Indian Journal of Fibre & Textile Research
Vol. 50, March 2025, pp. 62-69
DOI: 10.56042/ijftr.v50i1.5209

Performance investigation of protective clothing against low-pressure steam and molten aluminium

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Received 28 August 2023; revised received and accepted 3 April 2024

This study evaluates the performance of inherent flame-retardant (FR) fabrics under low-pressure steam exposure and characterises their response to hot surfaces, convective and radiant heat, and molten aluminium—one of the most common industrial hazards in India. The investigation compares FR-treated cotton, 100% para-aramid fabric (325 g/m²), and *Savesplash*® fabric (550 g/m²), a blend of FR viscose, para-aramid, and high-shrink PVC fibre. The fabrics are coated with neoprene on one side using the knife roller coating method. Results indicate that *Savesplash*® outperforms 100% para-aramid fabric in convective, radiant and contact heat resistance due to its higher thickness and weight. In the case of molten aluminium, both fabrics demonstrate superior performance when the molten aluminium is poured onto the coated side. However, under low-pressure steam conditions of 3 bar at 120ºC, 100% para-aramid exhibits better resistance than *Savesplash*®. Further research is required to assess aluminised fabrics under higher temperatures, increased steam pressure, and varied molten metal exposures.

Keywords: Molten metal, Neoprene coating, Para-aramid fabric, *Savesplash*®, Thermal hazard

1 Introduction

Steam leakage is a serious threat in various industries, such as oil, gas, steel, power plants, food processing, and garment manufacturing, to name a few. Additionally, sectors such as metal processing, textiles, chemicals, leather, paper, and foundries pose a risk of multiple thermal hazards, including low-pressure steam exposure. When steam penetrates protective clothing, it condenses over the wearer's skin, releasing latent heat, which can cause severe burn injury. The thermal energy transferred through this phase change is a primary factor in steam-related burn injuries. While workwear developed from inherent flame-retardant (FR) fibres offer protection against short flames, contact heat and other bench-scale tests, it fails to safeguard against low-pressure steam exposure up to 5 bar. Consequently, workers in these industries face persistent risks to their safety and well-being[1].

Firefighters are also vulnerable to steam exposure during firefighting operations. Steam may originate from water in hosepipes, environmental moisture such as dew and rain, or even from trapped moisture within protective clothing[2]. The water used for extinguishing fire can convert into steam[3], or pressure pipelines may burst, in the case of structural firefighting[4]. Such conditions can result in fatal and non-fatal injuries such as burns, strain, bruises, and toxic gas inhalation[5]. Although extensive research has been carried out to improve the performance of firefighting suits against flash fire and high-intensity thermal radiation, studies indicate that steam and hot water penetration through protective gear account for 65% of burn injuries in firefighting[6]. Various test rigs have been developed to assess the performance of protective clothing under these conditions[7]. Studies have shown that at high steam pressure, protective clothing compresses, leading to increased heat transfer to the wearer[8]. Further, fabric properties such as thickness, density, air permeability, water resistance, and thermal insulation are critical in determining protective performance[3,9,10].

Another major hazard associated with extreme working environments is molten metal exposure, particularly prevalent in metal processing, mining, construction, welding and foundry industries[11–13].

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Molten metal splashes can cause serious burn injuries to the skin, as commonly used molten metals exceed temperatures of 500ºC. Additionally, the density, temperature and volume of splashed molten metal significantly affect the performance of protective clothing. Also, the fabric surface reactivity varies with the type of molten metal exposure (such as aluminium, copper, steel, iron, zinc, lead, etc.) during splash. Thus, specialised protective clothing is required for different types of molten metal exposures. Initial research focused on wool blends and FR-treatment of cotton, revealing that FR-treated cotton provides protection against iron and steel, whereas wool, FR viscose and their blends offer better protection against aluminium. Recent studies suggest better protection against molten metal for aluminised coating, specialised nanomaterial coatings, and shape memory alloys[14,15].

Although significant advancements have been made in developing protective clothing against molten metal hazards, commercial production of these advanced materials remains complex and challenging, particularly in countries such as India, where dual-mirror-coated aluminium and advanced protective materials are largely imported. This study aims to develop cost-effective inherent flame-retardant (IFR) para-aramid-based blended fabrics with neoprene coating that can be scaled up easily. The efficacy of the developed fabrics was evaluated by exposing them to different thermal hazards, including low-pressure steam, and their performance is compared with each other along with the FR-treated cotton.

