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Moisture management properties of cut protective workwear

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The essential characteristic of a fabric used for clothing is its capacity to transfer and evaporate moisture efficiently. This study investigates the impact of weave structure on the moisture management properties of cut-protective workwear fabrics, focusing on three weave structures: 6-end satin, 2/2 twill, and 1/1 plain. The total number of nine sets of hybrid woven fabric samples was made by using para-aramid/modacrylic/stainless steel wrap spun yarn, ultrahigh molecular weight polyethylene (UHMWPE)/polyester/ stainless wrap spun yarn and para-aramid staple spun yarn. Fabric samples were analyzed using a moisture management tester to quantify six parameters: wetting time (top/bottom), absorption speed, spreading rate, wetting radius, one-way transport capacity, and overall moisture management capability following standard AATCC 195-2011. Weave pattern significantly influences moisture regulation, with 6-end satin outperforming twill and plain weaves. The 6-end satin exhibited a faster absorption rate, a larger wetting radius, and superior one-way transport capacity compared to other structures. The 6-end satin structure is optimal for cut-protective workwear requiring rapid moisture transfer, enhancing wearer comfort in demanding environments.

Keywords: Comfort, High performance yarn, Spreading speed, Weaving design, Wetting time

1 Introduction

Workplace cut injuries frequently occur in industries such as automotive, glass, and metal manufacturing, necessitating the use of protective workwear. Due to rapid globalization and growing awareness regarding work place safety protection among workers, the demand for protective workwear has accelerated. Workers are now more conscious of their safety, health, and working environment. One of the most effective risk management strategies to mitigate occupational hazards is the use of cut protective workwear. In environments where certain risks pose potential threats to life or serious injury, protective clothing becomes essential. By incorporating improved anti-cutting capabilities, such workwear enhances both safety and productivity by reducing the number of cutting-related injuries.

The cut-resistant durability of yarns and fabrics plays a crucial role in determining the effectiveness of protective clothing. However, comfort is also a key factor, as workers are less likely to wear protective gear consistently if it causes discomfort, ultimately affecting productivity and efficiency. Comfort in textiles is defined as "a neutral state compared to the more active state" or "the absence of unpleasantness or discomfort"[1]. Sensorial (tactile), psychological, and thermophysiological comfort are the three fundamental forms of comfort[2–4]. The clothing's capacity to regulate heat transmission, moisture management, and air permeability (AP) significantly contributes to thermophysiological comfort[5,6]. Skin temperature is mostly influenced by thermal conductivity. Comfort becomes greater when the body's surplus moisture is eliminated[7].

Many studies have explored the comfort properties of protective apparel, particularly for firefighters[8–13]. Studies on the comfort of other protective apparel, such as ballistic and workwear, are rather scarce[14,15]. A common issue with such clothing is inadequate breathability, which can lead to excessive perspiration accumulation, making the garment damp and uncomfortable. Since the human body is homoeothermic, it regulates temperature by modifying vasomotor activity. Typically, thick and heavy protective clothing restricts heat and moisture dissipation, resulting in thermal stress[16]. To prevent overheating, the body produces perspiration, which, if not managed effectively, can lead to discomfort and reduced efficiency.

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Garment transport properties, environmental conditions, and metabolic heat production influence the thermal balance of the human body. While body metabolism and environmental factors remain constant, fabric properties can be optimized to enhance comfort. The transport characteristics of the fabric, which include temperature resistance, moisture vapour evaporation, air permeability, and water vapour permeability, are largely dictated by structural parameters[11,17,18]. The attributes of fibre and fabric structures greatly influence the thermal state of the body[19]. The interplay and relationship between the characteristics of the fabric's component fibres, yarn, clothing structure, and chemical finishes added during the fabric's manufacture can determine the comfort attributes of the material[20].

