A Review on Breathable Fabrics Part – I: Fabric Construction

S. B. Vhanbatte*, Bharti Thakur & R. L. Gotipamul

Department of Textiles, DKTES's Textile and Engineering Institute, Ichalkaranji, (MS), India

Abstract

Waterproof breathable fabrics are expected to exhibit contradictory requirements including impermeability for penetrating water and permeable for moisture vapour. To accomplish these objectives for rainwear, sportwear, medical and workwear applications; the methods like coating or lamination are employed. The coating chemical layers or laminating films have either hydrophilic or hydrophobic characteristics and results into resistance to water penetration and permit water vapours to transmit across the specimen. In the present review, need of breathability, historical development in breathable fabrics, manufacturing approaches and related mechanisms are discussed along with the recent developments in coating chemicals.

Keywords: Breathable textile, coating, lamination, moisture vapour transmission, physiological comfort.

***Corresponding Author:**
Dr. Shirishkumar Vhanbatte
Associate Professor
Textile Engineering, Department of Textiles
DKTES's Textile and Engineering Institute,
Ichalkaranji – 416 115 Dt. Kolhapur (MS)
E-mail: shirishkumar.vhanbatte@gmail.com

1. Introduction

To protect the human body from extreme weathering conditions like water or rain, sleet or snow fall and wind, waterproof breathable fabrics are preferred. Waterproofness and breathability are two contradictory functions expected from same fabric. Waterproof means fabric impervious to water. It prevents entirely the penetration as well as absorption of water. At the same time, it should exhibit the breathability by allowing effective transmission of moisture from microclimate between skin and clothing, to outside atmosphere [1]. The applications of such fabric include foul weather leisure wear, sport wear, rain wear, specialized medical safety equipment and military usage. The breathability along with high standard waterproof property from fabric is anticipated, depending on level of protection required. The wide range of end user products have categorised as leisure for heavy duty foul weather and fashionable weather protection including over trouser, cagoules, hats, gloves, rain wear, skiwear, golf suit, tents, sleeping bags and covers. Under the work wear products were classified as foul weather and domestic transport including survival suits, military protective clothing, surgical garments, hospitals drapes, mattresses and covers, tarpaulins, filtration, clean room wear, car covers, smoke covers and cargo wraps [1].

2. Thermal Comfort

Too much always creates discomfort; too hot, too cold or heavy rain, further wind and sleet disturb physical comfort. Theoretically, all these factors are directed to thermal properties of physical comfort [1, 2 & 3.] Core body temperature for human is 37°C, and skin temperature is 3 to 5°C lower than the core. Due to physical activity, metabolic activities or psychosomatic reasons, body temperature increases. The core body temperature at 45°C and beyond may result in disastrous consequences. During physical activity, body attains cooling mainly by producing sweat. When water in the body evaporates in the form of moisture, it absorbs latent heat from body and provides cooling affect. Every litre of water evaporate from body absorbs approx. 539 kcal energy as latent heat and reduces body temperature [4]. Researchers elucidated physical activities and corresponding wark rate [3]. Sleeping and sitting activity have 60 and 100 watts work rate respectively. Walking gently, actively or carrying light to heavy packs exhibit work rate from 200 to 500 or even more than 1000 watts depending on intensity of activity and fitness. The equivalent water evaporation rate given is 38 g day^{-1} $Watt^{-1}$. To elucidate, the work rate for active walking is 300 watts, for cooling, equivalent water evaporated is 11,500 $g.day^{-1}$ or 480 $g.hr^{-1}$. Some amount of water gets evaporate in respiration and major amount through skin.

The rate of evaporation depends on relative humidity. As physical work continues, the amount of moisture increases inside microclimate exists between body skin and clothing material. The moisture absorption capacity of air inside microclimate decreases with time as amount of moisture increases with activities [2, 3 & 5]. Therefore, even though the temperature is lower, discomfort increases. If sweat produced is higher than the rate of evaporation, the body is prevented from the cooling effect; the core body temperature increases and results into hyperthermia.