2 Materials and Methods

Two types of para-aramid-based samples were developed in-house, whereas FR-treated cotton was supplied by JCT, Phagwara. The 100% para-aramid woven fabric (295 gsm) was developed using Ne 10/2 para-aramid yarns (78.96 cN/tex), which were processed from fibres of 1.7 dtex and 51 mm fibre length. The *Savesplash*® fabric was created from a yarn blend comprising IFR-viscose (1.7 dtex, 51 mm), para-aramid (1.7 dtex, 51 mm), along with innovative FR high-shrink fibres (2.3 dtex, 40 mm) in a 60/25/15 ratio. The high-shrink fibre used in this study was polyvinyl chloride (PVC)-based and imported from Europe. The yarn strength of *Savesplash*® yarn was 11.20 cN/tex.

The 100% para-aramid fabric was weaved on an automated sample rapier loom (CCI Tech Inc.), whereas *Savesplash*® fabric was knitted on an interlock circular knitting machine (GG 18) and dyed black to hide dirt. The dyeing and finishing process increased its gsm to 520 because of the shrinkage of PVC fibre. Both fabrics, including FR-treated cotton, were coated with 30 gsm of neoprene using knife roller coating on one side. The developed fabrics and their specifications are shown in Fig. 1 and Table 1, respectively. The fabrics were subsequently tested for their physical properties and thermal performances. Before testing, fabric samples were conditioned for 24 h at 20 ± 2ºC and 65 ± 2% relative humidity.

The performance of the fabrics was analysed as per ISO 11612:2015, with tests such as thermal shrinkage, tensile strength, and tear strength, along with exposure to various thermal hazards. The fabrics were washed five times as per ISO 6330:2021 before testing. Thermal performance was examined against

Fig. 1 — Neoprene-coated fabrics (a) FR-treated cotton, (b) 100% para-aramid fabric, and (c) Savesplash®

Table 1 — Fabrics characteristics

Fabric	Type	Areal density g/m^2	Thickness mm	Thermal conductivity W/mK
FR-treated cotton	Woven (EPI/PPI) and coated	374	0.547	68.9
100% para-aramid	Woven (EPI/PPI: 70/42) and coated	325	0.77	45.1
Savesplash®	Knitted (CPI/WPI: 42/32) and coated	550	1.13	56.7

*EPI: Ends per inch, PPI: Picks per inch, CPI: Courses per inch and WPI: Wales per inch flame spread, contact heat, convective heat, radiant heat, molten metal and steam exposure.

As there is no standard for testing against low-pressure steam, samples were physically examined, and temperature rise was reported at 3 bar and 120 ºC steam exposure.

The basic fabric properties such as areal density (GSM), thickness and thermal conductivity were measured in accordance with ASTM D 3776:2009, ASTM D 1777:1996 and EN 31092:1993, respectively. Durability assessments were conducted by evaluating their tensile and tear strength per ISO 13934-1:2013 and ISO 13937-2:2000. Residual tensile strength was also evaluated after molten metal exposure.

For flame-spread testing, fabric samples underwent a limiting oxygen index (LOI) test as per ISO 4589-1:2017 to assess oxygen requirements before and after coating. The flame spread test was conducted as per ISO 15025:2016 on a T419 Protective Clothing Flame Spread Tester, with a horizontal flame length of 25 ± 2 mm and a vertical flame length of 40 ± 2 mm. Surface and bottom edge ignition tests were conducted for 10 s, with burner flame oriented at 90º and 30º from the vertical, respectively.

Contact heat transmission testing was conducted on a T424 Contact Heat Transmission Testing Machine in accordance with ISO 12127-1:2015. Samples were placed in contact with a heated cylinder at 250 ºC, and threshold time was evaluated by measuring the increase in temperature of the sample by 10 ºC.

Heat Transfer Index (HTI) was measured as per ISO 9151:2016, determining the mean time for a temperature rise of 24 ± 0.2 °C. Samples were placed horizontally on a specimen holder and exposed to the heat flux of 80 ± 2 kW/m^2.

