



Development of molten metal splash-resistant clothing for foundry workers using sustainable jute-based textile materials^a

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In this study, ten clothing samples (seven 100% jute and three jute-cotton union) with different weaves have been prepared and then treated with durable organo-phosphorous-based flame-retardant (FR) finishing. The DSC study carried out on untreated and FR-treated jute-cotton union fabric shows a lower thermal decomposition temperature in FR-treated fabric. The TGA study also reveals a higher residue remaining at 400°C of FR-treated fabric. The FR-treated fabric samples are studied for their molten metal splash resistance (iron and aluminium metals) after 5 wash cycles. All three samples qualify for the minimum protection level of E1 for molten metal splash iron. The study shows that twill weave fabric provides better protection for molten metal splash iron as compared to other weaves. In the case of the molten metal splash (aluminium) test, only jute-cotton union fabric samples pass the D1 level. These FR-treated samples also pass the minimum criteria of limited flame spread, convective and radiant heat transmissions.

Keywords: Contact heat, Convective heat, Jute fabric, Molten metal splash, Radiant heat, Jute-cotton union fabric

1 Introduction

Fire hazards are one of the most life-threatening hazards. The textile material acts as fuel during a fire accident. It is a well-known fact that the majority of fire accidents occur due to these textiles. To protect from fire hazards, clothing made from inherent flame retardant (FR) fibres or FR chemical-treated fabric is used. FR finish can react chemically with the fibre's molecular structure, or it can cross-link at the surface of the fibre or self-polymerize. An FR finish tends to retard the development of fire/combustion during material pyrolysis or decomposition, heating, flame propagation, and ignition. FR chemical-treated fabrics are mostly not durable, and their FR property decreases with repeated washing. On the other hand, inherent FR fibres, like aramids, FR-viscose, modacrylic, etc., are durable in FR properties. Further, fabrics produced using modacrylic, only FR viscose, Nylon 66 fibres, and their blends, show that flame and thermal resistant properties are influenced by fibre blending ratio¹.

Protection against molten metal exposure is essential for foundry workers. Generally, there are three kinds of molten metal exposures in these industries: welding droplets, poured molten metal, and molten metal

splashes from an electric arc. Such industries create immense hot environments, causing discomfort and leading to losing attention in short-term exposure or heat stress hazards in long-term exposure. Distinct fabrics are exploited in industrial work wear, ranging from cotton to special fibres such as modacrylic, leather, wool, aramid, including aluminized fabrics, etc for protection against molten iron. Barker and Yener² worked on protective clothing material for workers to protect them from molten iron splash hazards. They concluded that molten iron resistance property of fabric relies upon fabric thickness, air permeability, weight and flammability properties. One of the studies reported the protection properties of Zirpro-treated FR wool along with other protective clothing materials against aluminium splashes and convective/radiant heat³.

While cotton, polyester, aramid, and modacrylic-based fabrics are commonly used for molten metal splash-resistant work wear, many of these fibres are not sustainable. After cotton, jute is the second plant fibre, used in the textile abundantly in the world. Jute is a renewable resource that can be grown without fertilizers and pesticides, making it a more sustainable alternative to cotton and synthetic fabrics⁴. Jute fabric also has a low carbon footprint, as its production requires less energy and resources than synthetic fabrics. This fibre is eco-friendly. The life cycle assessment (LCA) and energy analysis also reflect their eco-computability and economic sustainability⁵.

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The untreated jute fabric has 20.5 % Limiting Oxygen Index (LOI) value as compared to cotton (18.4%)⁶. This LOI value indicates that jute is a flammable fibre and requires treatment with FR chemicals to become flame retardant. Phosphorous-based compounds have been proven to be effective FRs. It has been reported that FR efficiency can be improved by adding nitrogenous compounds, especially with reduced phosphorous quantities in the P-N system. Despite this, little research has focused on developing molten metal splash-resistant jute-cotton union fabrics. In this work, various jute-cotton union fabrics with different weave structures are developed and finished with a durable FR finish. These samples are studied for molten metal splash resistance, FR and other comfort properties.

2 Materials and Methods

For the development of jute-cotton union fabrics, singly-ply jute yarn of 4.8 lbs (3.6 Ne approximately) was used as weft, and this yarn was purchased from M/s Birla Jute Corporation Ltd., West Bengal, India. The cotton yarn of 4.55 (2 ply) used in warp, is sourced locally. The properties of both yarns are shown in Table 1. During weaving, cotton yarn as warp and jute yarn as weft were used. In all cases, the warping of cotton yarn was carried out on the CCI sample warping machine (model no SUU 550). Three types of woven fabrics, plain coded as JC1, 2/2 twill coded as JC2, and mock leno coded as JC3, weaves were manufactured on CCI sample rapier loom (model no SL 8900 EG).

Seven 100% jute fabric samples (coded as 100J1 to 100J7) were procured from the market. Out of seven samples, four samples were plain weaves, and the remaining three had twill weaves. These samples were desized, scoured, bleached and tested for various properties Table 2. The areal density (GSM) of these samples was in the range of 357-550.