On the other hand, there are chances of reduction in core body temperature. During rest, most surplus heat energy from body is lost either by conduction or radiation. When cloths are wet, shivering takes place. In these cases, the body loses heat more rapidly than it is being produced. This phenomenon is known as hypothermia. The core body temperature at 24°C and below may also result in disastrous consequences. Either reduction in thermal conductivity inside the microclimate or higher thermal transmission, both causes loss in comfort.

3. Breathability

To maintain physiologically comfortable temperature range, the clothing has to permit the passage of perspiration produced during various physical activities. Clothing comfort sensation is determined by a balanced process of vapour and heat exchange between body and atmosphere across clothing. The ability of the clothing fabric to allow moisture vapour to penetrate through fabric and diffuse in the atmosphere is referred as breathability; however, it is a general, qualitative and absolute term, because it is used as ‘extremely’ or ‘high’ or ‘low’ breathable. It’s quantitative expression or degree of breathability is measured in terms of moisture vapour transmission rate (MVTR) and expressed as grams of moisture passed through fabric per square meter per day [6]. For a medium level physical activity, a breathability rating of 5000 – 8000 grams may be fine; whereas for heavy activities the recommended clothing shall have rating in the range of 10,000 – 15,000 grams. In case clothing meant for longer exposure to foul weather, the manufacturer claim rating of MVTR >20,000 grams. In brief, larger the number, the fabric is more breathable; however, prediction of exact rating is always difficult as moisture transportation across the fabric or clothing assembly depends on multiple factors like temperature, relative humidity, rate of sweating, layers in clothing assembly etc. Normally heavy physical activity may be for short time, which may generate uncomfortable condition for time being; however, the lag of moisture transportation across the fabric should be minimum to achieve comfortable situation again.

The fabrics employed to manufacture extreme weather clothing assembly also resists water to penetrate inside. The evaluation of waterproofness is equivalent of placing a square tube of 1 inch side over the fabric and height of water column required to leak is measured. The pressure generated by hydrostatic head breach the coated or laminated textile material and height of water column in millimetres is expressed as waterproof rating. The rating of 5000 mm is considered as waterproof material. Depending on weather conditions and degree of waterproofness required the ratings have recommended. The rating of 5000 mm provides some resistance to light rain, dry snow without pressure. The clothing with 10000 mm rating resists light rain and average snowfall with light pressure. For exposure to heavy intense rain or slit for longer period more than 20000 mm rating is required. Larger the number, the fabric is more resistance to water penetration.

Commercially for hiking or skiing the recommended jackets are of 10K/10K types. First 10K indicates fabric is resistance to 10000 mm hydrostatic head whereas second 10K describes breathability of fabric equivalent to 10000 grams of water through 1 sq. m within 24 hours.

4. History of waterproof breathable fabrics

A detailed review on history of waterproof breathable material [7] explain that in ancient time, waterproof shelters, clothing for hunting or farming, for sports or outdoor activity during adverse climatic condition were required and existing materials were used. The material preferred include leather and textile made from natural fibres like silk and wool and further cotton and linen. The record indicates the use of oil on silk fabric was common in historic times. Oily cloth won’t allow water to penetrate and used for shelter, covering and as containers. Linen or cotton cloth coated with linseed oil was used as sail cloth, further oil was replaced by paraffin wax. The use of intestine and stomach of seal or whale was also recorded.

Early attempts of use of rubber were not successful because at hot temperature it becomes tacky and at lower temperature shown hardness, may be because of its glass transition. In 1823, a Scottish chemist – C Macintosh patented his work involved sandwiching moulded rubber between fabric coated with rubber – naphtha mixture. Further the process of vulcanizing the rubber improved the quality of this product. The use of fats, waxes, oils, varnishes, pigments, gutta-percha, Indian rubber or water-insoluble metal oxides were used to fill-up the fabric interstices and block the water permeability for serve the purpose.

Initially, these waterproof products were welcomed by market however, very soon it was realised that they are preventing penetration of moisture to either side and are not sufficiently comfortable. Staying dry is not about only preventing water to get inside the clothing but letting sweat out is also essential. The solution to this problem led to introducing waterproof breathable fabric.