Radiant heat exposure performance was evaluated as per ISO 6942:2022, with samples subjected to a heat flux of 20 kW/m^2. The time required to raise the temperature by 24 ºC (Radiant Heat Transfer Index ($RHTI_{24}$)) and time needed to raise the temperature by 12 ºC ($RHTI_{12}$) in the test specimen were determined during the exposure, and the heat transmission factor (TF) was calculated using Eqs. 1 & 2:

$$Qc = \frac{(m c_p 12)}{(t_{24} - t_{12})} \quad ...(1)$$

$$TF = \frac{Q_c}{Q_0} \quad ...(2)$$

where m, c_p is mass and specific heat of copper; ($12/t_{24}$-t_{12}), mean rate of rise in temperature of copper calorimeter after exposure in the region of 12 ºC and 24 ºC rise; Q_c and Q_o represent transmitted and incident heat flux densities, respectively.

Molten metal exposure testing followed as per ISO 9185:2007, with 100 g of molten aluminium poured onto a sample positioned at an angle of 60±1º from the horizontal (Fig. 2). A PVC sheet behind the sample acted as a PVC sensor film to assess damage. The change in visual appearance of the PVC sheet and adherence of molten metal to the samples was noted.

Additionally, microstructural analysis before and after exposure was conducted using an optical microscope (LEIKA DM 2700 P:2018). The severity and characteristics of fabric impairment were assessed by considering two classifications: the amount of charring to the fabric and damage to the PVC sensor film. Fabric impairment was graded using a subjective charring scale (Table 2). The fabric performance against molten aluminium splash was determined by the extent of damage to the PVC sensor film.

There is no specific standard for conducting steam heat transfer tests on protective clothing[10]. A test rig was fabricated at HPT Pvt. Ltd. (Panipat, India) (Fig. 3). Steam at 3 bar and 120 ºC was applied from a 50 mm distance, with a counter force of 3.5 N securing the

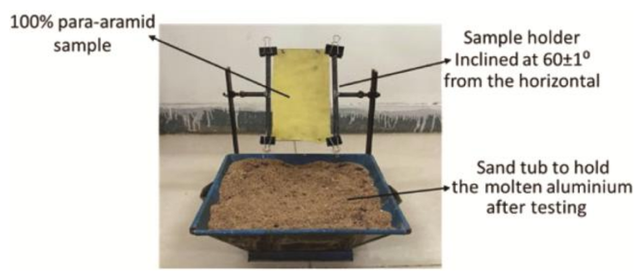

Fig. 2 — Molten metal testing: sample test frame

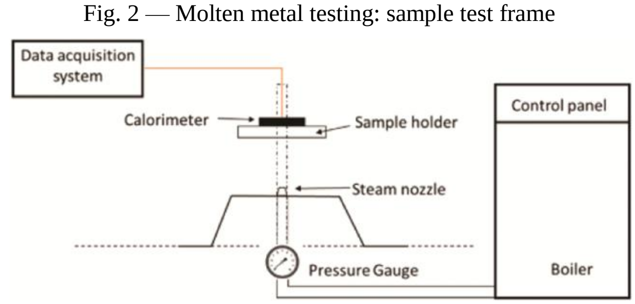

Fig. 3 — Test rig for steam testing

Table 2 — Subjective grading system to evaluate fabric damage[16]

0 = No discoloration
1 = Slight scorching (small, light brown areas)
2 = Slight charring (predominantly brown areas)
3 = Moderate charring (predominantly black areas)
4 = Charred (black, brittle and cracking)
5 = Severe charring (severely brittle with large holes or cracks)

sample. The performance of the sample was evaluated by determining the steam heat transfer index (SHTI 24), which is the time required to increase the sample temperature by 24 ºC under steam exposure[4].

Flexibility testing was conducted in accordance with ASTM D 1388:2018 on Shirley Stiffness Tester using the cantilever method to determine bending length and flexural rigidity. Flexural rigidity was calculated using the following eq.:

$$G\ (\mu\text{Joule/m}) = 1.421 \times 10^{-5} \times \text{GSM} \times (\text{bending length})^3 \quad \ldots(3)$$

3 Results and Discussion

The durability of the evaluated fabrics is reported in Table 3. The tensile and tear strength of the woven fabrics are more than the knitted fabric, *Savesplash*®, which aligns with the yarn strength results in section 2. The elongation at break, however, is more in *Savesplash*®, which is attributable to its knitted structure.