The primary factor influencing physiological comfort is the movement of perspiration through the fabric. Hydrophilic materials effectively absorb moisture. Various combinations of hydrophobic and hydrophilic fibres are used in tests. As the hydrophilic content in the blend increases, water permeability also rises. However, moisture transport decreases when the proportion of hydrophilic groups becomes too high[21]. A study by Nayak *et al.* [22] reported that polyester exhibits superior mechanical qualities than cotton cloth but has poorer thermal characteristics. The study also examined the comfort aspects of these materials. Working with a combination of olefin and cotton yarns, Negola *et al.*[23] observed that olefin, being lightweight, sinks into the fabric, allowing cotton to surface on the outside, resulting in a dyeable and comfortable fabric.

Microdenier polyester fibres demonstrate superior wicking performance compared to regular denier fibres. Due to the larger surface area of spun yarn made from micro denier fibres, micro denier spun yarns exhibit higher water absorbency than those made from regular denier polyester[24]. The direction of the twist does not significantly affect the wicking property. A study on the comfort characteristics of woven fabrics made from hollow fibrous assembly and staple twist-less yarn reveals that hollow fibrous assembly fabrics have superior thermal properties, including water vapour permeability, thermal resistance, and water absorption. However, air permeability and wicking rates are higher in staple twist-less fabric. As the twist level increases, the wicking rate of polyester ring-spun staple yarns decreases along their length[25].

Ren and Ruckman[26] investigated how fabric moisture content and condensation affected the water vapour transfer rate. Fabric thickness and thermal insulation are closely linked[2]. Inter-yarn porosity significantly affects fabric permeability, which, in turn, depends on pressure as well as the structure and nature of the fabric[27]. Twill weaves, known for their enhanced transport properties, are rated highly for summer wear. A double-faced woven fabric with an inside layer of polyester fibre and an outside layer of wool fibre was developed by Cohen and Makkabim[28]. Perspiration diffused through the cloth on the interior face before evaporating from the outer surface. With no additional treatment, the honeycomb microporous polyester woven structure demonstrated improved water vapour transport and rapid dry attributes[29].

Moisture management is a vital aspect of contemporary clothing design. The microclimate between the skin and the garment is essential for maintaining thermal balance, as it governs moisture management and directly affects wearer comfort. The way fabrics absorb sweat and dry influence the tactile experience of clothing. Effective moisture management fabrics can transport sweat as vapor when the wearer is inactive and move liquid moisture to the garment’s surface for evaporation during activity. This dual capability is central to what is known as moisture management properties. The efficiency with which moisture moves from clothing to the environment depends on factors such as the fabric's moisture-absorption capacity, where moisture accumulates, its source, and the duration of exposure to heat. The process of transferring heat and water vapor through clothing is complex, involving evaporation, condensation, and the absorption and release of moisture. Proper moisture regulation is especially important in cut-resistant workwear, as it helps maintain comfort by wicking sweat, supporting temperature control, and reducing skin irritation. These qualities not only improve comfort and health but also enhance performance, safety, and productivity in challenging work environments.

The performance and comfort of cut-protective workwear are determined not only by the protective materials used but also by the fabric’s ability to manage moisture effectively. Among the various factors influencing moisture management, the fabric's weave structure is pivotal. Weave structure dictates how yarns are interlaced, directly affecting the fabric’s porosity, capillarity, and surface characteristics, which govern the movement and evaporation of moisture. Studies specifically addressing the influence of weave design on moisture management in cut-protective workwear are scarce. Despite the growing significance of weave structure, limited research has focused on its impact on moisture regulation. This study aims to evaluate the effect of weave design on the moisture transport properties of cut-protective workwear fabrics made from high-performance yarns.

2 Materials and Methods

2.1 Materials

High-performance yarns were fabricated using para-aramid, modacrylic, ultrahigh molecular weight polyethylene (UHMWPE), polyester (PET), and stainless steel (SS) filament fibres through staple spun and wrap spun spinning methods. These yarns were directly sourced from High Performance Textiles Pvt. Ltd. In Panipat, Haryana, India. Three different weave structures — plain, 2/2 twill, 6-end satin — were employed to develop nine hybrid woven fabric samples using a shuttle loom machine. The fabric samples were categorised based on three yarn compositions: para-aramid/modacrylic/SS wrap spun yarn (Sample A), UHMWPE/PET/SS wrap spun yarn (Sample B), and para-aramid staple spun yarn (Sample C) (Table 1). Each weave structure incorporated these three material combinations while maintaining a uniform thread density of 1340 ends/m in the warp direction and 1970 picks/m in the weft direction.