The development in waterproof breathable took place in United Kingdoms, mainly due to their climatic conditions. Ventile clothing used by British military pilots were impenetrable to arctic winds and icy water and showed to be tenfold better performance of existing products at that time. Unlike rubber or plastic-coated textiles, they were made from closely woven cotton fabric allowing sweat to transfer to atmosphere and referred as first-generation breathable products.

Gore-Tex® [8] introduced PTFE polymer based waterproof breathable fabric about 50 years before. A solid polymeric film was heated and subjected to a sudden, accelerated expansion to the tune of 800% where it resulted into 70% porosity or air content. The expanded - ePTFE – was used as waterproof breathable membrane as it was claimed to have 1.4 million tiny holes per sq. cm. These tiny holes get blocked due to contamination and exhibited the reduction in performance. Further, the Gore-Tex® developed hydrophilic PU based coated textile with improved performance and still it is used for commercial applications like windcheater. Based on this scientific theory, many developments were taking place in waterproof breathable textiles.

5. Waterproof breathable fabric constructions

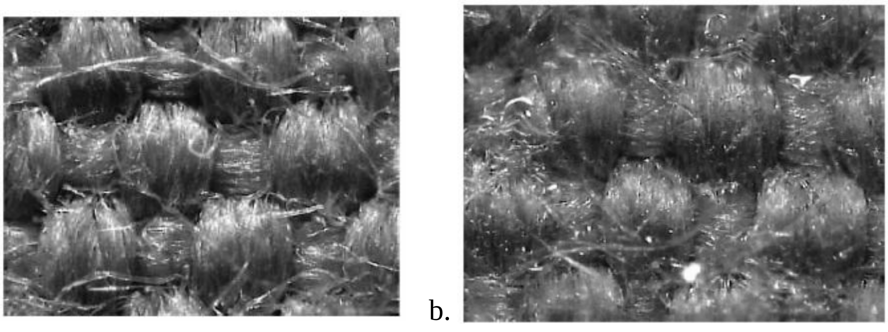
Many previous workers have reviewed the fabric construction used for waterproof breathable fabric and their assembly made for suitable end application coating like extreme weathering conditions or sportswear [1, 2, 7, 8]. Water resistance and moisture permeable fabrics can be manufactured by several ways and classified as:

- Densely woven fabrics.
- Membranes
- Coated
- Smart breathable and biomimetic

5.1 Densely Woven fabric

Ventile was the first reported breathable woven fabric by Shirley institute UK. The fabric was made from long staple, low twist and mercerised yarn. High-dense Oxford weave was used where in plain weave two ends run in pair. Because of minimum weft crimp, to some extent fibres are parallel to fabric surface. This fabric has high cover factor, flat surface with good abrasion resistance and lower stiffness.

Normally, either water vapour or liquid water transmitted across fabric through inters yarn spaces and diffusion through individual hydrophilic fibres. In addition, liquid water transmission takes place by capillary within fibres. Initially, Ventile is not waterproof, however when it comes in contact with water, as shown in figure 1, the cotton fibres swell and inter yarn space get reduced significantly from about 10μm in dry to 3 – 4μm in wet state. This can prevent the penetration of water for about 20 minutes when the wearer is submerged.



a. b.

Figure 1 – a) dry (Ventile fabric), b) wet (Curtesy: Woodhead Publishing Ltd.) [2]

The water repellent finish can improve fabric functionality when used as rain wear, however, as it is not coated or inter yarn pores are not blocked, it exhibits good breathability but lack in waterproofness for prolonged exposure to rain. Depending on end use applications, the Ventile can be engineered with fabric weight from 170-295 $g.m^{-2}$. High density fabric made from micro-denier synthetic filament / fibre ensures tiny inter fibre / filament spaces. This shows very good wind proofness and vapour permeability [9, 10]. The fabric constructions like taffeta, twill or oxford weave treated with water repellent finish are used for various functional garments. Dense fabric made up of either cotton or synthetic material shows good permeability to water vapour however water proofness is limited for prolonged exposure.