Para-aramid blended fabrics are commonly used in India for protection against thermal hazards due to their inherent flame-retardant properties arising from their aromatic structure and low hydrogen content. This study evaluates a uniquely designed single-sided neoprene-coated para-aramid fabric and para-aramid/FR viscose/high-shrink IFR fibre blended fabrics for various thermal hazards. Subsequent work assesses temperature increases, particularly in response to molten metal exposure and low-pressure steam.

FR viscose fibres are produced by incorporating FR additives into the cellulose solution before extrusion, ensuring inherent flame retardancy. Including FR viscose in para or meta-aramid blends enhances moisture management while reducing costs. Table 4 presents the results of different thermal exposure tests, with molten aluminium resistance discussed in Section 3.5, along with fabric flexural rigidity.

3.1 LOI and Flame Spread Test

After five wash cycles, the LOI of the coated cotton sample is 20, whereas normal cotton LOI varies from 16 to 18[17]. The LOI values of the para-aramid and *Savesplash*® fabrics before and after coating remain consistent at 34 & 33 and 33 & 33, respectively. After the LOI test, fabric samples were exposed to the flame spread test. Continuous burning is observed in the FR-treated cotton sample (coated and non-coated sides) for both the surface and edge ignition flame spread tests, indicating the loss of FR properties after five washes. In contrast, para-aramid and *Savesplash*® samples, developed by inherent flame retardant fibres, exhibit no after-flame or after-glow. This behaviour may be attributed to the presence of IFR fibres such as para-aramid[18,19], FR viscose and high shrink fibres with LOI values greater than 29[20]. In addition, the polymerisation of phosphoric acid in FR viscose enhances *Savesplash*®'s flame resistance[21].

The softness and flexibility of the FR viscose blend in *Savesplash*® contrast with the stiffness of the 100% para-aramid fabric, which is stiff and harsh. When tested on the coated side, the flame resistance remains constant. No dripping of the neoprene coating is observed, likely due to the very fine coating of 30 g/m². Moreover, neoprene is already being used in the automotive industry where high temperature is involved[22]. The fascinating properties such as chemical resistance, strength and light weight add additional benefits to the newly developed *Savesplash*® and para-aramid fabrics.

Table 3 — Tensile and tear test results of samples

Fabric	Tensile strength, N				Tear strength, N	
	Warp/courses	Elongation at break %	Weft/wale	Elongation at break, %	Warp/course	Weft/ wale
FR-treated cotton	1449	17.11	4281	12.14	57.7	26.3
100% para-aramid	3010	22.64	4031	25.73	267	397
Savesplash®	566.4	279.1	282.5	119.1	44.8	23.9

Table 4 — Thermal performance of developed fabrics

Fabric	Flame spread test		Contact heat T_t, s	Convective heat TI_{24}, s	$RHTI_{24}$ s	$SHTI_{24}$ s
	After flame, s	After glow, s				
FR-treated cotton	60*	8	NA	NA	NA	NA
100% para-aramid	0	0	6.2	13	59	51
Savesplash®	0	0	6.8	20	73	69

*Continuous burning observed at the sample edge

3.2 Contact Heat Transmission Test

Due to the failure of FR-treated cotton fabric in the vertical flame spread test, it has not been tested for other thermal hazards such as contact, convective, and radiant heat transmission tests. However, molten metal exposure is tested to compare it with other fabrics. The FR-treated cotton fabric is being used in the molten metal industry at a large scale, but it may lose its FR property after multiple washes or prolonged usage.

Savesplash® exhibits a higher threshold time than 100% para-aramid fabrics when tested in accordance with ISO 12127-1:2015. Despite its lower para-aramid content and higher thermal conductivity, its superior performance is attributed to its greater GSM and thickness. Additionally, the inclusion of high shrink fibre in *Savesplash*® results in pre-shrinkage of knitted fabric before final garmenting, further reducing heat transmission. Previous studies suggest that blending FR viscose in aramid makes fabric comfortable and improves physiological performance[23].