2.2 Methodology

2.2.1 Physical Properties

The physical properties of the fabric samples were evaluated according to ASTM standards[30,31]. Thread density in both the warp and weft directions was measured using a pick glass as per ASTM D 3775-12, with the mean of ten readings recorded for accuracy. Areal density (g/m^2) was measured using an electronic weighing scale, following the ASTM D 3776-09 standard, with five readings taken from specimens of 10 cm × 10 cm size. The prepared fabric samples were tested for cut resistance with a Tono-dynamometer (IRSST, Germany) using a straight blade. The data were analyzed following the stipulations of the EN 388:2016+A1:2018 standard[32]. Fabric thickness (mm) was assessed using the Digital Thickness Gauge at a force of 20 gf/cm^2, as per ASTM D 1777-96 standard. Bulk density (kg/m^3) was calculated as the ratio of areal density to fabric thickness. Fabric porosity was determined using the following equation 1:

$$Porosity = 1 - \frac{Fabric\ density}{Fibre\ density} \quad \ldots (1)$$

2.2.2 Moisture Management Properties

Moisture management properties were assessed following the AATCC 195–2011 test method using the SDL ATLAS M290 Moisture Management Tester (MMT). This tester measures a textile's ability to handle liquid moisture by sandwiching a fabric sample between two horizontal electrical sensors (upper and lower), each with seven concentric pins. A pre-measured volume of test solution is put into the centre of the upward-facing test specimen surface to track electrical conductivity changes as the test solution moves radially across the top and bottom surfaces or through the fabric. Moisture management characteristics were evaluated using the following indices:

a) Wetting time: The time taken for liquid moisture to wet the fabric surface (measured separately for top and bottom surfaces).
b) Absorption rate: The rate at which fabric absorbs liquid moisture (measured separately for top and bottom surfaces).
c) Spreading speed: The speed at which liquid spreads radially over the fabric's surface (measured separately for top and bottom surfaces).

Table 1 — High-performance yarn characteristics

Yarns	Linear density Ne	Ply twist m^{-1}	Twist direction	Core: sheath, %	Structure
Sample A	13	355	Z	36:64	Wrap spun
Sample B	13	UHMWPE- 160 PET- 435	UHMWPE-S PET- Z	36:64	Wrap spun
Sample C	13	236	Z	-	Staple spun

Table 2 — Physical properties

Sample code	Areal density, g/m^2	Cut resistance	Thickness, mm	Bulk density, kg/m^3	Porosity
Plain-A	157	B	0.44	356.82	0.754
Plain-B	156.1	B	0.42	371.67	0.720
Plain-C	155	B	0.40	387.50	0.705
2/2 Twill-A	160.1	B	0.53	302.08	0.889
2/2 Twill-B	159	B	0.50	318.00	0.868
2/2 Twill-C	158	B	0.48	329.16	0.795
6 end Satin-A	162.3	C	0.57	281.23	0.934
6 end Satin-B	161.0	C	0.55	292.73	0.925
6 end Satin-C	160.4	C	0.54	297.04	0.920

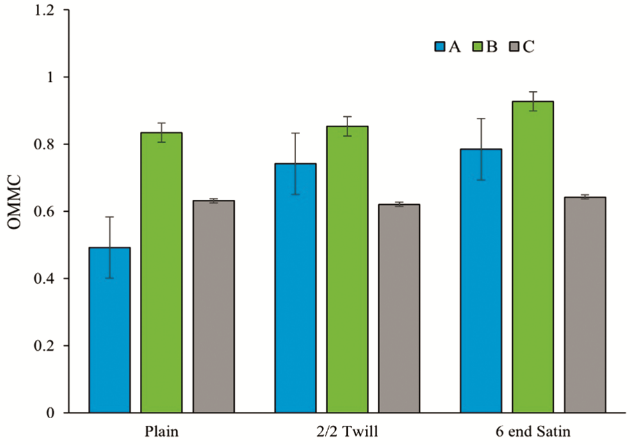

Fig. 1 — Effect of weave design on overall moisture management capacity of cut protective workwear fabric

d) Maximum wetted radius: The furthest radial extent of liquid spread from the point of application (measured separately for top and bottom surfaces).
e) Accumulative one-way transport index: The difference in moisture accumulation between the fabric's top and bottom surfaces.
f) Overall moisture management capacity**:** A comprehensive measure of the fabric's ability to manage liquid moisture.