5.2 Membranes

Waterproof breathable fabric developed by laminating polymeric membrane offer high resistance to water penetration and allow vapour to diffuse. Microporous with 0.1 – 50 μm size and thickness of about 10 microns made out of polyurethane, acrylic, poly-tetrafluoroethylene, polyvinylidene fluoride or poly-amino acids are used to laminate textile material. PU can be modified as per end use requirement by altering base monomers are also flexible and tough and therefore, most preferably used. A thin film of expanded polytetrafluoroethylene polymer introduced by Gore-Tex, is claimed to have 1.4 billion micropores per sq. cm. The micropores sizing 2 – 3 μm are much smaller than water droplet however, water vapour molecules are much smaller and can escape through these pores as shown in figure 2.

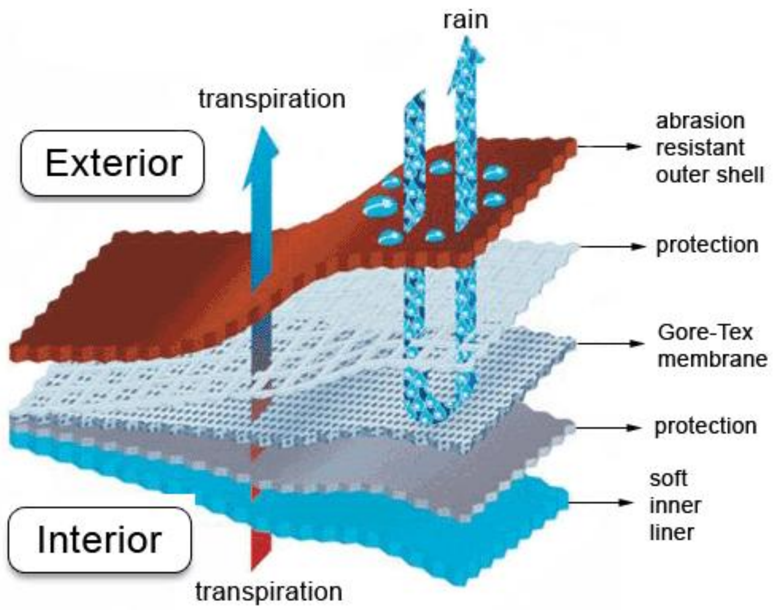


Figure 2 - Moisture transfer through membrane: Gore-Tex® construction

(Curtesy: Gore-Tex®) [8]

However, moisture transportation through hydrophilic polymer membrane shows diffusion mechanism. Polymer containing hydrophilic functional groups like –O–, CO–, –OH, $–NH_2$ in block copolymer segment, with which moisture can form reversible hydrogen bond. As moisture vapour pressure increases at one side, vapour molecule diffuses through film by stepwise moment along the functional groups in polymer chain, to the other side of lower vapour pressure. The diffusion takes place mainly in soft segment or amorphous region of polymeric film and depends on temperature, vapour pressure at either side of membrane and thermal motion of polymeric chains as represented schematically in Figure 3. The presence of moisture may cause swelling of highly hydrophilic polymers and influence the rate of vapour diffusion. Polyvinyl alcohol, or polyethylene oxide containing segments may swell in presence of water and cause poor wet abrasion resistance. A properly balanced hydrophilic polymer segment provides adequate swelling to allow diffusion of water vapour and retains film strength. Hydrophobic polymer containing polyethylene oxide segment showed lower binding energy to water vapour causing faster diffusion and also offer flexibility and soft handle.

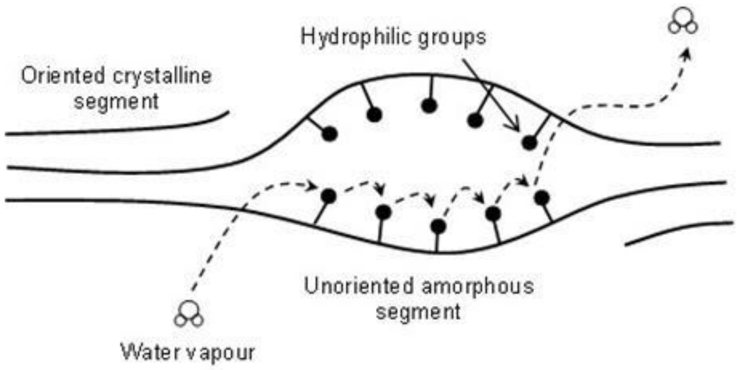


Figure 3 - Schematic representation of moisture diffusion through hydrophilic membrane [1]