3.3 Convective Heat Transmission Test

Savesplash® performs better than 100% para-aramid fabric in convective heat transmission. The HTI_{24} rise for *Savesplash*® was 20 s, compared to 13 s for 100% para-aramid (Table 4). Further, in context of *Savesplash*®, the FR viscose/aramid blend fabrics maintained the structural integrity, which is essential to prevent the hot fabric from coming in contact with the skin of the end user and causing burns and to prevent exposure of the skin during shrinkage. Further, any shrinkage in fabric could cause seams in the garment to break open during fire[23].

3.4 Radiant Heat Transmission Test

The $RHTI_{24}$ for *Savesplash*® is 73 s, whereas 100% para-aramid fabric is 59 s. Fabric thickness and weight significantly influence heat transmission performance. The heat transmission factor (TF) was 0.11 for *Savesplash*® and 0.13 for the 100% para-aramid fabric. A lower TF value indicates superior performance. Figure 4 (a) and (b) illustrate the impact of weight (areal density) and thickness on heat transmission during different tests, respectively. The fabrics were rated in accordance with ISO 11612:2015, as given in Table 5.

3.4.1 Resistance against Steam Exposure

Steam protection depends on mass and heat transfer characteristics. Research indicates that impermeable fabrics offer better resistance to hot water and pressurised steam, aligning with Darcy's law[3]

This concept is applied in developing 100% para-aramid and *Savesplash*® fabrics, which feature a fine neoprene coating. The coated samples perform well because they restrict the mass transfer, thereby improving thermal performance. However, unlike contact, convective, and radiant heat transmission tests, 100% para-aramid fabric performs better than

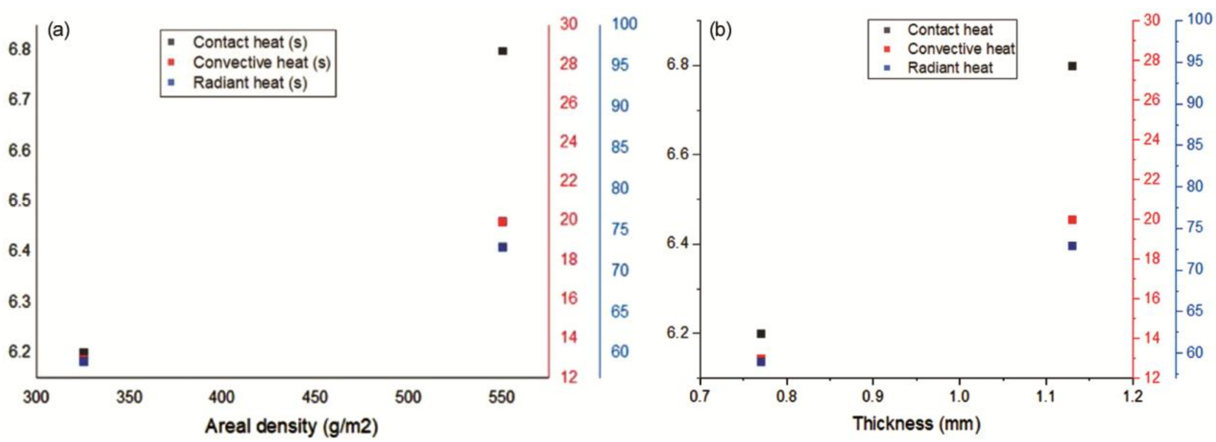

Fig. 4 — Variation in performance time (s) of protective clothing with respect to (a) weight, and (b) thickness

Table 5 — Thermal performance of developed fabrics

Fabric	Flame spread test	Convective heat transmission HTI_{24}, s	Radiant heat transmission $RHTI_{24}$, s	Resistance against molten metal*	Contact heat transmission T_t, s
100% para-aramid	A1, A2	B2	C3	D1	F1
Savesplash®	A1, A2	B2	C3	D1	F1

Savesplash® in steam exposure resistance, which could be due to the tightly woven structure[24], making it less porous than the knitted fabric (*Savesplash®*).

[*]Samples passed this test while testing the coating side of fabric

3.5 Resistance against Molten Metal

Molten aluminium resistance testing (ISO 9185) is conducted using 100 g of molten aluminium at 780 ± 20ºC. When tested on the fabric side, molten aluminium adheres to all fabrics, causing damage to the PVC sensor film (Fig. 5).

