid film is more breathable in non isothermal conditions [21]. Micro porous films are less durable and their performance deteriorates due to blockage of pores with contamination, body oils, dirt, etc., as well as waterproofing characteristics may be affected when film is stretched at knees and elbows. Hydrophilic films and coatings are not affected by washing or stretching [22]. The presence of rain causes saturation of hydrophilic

sites in hydrophilic membranes or coatings, causing a wet and clammy sensation [23]

G. Limitations of Conventional Waterproof Breathable Fabric

The traditional protective role of clothing has been passive, restricted to choosing the proper material for certain physical conditions of the body and the environment, always with the aim of keeping the wearer comfortable and healthy. In most cases, during active sporting, the physiological function of clothing has been limited to preventing air circulation around the skin of the wearer and thus avoiding the exit of air reheated by the skin. In extreme warm and sunny environments, normal breathable clothing directly protects the wearer from sunburn and extensive heating but gives discomfort to the wearer as it not performing well for thermoregulation of the body. Nevertheless, these simple physiological functions of clothing cannot meet current consumer demands, which are closely related to the demands of high performance and efficiency. Modern changes in lifestyle and the sophistication of consumer demands create the current situation in which the actual aim of clothing is changing from traditional simple protection to necessary functionality and added value, especially within the areas of work wear, leisure wear, and sportswear. Therefore, although in the contemporary world practical protection remains the main reason for our need for clothing, currently it often has an active role in adapting to changes in physiological needs in the accordance with the activity of the wearer and changes in the environment.

H. Smart Fabrics for Performance Enhancement

This new functionality is known as active comfort regulation and can be achieved by implementing so-called smart technology. Hence, smart textiles are usually defined as textile materials or products that can sense and interpret changes in their local environment and respond appropriately. Today, functional finishing technology, which includes smart coatings, is considered a specific technology that could provide active comfort regulation function to textile materials. The following are the some of the functional finishing materials have been applied to the textiles using surface modification techniques,

- ✓ Phase Change Materials (PCMs),
- ✓ Stimuli-Responsive Polymers (SRPs),

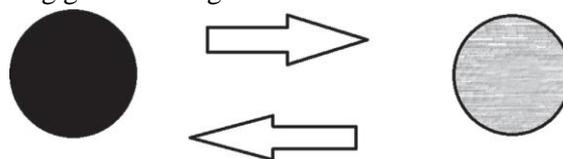
- ✓ Shape Memory Polymers (SMPs), etc.,

By redesigning the textile material surface, operating at a microscopic level, new added-value textile material can be created by smart coating. It can be use of conventional textile fibres and, by modifying a very thin surface layer of the material, to create modern smart textile materials that not only keep us warm, dry, and comfortable but are expected to react and interact with a wide range of stimuli and situations. Facilitated by technological advances in smart coatings, active comfort regulation by smart textiles and clothing has expanded rapidly, providing the specific needs for the active sportswear.

I. Phase Change Materials

Responsive and adaptive functions of smart apparel must be capable of supporting abrupt microclimate changes, especially during exercise, particularly during active sport or under extreme environmental (cold and heat) conditions. In extreme climatic conditions, particularly in cold weather, in addition to proper thermal insulation, clothing should impart protection against wind, rain, and snow. Cold weather clothing should ideally have the features of being insulating, windproof, and waterproof [24]. The adaptive function of smart apparel is mainly directed toward an insulating function. Thermally active materials made by PCM microcapsules coating are able to improve the wear comfort of the garment by active thermal insulation [25].

Solid Heat is absorbed during liquid
Melting gives cooling effect



Heat is released during crystallization
gives warming effect

Figure 2 : Phase change process.