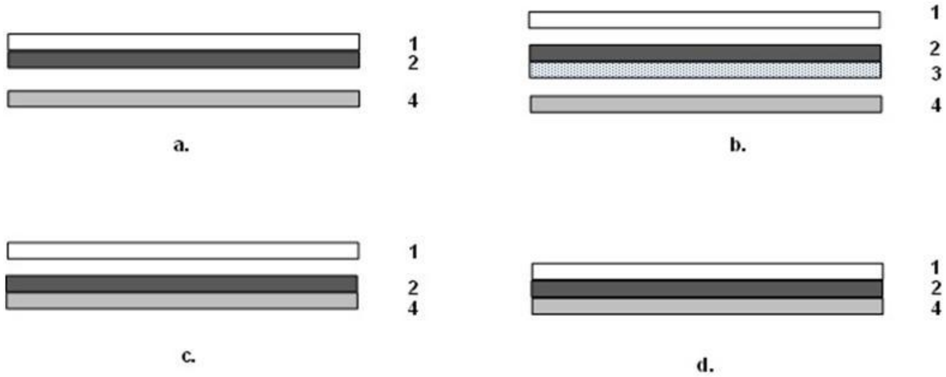


Figure 4 - Choice of inserting membrane in clothing assembly

High performance clothing is engineered as multi-layered assembly and membrane is introduced in clothing as per requirement which result in to breathability and care is taken not to affect the clothing aesthetic, feel and drape. In case of single layered clothing like rain wear or one time use medical practitioner protective clothing, membrane is fixed inside the clothing. However, in case of multi-layered clothing assembly, it is placed in such a way that, membrane is not exposed to either side of cloths; it remains inside attached to any one layer as shown in

The membrane can be laminated to underside of outer layer, though this effect on handle of garment, it exhibits good water and wind resistance (a); right side of interlining as insert, in this assembly outer layer handle is unaltered and thermal insulation can be improved by proper selection of interlining (b); lamination to inner fabric, this flexibility to use functional outer layer (c); and sandwiched membrane between outer and inner layer as three-layered assembly provides stiff material (d).

The commonly used methods of producing micropores in fine coated film includes wet or thermo-coagulation, foam coating etc., where polymeric molecules oriented as desired to form channels and orientation depends on process conditions as shown in Figure 5. Polyurethane paste prepared by dissolving in dimethyl formamide (DMF) and coated on textile substrate. The DMF is miscible in water. When coated substrate is either conditioned in humid atmospheric chamber or immersed in water bath for coagulation; the DMF in the coated paste get diluted and polyurethane get precipitated. Two-way mass transfer where water enters and DMF comes out from coated film helps for channelling. The rate of mass transfer is controlled by gradual increase in water concentration in DMF – water mixture in coagulating bath. Further coated material is washed thoroughly and dried. The techno economical problem encompassing use of costly solvent and its recovery restricted its commercial use.

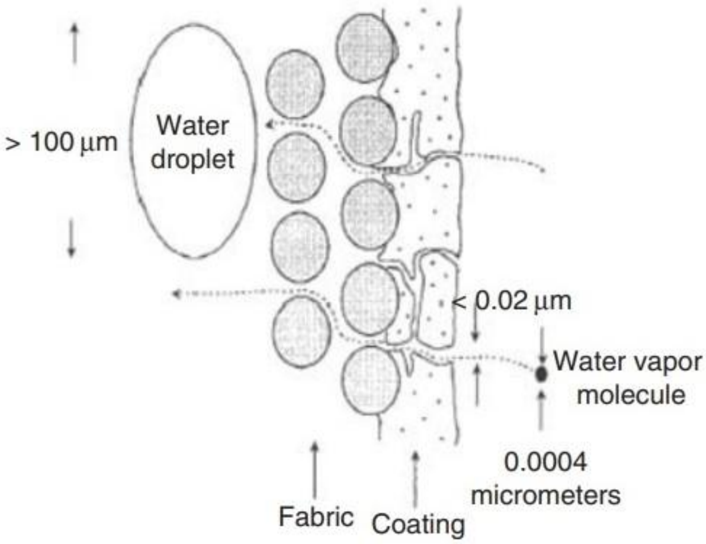


Figure 5 - Schematic representation of moisture transfer through porous coating
(Curtesy Sage Publication) [1]