For all samples, damage to the PVC sensor film is observed at locations where molten aluminium adhered to the fabric. The location on fabrics where molten aluminium slipped off after the exposure, no damage is observed, either for the fabric or the PVC sensor film. Similarly, when tested on the neoprene-coated side, no visible damage is observed either on the coated fabrics or the PVC sensor film (Fig. 6), as molten aluminium slips off the coated surface, resulting in insufficient time to raise the temperature of the PVC sensor film in all the fabrics.

Interestingly, the coated side of the cotton fabric also performed well. However, the fabric may fail against molten metal exposure just as it failed the flame spread test after prolonged fabric usage. Subjective analysis (Table 6) confirms that all coated fabrics effectively prevent molten metal adhesion. The surface morphologies before and after exposure to molten aluminium (coated side) are shown in Fig. 7. The adherence of the molten aluminium is not observed on the coated side through the naked eye, but microscale aluminium particles are observed under an optical microscope. Charring is observed with a blackish appearance (red circles) in different samples (Fig. 7).

3.6 Fabric Stiffness

Flexural rigidity tests show higher stiffness in the coated fabrics than in the non-coated fabrics (Table 7). The 100% para-aramid fabric exhibits the highest flexural rigidity, reducing flexibility compared to *Savesplash®* and FR-treated cotton.

Table 6 — Subjective analysis of samples

Sample	Fabric side	Coating side
FR-treated cotton	4	0
100% para-aramid	3	0
Savesplash®	2	0

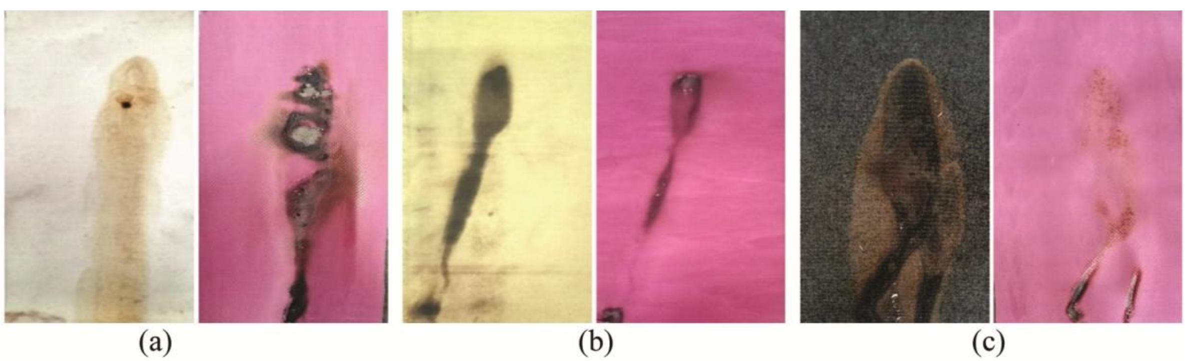

Fig. 5 — Effect of molten aluminium on fabric side (a) FR-treated cotton and damage of PVC sensor film, (b) 100% para-aramid and damage of PVC sensor film, and (c) Savesplash® and damage of PVC sensor film

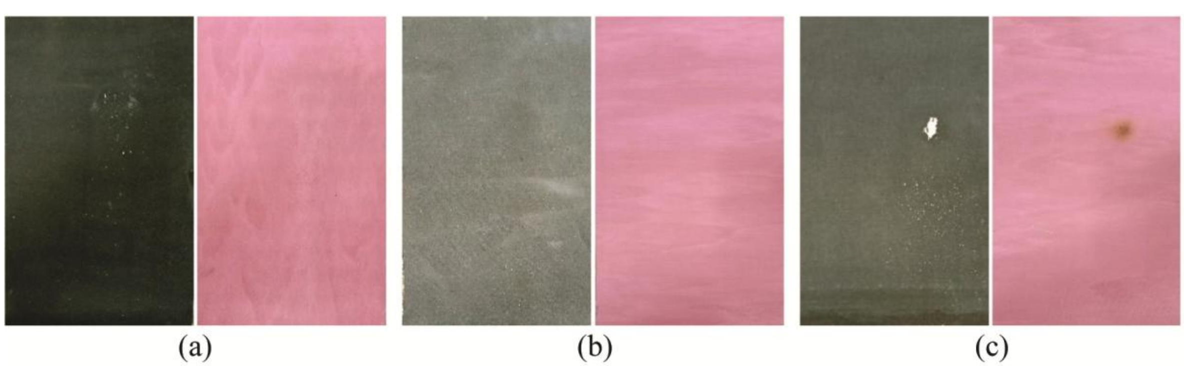

Fig. 6 — Effect of molten aluminium on neoprene-coated side of fabric (a) FR-treated cotton and damage of PVC sensor film, (b) 100% para-aramid and damage of PVC sensor film, and (c) Savesplash® and damage of PVC sensor film