3 Results and Discussion

3.1 Physical Properties

The physical attributes of each sample are demonstrated in Table 2. The 6-end satin weave shows the maximum fabric thickness due to its low interlacing frequency and increased yarn spacing compared to other weave designs. The increased thickness value contributes to leading the lower bulk density. The lower value of bulk density indicates higher porosity, as shown in Table 2 due to a smaller air gap between the binding points in the clothing structure. Porosity is key in clothing's moisture management, influencing breathability and comfort. Highly porous fabrics facilitate airflow and moisture transfer, keeping the wearer cool and dry. Effective porosity is essential for enhancing the performance and comfort of protective gear, especially in changing temperature and humidity conditions. The cut protection level improves with higher areal density due to the higher strength of tight clothing construction. 6-end Satin is characterized by long floats and fewer interlacings, leading to higher thickness and porosity. The increased yarn mobility and the ability to redistribute force during cutting likely contribute to the higher cut resistance (Level C). On the other hand, plain and 2/2 twill are characterized by tight, interlaced yarns, resulting in higher bulk density and lower porosity. However, the high degree of interlacing may limit the yarns' ability to move and absorb energy, resulting in lower cut resistance (Level B).

3.2 Moisture Management Properties

3.2.1 Overall Moisture Management Capacity (OMMC)

Figure 1 shows the OMMC, which combines the absorption rate, the one-way liquid transport index, and the liquid spreading speed. All fabrics fall within the range of fair to extremely good when rated based on the grading scale[33].

An enhanced ability to manage moisture generally indicates an improved fabric's overall moisture-transfer performance. The plain weave exhibits the lowest OMMC value due to its higher bulk density and lower porosity, which affects its moisture transfer properties. Table 3 provides a categorisation of manufactured textiles to directly evaluate the overall moisture-management qualities of the fabrics. The results indicate that all fabrics are suitable for apparel applications, with 6 end satin demonstrating the highest efficiency in

Table 3 — Grading specifications of Moisture management properties

Parameter	Grade				
OMMC	1	2	3	4	5
	0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	>0.8
	Very poor	Poor	Good	Very good	Excellent

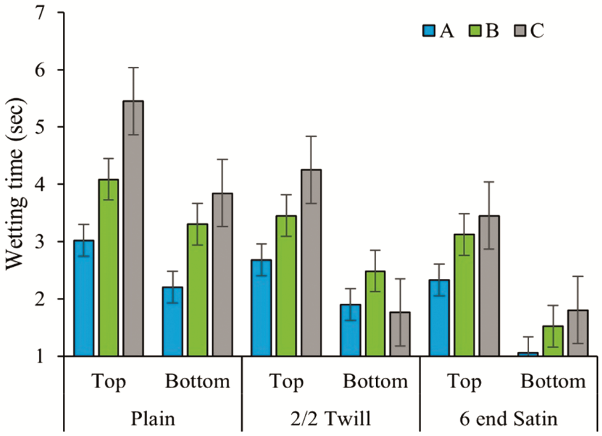

Fig. 2 — Effect of weave design on wetting time of cut protective workwear fabric

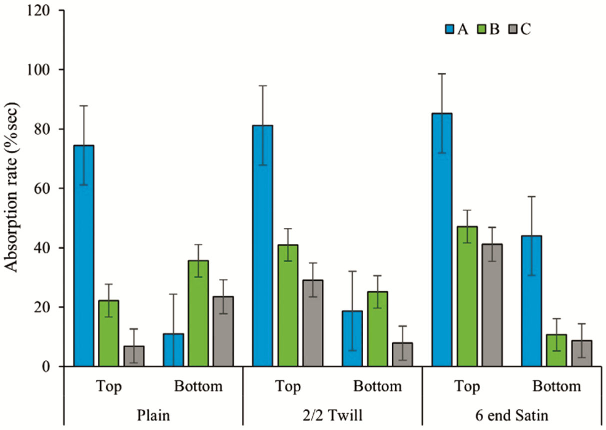

Fig. 3 — Effect of weave design on the absorption rate of cut protective workwear fabric.