Other wet coagulation practices include, use of polyamide solution in acid dope, applied on textile substrate by coating to about 50μm thick and immediately neutralised using sodium hydroxide further washed and dried. Micropores can also be developed on textile by leaching out of salt from coated film of Porvair, Porell, Permair etc., in water bath. Coating paste additives like inorganic filler – silica, magnesium oxide of submicron size and application of water repellent finish improves waterproofness and breathable performance.

Thermocoagulation is another interesting method used to develop microporosity in coated film. 15 – 20% PU solution is prepared using solvent mixture of methyl ethyl ketone, toluene and nonsolvent water. Coated substrate is subjected to heat treatment where low boiling solvent evaporates and leading to formation of precipitation of PU in nonsolvent. Further porosity is developed when remaining portion of solvent and nonsolvent get evaporate from coated film.

The mixture of Polyurethane and polyacrylic acid is added in bath containing foaming agent and generated foam is applied on nylon fabric. Further it is dried, calendared and treated with water repellent finish to waterproofness. Similarly, various other attempts are reported for generation of microporosity in coated film by solvent extraction method; solubilizing one component from polymer mixture coated on textile substrate. Owing to micron to submicron size of channel formed in coated film, water droplet is prevented to penetrate whereas comparatively smaller molecules of water vapour get diffused through them.

5.3 Hydrophilic coating

Hydrophilic coating exhibit same moisture vapour transportation mechanism as hydrophilic membrane [13]. However, the difference between hydrophilic and micropore lies in the mechanism of vapour transportation. Micropore film has tiny holes or channels through which water vapours get escape from microclimate between skin and clothing to atmosphere. In case of hydrophilic films, because of increasing moisture vapour pressure in microclimate, moisture adsorb on hydrophilic site in polymeric film and slowly diffuse in the film step by step along the hydrophilic functional groups in polymer chain segment. Once it reaches to other side of film, it gets desorbed and escape to atmosphere.

Generally, polyurethane-based coating containing soft segment provide the space to water vapour to diffuse inside [7]. The hydrophilic sites based on polyvinyl alcohol and polyethylene oxide are introduced in PU coating base as block copolymer. Hydrophilic component swells in presence of excess moisture and reduces durability or abrasion resistance, therefore, the balance between hydrophobic and hydrophilic segments is optimised to performance in terms of moisture vapour transmission, flexibility, durability, resistance to abrasion and dry-cleaning solvent. Polyacrylic-acid based coating material also exhibit moisture transportation through adsorption, diffusion and desorption mechanism. To achieve mechanical strength, crosslinking agents are added in coating formulations. The length of cross-linking agent and its amount in coating formulation are the factors influencing vapour permeability, swelling and mechanical strength.

5.4 Smart breathable biomimetic

Understanding the phenomenon occur in nature and modifying them to achieve on artificial product in named as biomimetics. The trademark 'Lotus effect' is based on super hydrophobicity. the incorporation of roughness and repositing hydrophobic particles like lotus leaf is the basis of the achievement. the contact angle increases and spherical droplet rolls off when leaf tilts at small angle (Figure 6). The hydrophobic material used was carbon fluorine based nano reactants [11].