Like Paraffin, Phase Change Material acts as storage of heat in garments. It provides a thermal balance between the heat generated by the body while engaging in a sport and the heat released into the environment. Figure 2 shows the functional principle of PCM coated material

working during the action of the wearer. When a material changes phase with increasing temperature, e.g. from solid to liquid state, a large quantity of latent heat is absorbed. This input of heat is necessary to transform the solid material to the liquid state, and the change will occur at an almost fixed temperature, i.e., the melting point of the material. The heat is, in effect, stored in the material in its liquid state and is only released when the liquid is cooled back to its solid state. This behavior forms the basis of phase change materials. However, the clothing layer containing PCM must go through the transition temperature range before the phase change in PCM occurs and either release or absorb heat depending on the ambient conditions. This means that active comfort regulation cannot be achieved under steady-state thermal conditions, so the wearer has to impose some activity to cause a change in the temperature of the PCM-containing fabric. The need of PCM for constant charging and recharging is the main reason why PCM microcapsule-coated clothing is mainly used for active wear, work wear, and outdoor sports apparel [26].

J. Shape Memory Polymers

Shape memory materials (SMMs) are a set of materials that can change their shape, as the result of an external stimulus, from some temporary deformed shape to a previously programmed shape. The shape change is activated most often by changing the surrounding temperature, but with certain materials stress, a magnetic field, an electric field, the pH value, UV light, and even the presence of water can be the triggering stimulus. Among the variety of available SMMs, SMPs are suitable for producing smart coatings for textiles.

The most readily available SMP for use in textiles is segmented polyurethane (SMPU), which is two-phase heterogeneous structure consisting of a rigid fixed phase and a soft reversible phase. The reversed phase is used to hold the temporary deformation and the fixed phase is responsible for memorising the permanent shape. The permanent shape can be memorised and recovered automatically from the temporary deformation with the trigger of heating [27]. SMPs can be incorporated in the form of films in multilayer garments for protective clothing, sportswear, or leisure wear. Using a composite film of SMP as an interlining (i.e., membrane) in multilayer garments, outdoor clothing can have an adaptable thermal insulation and be used as

performance clothing with variable adaptable clo values [28,29].

K. Stimuli-Responsive Polymers

One approach to obtaining active comfort regulation in smart textiles is based on using SRP coatings integrated into the fabric structure. The main challenge of this approach is to integrate SRP durably to a textile material surface in such a way that it retains its responsive behaviour. Hydrogels are widely used in a variety of applications and are usually defined as three-dimensional cross-linked polymeric networks that can imbibe large amounts of water. If a hydrogel is prepared from SRPs, it has added functionality and display changes in solvation in response to certain stimuli such as temperature, pH, ionic strength, light, and electric fields. Hydrogels responsive to temperature and pH have been the most widely studied systems because these two factors have physiological significance. Once incorporated into a textile material surface, it is likely that SRP microgel particles act as a temperature sensor and a valve to regulate water vapour permeability [30].

L. Smart Coating to Enhance Comfort in Sportswear

Enhanced wearer efficiency under extreme weather situations can be reflected in significantly extended wearing times of the garments without the occurrence of heat stress. The longer wearing times further lead to significantly higher productivity, and the more comfortable wearing conditions result in a reduced number of accidents. This is an important aspect for work wear and outdoor sports apparel. Thermally active materials made by PCM, SMP and SRP coating are able to improve the wear comfort of the garment by active permeability control. This is a fundamental feature of smart breathable fabrics. To keep the wearer dry and comfortable during sweating, the vapour from sweat must be transmitted through the porous structure of textile material toward the outer layer, where it evaporates immediately. This makes the wearer feel dry and comfortable during in action.

M. Functions of Smart Coatings

The processes of active permeability control in SMPs and SRPs coated textiles are based on their ability to act as a switch to control the transmission of water vapour. The wearer's comfort can be improved if the material possesses high water vapour permeability at higher temperatures and low water vapour permeability at

lower temperatures. At temperatures below the switching temperature, SMP/SRP coating on the material surface exists in a glassy/expanded state, whereas at higher temperatures it exists in a rubbery/collapsed state. Thus, SMP/SRP-coated fabric could have water vapour permeability controlled by closing and opening the permitting SRP microgel particles as valves for water vapour passage through the textile material.