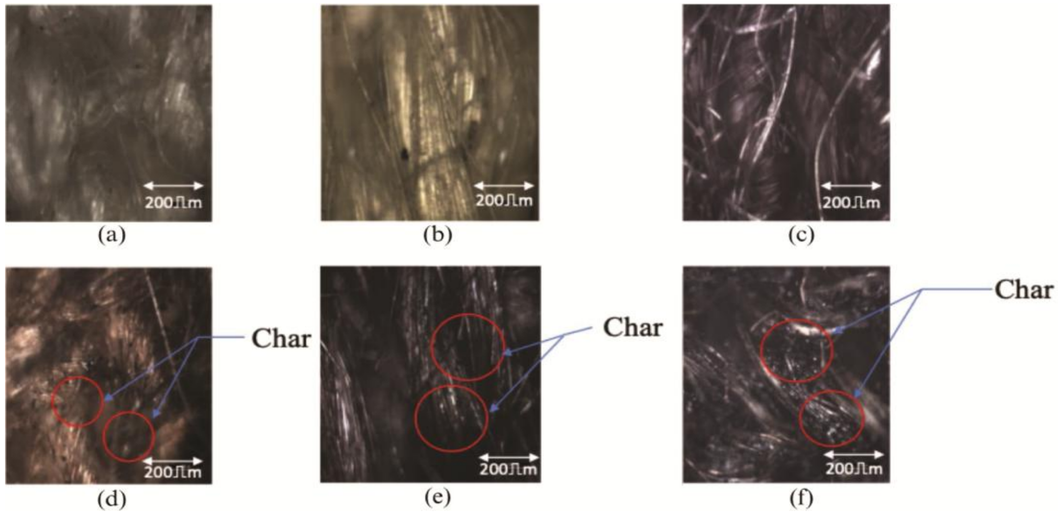

Fig. 7 — Surface morphology of coating before molten metal splash (a) FR-treated cotton, (b) 100% para-aramid, (c) Savesplash®; and after molten metal exposure (d) FR-treated cotton, (e) 100% para-aramid, and (f) Savesplash®

Table 7 — Fabric stiffness test

Samples	Flexural rigidity, µJoule/m	
	Coated side	Non-coated side
FR-treated cotton	9461.11	3546.78
100% para-aramid	10621.82	3835.84
Savesplash®	1688.14	1163.54

Higher flexural rigidity indicates reduced fabric flexibility, which is crucial in garment comfort considerations.

Conclusion

This study evaluates the durability, thermal resistance, and mechanical properties of para-aramid and *Savesplash®* fabrics, demonstrating their potential for protective applications. The findings indicate that thin single-sided coated fabrics provide effective protection against low-pressure steam and molten aluminium exposure, provided that the coated side faces the molten metal. *Savesplash®* consistently outperformed 100% para-aramid fabric in key thermal tests, including contact heat transmission, convective heat transmission, and radiant heat transmission, due to its high GSM, structural integrity, and FR viscose content. However, FR-treated cotton may lose its flame-retardant properties after multiple washes or prolonged use, although its coated side performs satisfactorily under molten metal exposure. The performance of the fabrics against steam exposure is influenced by both mass and heat transfer, with 100% para-aramid fabric demonstrating superior resistance due to its tightly woven structure. Additionally, the thickness and weight of fabrics positively impact their resistance to various thermal hazards. The comparable performance of inherent flame-retardant fabrics—100% para-aramid and *Savesplash®*—in flame spread, convective, radiant, and contact heat transmission tests suggests that *Savesplash®*, with its higher GSM and thickness, offers an advantageous alternative. Moreover, the lower para-aramid content in *Savesplash®* results in a lower cost per meter, making it commercially viable. Further studies evaluating the performance of single-side coated fabrics upon exposure to different molten metals, such as iron, brass, etc., can be considered. Moreover, the developed fabrics can be aluminised on the fabric side for further performance enhancement.

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