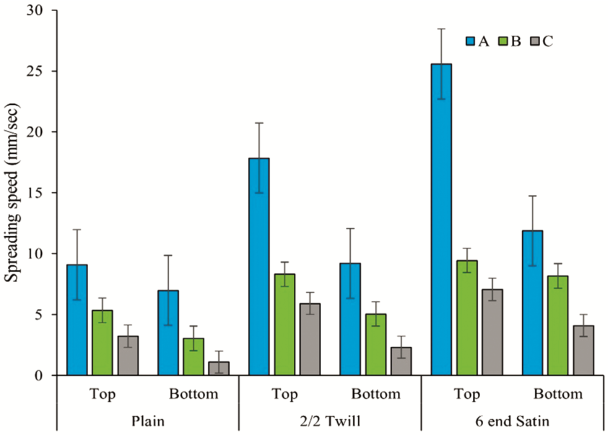

Fig. 4 — Effect of weave design on the spreading speed of cut protective workwear fabric

moisture control. The increased surface contact area in the 6 end satin weave facilitates better moisture movement from the fabric's underside. Additionally, fabrics composed of stainless steel/UHMWPE/polyester fibres perform best across all weave structures due to polyester's superior wicking properties.

3.2.2 Wetting Time

Figure 2 presents the wetting time for the top and bottom surfaces of the fabric samples, seconds after the test begins. The results indicate a clear difference in wetting times between the two surfaces, attributed to the time required for moisture to pass through the fabric's thickness. Samples woven with 6-end satin exhibit shorter bottom wetting times than 1/1 plain and 2/2 twill weave designs. This is because the 6-end satin weave has more float lengths of warp yarn. A strong correlation exists between a fabric's absorbency level and wetting time, with shorter bottom wetting times suggesting superior moisture control.

3.2.3 Absorption Rate

Figure 3 illustrates the impact of weave design on the absorption rate. Typically, a fabric's bottom surface absorbs more energy than its top surface.

This occurs because a significant portion of the liquid disperses or settles at the bottom. Absorption capacity depends on structural openness, yarn structure, fibre composition, and weave design. The findings indicate that fibre composition is a key determinant of absorption rate. Fabrics woven with stainless steel/modacrylic/para-aramid fibres exhibit higher absorption rates due to modacrylic fibres superior moisture retention properties. Structurally, absorption rates follow the trend: 6-end Satin > 2/2 Twill > Plain, primarily due to differences in weave pattern, bulk density, and fabric thickness.

3.2.4 Spreading Speed

The spreading speed of moisture within a fabric depends on capillary action and evaporation behavior. As shown in Fig. 4, moisture spreads faster on the top

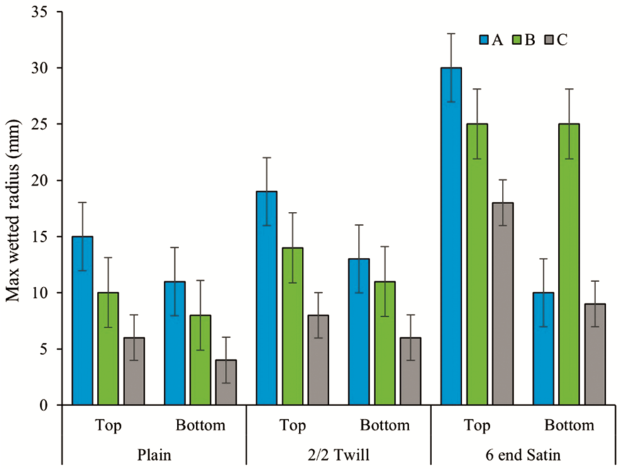

Fig. 5 — Effect of weave design on the maximum wetted radius of cut protective workwear fabric