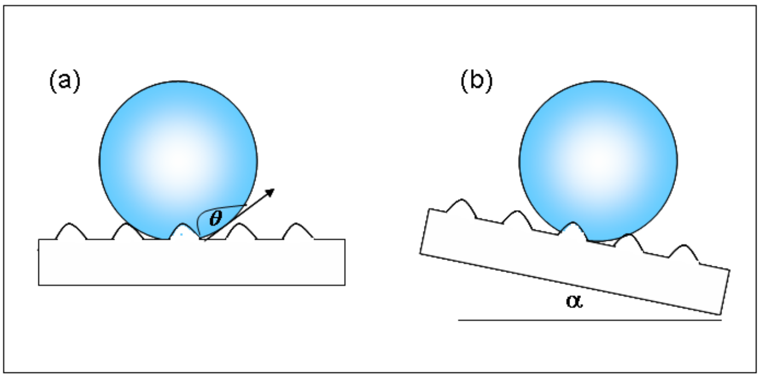


Figure 6 - A water drop on a rough lotus leaf surface:
(a) the contact angle,θ (b) the roll-off angle,α [11] (Curtesy- NISCAIR)

The 'Stomatex' trade name for comfortable clothing and footwear is based on function of leaf stomata which opens and release moisture when required depending environmental conditions. The closed cell neoprene foam with stomata like aperture at apex helps to release moisture when produced at higher rate and return to passive state when user is in rest. The evolution in biological species follow the rule of 'survival of the fittest' and understanding more about natural phenomenon can lead to new research avenues in the field of smart materials.

6. Development in breathable coating material

A class of material - polyurethane made remarkable market growth as coating base owing to its versatile properties and two-phase morphology [12, 13 & 14]. Polyurethane is scuff resistance, possess flexing endurance and is permeable to moisture vapour. Preparation of water bourn polyurethane using as amphiphilic diol for breathable waterproof textile coating has elaborated [15]. Upon introduction of PTMEG, swelling in water as well as mechanical properties found increased. When PU based coating along with silica in aerogel form was applied, it was resulted into improved breathability, resistance to chemical and water penetration [16]. Further it was reported that the adhesion between and cotton and PU coated film was found increased against abrasion. As amount of aerogel silica particles were increased, the water repellence as well as water vapour transmission properties also improved considerably. Wide range of PU based membrane and its results were reviewed [14] along with the developments.

A proof breathable fabric developed on basis of electro spun nanofibers and evaluated for its performance [17]. Different level of breathability and barrier performance were achieved by varying layers, web density or layered structure on textile substrate. This material exhibited the higher level of resistivity of water penetration compared to densely woven fabric and comparatively more water vapour permeability than coated or laminated material. Proper selection of base electro spun material, layer structure and textile substrate have potential to be adopted in waterproof breathable fabric for various end application. Another researcher [18] developed electro spun nano fibres web with finer fibres, smaller pore size, higher porosity made out of polyurethane, fluorinated polyurethane, alkyl silane functionalised graphene. Further he has developed a hot-press technique for adhesion of this material with textile substrate. The report showed that the material exhibits hydrostatic water head of 80 kPa and vapour permeability of 7.6 kg/m^2day.

It reported that benzotriozol derivative improves UV resistivity and fluorocarbon resin type compound improves water repellence of high pre-forming material [19]. The use of PVA along with PPAc cross-linker showed moisture vapour transmission through coated film is due to diffusion mechanism and coating film has no micropores [20]. This material exhibit resistance to hydrostatic water head at 1400mm water head and showed

2165g/m^2day vapour transmission. The modification in base coating polymer [21, 22] for development of temperature sensitive poly (n-tert-butylacrylamide-ran-acrylamide 27:73) and is coating along with BTCA. Below 15°C it swells more than 800% while above 40°C swelling reduced to 50%, the deswelling took place faster. The moisture vapour transmission of such coated material was increase from 58 to 94% from 15 to 45°C and suggested to incorporate such smart material in changing environmental temperature for suitable application.

7. Summary

A lot of work has been carried out to achieve waterproof and breathable fabric for various extreme weathering conditions and also to achieve comfort in work wear. Mechanical and chemical means were developed for waterproofness as well as breathability. However, there is still tremendous scope for improvement in terms of development of suitable membrane or coating material. Different applications, such as high-altitude clothing, medical application, sport wear and work wear; required different desired and essential properties and since long they remained topic of research interest.

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