Performance swimwear like Speedo® became highly popular in the 2004 Olympics and completely changed the scenario of the swimwear market. Lightweight shield by Gore-Tex® has completely replaced bulky multilayered protective sportswear. Outlast® offered the smart solution for extreme cold clothing with phase changing materials (PCMs). Nike® sphere shirt open completely new avenues of moisture sensitive clothing.

N. Role of Nano fibres in Active Sportswear

Nanofibers with diameters less than 100 nm, large surface area (1000 times more than microfibers) and excellent mechanical properties provide wide applications including sport apparel and sport shoes such as waterproof and windproof sportswear for canoeing, cycling and mountaineering [31]. Several fabric companies have utilized nanotechnology to develop a wide range of sports apparel. Scholler, a Swiss company, has developed a nano-based technology to produce clothing with optimal balance of comfort, air permeability, wind and water resistance and self-cleaning property for extreme cold weather sports such as mountaineering and ski. The produced sportswear also benefit from rain- and snow-repellent feature [32]. UK-based company, JR Nanotech, has developed ‘‘SoleFreshTM’’ socks treated with silver nano particles eliminating athlete’s foot odor [33,34].

III. METHODS OF ASSESSING SPORTSWEAR PROPERTIES

Standard methods are required for assessing the different properties of sportswear incorporated with nanotechnology, Water-proof breathable fabrics are studied based on spray test ISO 4920:2012, in which the fabric resistance to surface wetting is investigated by spraying the specific amount of distilled water and comparing the sample with standard pictures. Determination of resistance to water penetration based on hydrostatic pressure is also important and is

conducted by subjecting the fabric sample to a steadily increasing pressure of water on one face until penetration occurs (ISO 811: 1989, BS EN 20811: 1992). The resistance to water-vapor permeability is also studied according to ISO 15496: 2004, in which fabric weight change is related to breathability and the value more than 20,000 g/m² per day is regarded as a sample with high breathability. Determination of water repellency of fabrics by Bundesmann rain-shower test [35-37] rain tests are among the other standard methods associated with water-proof breathable fabrics [39-41].

IV. FUTURE TRENDS

Potential future benefits of apparel adaptive comfort regulation by smart coatings involving the application of PCMs, SMPs, and SRPs are significant. Hence, the use of smart coatings to improve comfort will undoubtedly continue to expand into apparel applications. However, all available technologies have limitations and still have the potential to develop. Although a high level of adaptation to outdoor weather by smart clothing has been achieved, many problems remain in certain areas. Among the challenges remaining, improvement in the efficiency of the systems is the main task, which includes enhancing the response time, improving durability and material processability, and assessing the lifecycle of smart clothing. Currently, among various types of PCMs (organic, inorganic, and bio-based) organic-based PCMs are mostly used in textile applications because they offer maximal revenue. Nevertheless, strict regulations about being noncombustible and requirements regarding biodegradability are motivating the growth of bio-based PCMs. With a reduction in price, bio-based PCMs can overtake the main role in future treatments of textiles with PCMs [42].

V. CONCLUSION

Smart coatings currently provide great potential in obtaining textile materials (ie, apparel) with active comfort regulation properties. Technologies for the smart coating of textile materials are based on applying different smart polymeric materials, such as PCMs, SMPs, and SRPs. These coatings successfully impart stimuli responsiveness to the textile material, making it an adequate raw material for the production of responsive performance apparel. Thermo physiological wear comfort is the main aspect of comfort which can

be influenced by innovative smart coatings for active comfort regulation in responsive performance apparel like active sportswear. In the 21st century, we have entered the exciting age of smart fabrics and smart clothing. To meet the functional requirements of sportswear, in addition to smart coating, new materials continuously appear, for which new applications are still being developed. With the tremendous variety of conventional textile fabrics and novel coating substances, there has never been a better time to innovate in the area of smart coatings for the improvement of comfort in apparel.

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