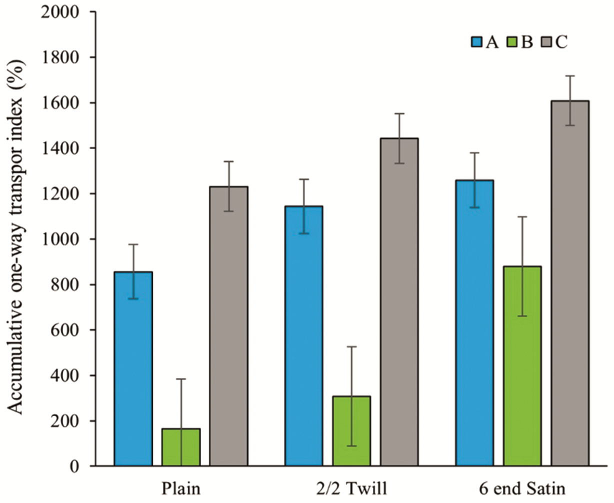

Fig. 6 — Effect of weave design on the accumulative one-way transport index of cut protective workwear fabric

surface, where liquid is applied, than on the bottom surface.

Among all weaves, 6-end satin exhibits the highest spreading speed, which is attributed to its low liquid retention capacity and more floating length of yarn, allowing for trans-planar movement. Additionally, this indicates that the fabric samples spread more quickly, and materials with faster top spreading speeds are thought to have superior liquid moisture management characteristics. The inter- and intra-fibre alignment and the yarn thickness also contribute to the spreading speed[34]. In contrast, plain and 2/2 twill woven fabrics exhibit slower spreading speeds due to their higher fabric bulk density and compact structure, which decreases the water's ability to move through the intra-yarn space.

3.2.5 Maximum Wetted Radius

Figure 5 presents the maximum wetted radius (MWR), measuring the extent of moisture spread across the fabric's surface.

The fabric's efficacy in transferring the liquid across its surface is shown by the multidirectional radiation of the input liquid. Regarding the absorption rate, the liquid began to flow in the direction of its force; most of it settled on the fabric's surface rather than being absorbed. The maximum wetted radius is achieved when it is conveyed[35]. The results indicate that plain and 2/2 twill weaves achieve greater wetted radii than 6-end satin weaves, as the former allows more moisture penetration into the fabric structure. The 6-end satin weave has fewer crossover points and longer float lengths, leading to increased liquid transport across the surface rather than absorption into the structure. Additionally, higher fabric bulk density correlates with a lower maximum wetted radius.

3.2.6 Accumulative One-Way Transport Index (AOTI)

The AOTI measures the difference in moisture accumulation between the top and bottom fabric surfaces.

The accumulative one-way transport index illustrates the movement of liquid from the fabric's top surface to its bottom. An AOTI value between 200 and 400 indicates excellent one-way moisture transport, while values above 400 signify exceptional transport efficiency[36]. The highest AOTI value is observed in the 6-end satin design fabric, attributed to the longer floating yarns (Fig. 6). Conversely, fabrics woven with stainless steel, UHMWPE, and polyester fibres exhibit the lowest AOTI values due to their hydrophobic nature, which limits water molecule bonding on the fibre surface.

4 Conclusion

The study demonstrates that weave design and fibre composition significantly influence the moisture management properties of cut protective workwear fabrics. 6-end satin exhibits the best overall moisture control among the three weave structures, while it facilitates the fastest liquid spreading due to its long warp floats and low retention capacity. Due to their hydrophobic nature, fabrics incorporating stainless steel, UHMWPE, and polyester fibres exhibit lower moisture transport efficiency. The cumulative one-way transport index confirms that 6-end satin achieves the highest moisture transfer rate, making it ideal for applications requiring quick-drying, breathable textiles. These findings provide valuable insights for designing cut-protective workwear with optimized moisture-wicking performance.

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