Laboratory-grade sodium hydroxide, hydrogen peroxide and acetic acid were used for scouring and bleaching. These treated fabric samples were dyed using vat dyes. For FR finishing purposes, Pyrovatex CP New (based on N-alkyl phosphopropionamide), cross linking agent Knittex CHN (melamine resin) and Invadine PBN (a surfactant) supplied by Huntsman International India Pvt Ltd were used. Cross-linking agents like Knittex CHN (melamine resin) provide effective crosslinking¹ between Pyrovatex CP New and cellulose-based material. The phosphoric acid (86% strength) was used as a catalyst during FR treatment and sourced from the local market.

2.1 Application of FR Finishing

All the samples were scoured and bleached in a single bath before FR finishing. The scouring and bleaching were carried out in the Laboratory Jigger machine after desizing. For this purpose, 0.5% of wetting agent based on the weight of fabric (owf), 3% owf hydrogen peroxide, 3.5% owf caustic soda, 2% owf sodium carbonate, and 0.5% owf sodium silicate were used. The temperature was set at 98°C. The total time at boil was 90 min.

Table 1 — Properties of jute and cotton yarns

Parameter	Jute yarn	Cotton yarn	Test standard
Count, Ne	3.63	4.55 (2 ply)	IS 1315
TPI	3.89	Double yarn: 14.35 Single yarn: 8.17	IS 832-2, IS 832-1
Single yarn strength, gf	1383	1258	IS 1670
Elongation, %	1.49	4.16	IS 1670
Tenacity, g/tex	8.50	9.70	IS 1670
Yarn unevenness, U%	21.98	8.46	ASTM D 1425
Hairiness index (h)	11.04	7.97	UT-5 SA 400
Total imperfections per km [thin (-50) + thick (+50) +neps (+200)]	1906.8	2.5	-

Table 2 — Properties of the desized, scoured and bleached fabrics

Sample code	Composition	Weave	EPI/PPI	Areal density, g/m ²
100J1	100% Jute	Plain (2 threads parallel in warp and weft)	29/11	374
100J2	100% Jute	Plain	19/15	382
100J3	100% Jute	Plain (2 threads parallel in warp and weft)	14/11	357
100J4	100% Jute	3/1 Twill	28/20	400
100J5	100% Jute	2/2 Twill	28/22	474
100J6	100% Jute	Plain	26/17	363
100J7	100% Jute	3/1 Twill	28/21	387
JC1	Cotton-Jute	Plain	32/25	420
JC2	Cotton-Jute	2/2 Twill	32/28	550
JC3	Cotton-Jute	Mockleno	32/30	452

After scouring and bleaching, the fabric was washed in cold water, neutralized with acetic acid and then dyed with vat dyes using a laboratory Continuous Dyeing Range (CDR). The FR finish treatment was imparted on the CDR using the pad-dry-cure method. To optimize the effect of FR finish on the molten metal splash (iron) property of the fabric, the concentration of Pyrovatex CP New was changed from 350 g/L to 500 g/L and Knittex CHN was changed from 50 g/L to 80 g/L. The concentrations of phosphoric acid and Invadine PBN were kept constant at 22 g/L and 10 g/L respectively, in all the studies. The optimization study was carried out on a scoured and bleached sample coded as JC1. The solution was applied to the fabric by adjusting 80% wet pick-up. After applying the recipe using a padder, the fabric was dried at 110 - 120°C for 60 s, followed by curing at 170 - 180°C for 120 s using a laboratory stenter⁷. The cured fabric was washed at 50°C with non-ionic detergent and soda ash, followed by drying at 110°C.

2.2 Mechanical Properties

Fabric mass (areal density) in g/m^2 , tensile strength, and tear strength were evaluated using ISO 3801, ISO 13934-1, and ISO: 13937-2 test methods respectively. As per ISO 11612, the minimum requirement for passing work wear fabric for tensile strength is 300 N minimum in both directions and for tear strength, the passing requirement is 10 N minimum in both directions after 5 wash cycles.

2.3 Colour Fastness Properties

All the fabric samples were dyed using vat dye in a single colour using the same recipe. Dyed fabric samples were tested for colour fastness to washing as per ISO 105 C10 C(3), colour fastness to rubbing as per ISO 105 X12, colour fastness to perspiration as per ISO 105 E0,4 and colour fastness to light as per ISO 105 B02 test methods.

2.4 Evaluation of Thermal Properties

Thermo-gravimetric (TGA) method provides important information about weight loss, thermal stability and thermal decomposition of materials under thermal effect. This method requires a small amount of sample (8 to 10 mg) for analysis. The study⁸ is carried out at a heating rate of 10°C/min using a Thermo-Gravimetric Analyzer (TA Instrument SDT Q600). The samples were subjected to TGA in a high-purity nitrogen environment under a

constant flow rate of 50 mL/min. A pre-programmed temperature range of 30- 800°C was set for carrying out the thermal decomposition of the samples. During the experiments, weight loss and temperature were continuously recorded to determine the thermal degradation rate (% weight loss/min), derivative weight loss and initial degradation temperature.

Differential Scanning Calorimetry (DSC) measures the temperature and heat flow associated with the transition in materials as a function of temperature and time^{9,10}. A DSC Q20 (TA instrument) thermal system using a sealed aluminium capsule was used to conduct the DSC analysis. The sample weighing approximately 7.0–8.5 mg was held at a single heating rate of 10°C/min and scanning temperature from 30°C to 400°C. Heat flow data were recorded based on an average value obtained from three experimental runs. The samples were subjected to DSC in a high-purity nitrogen environment under a constant flow rate of 50 mL/min.

2.5 Performance Properties

The performance properties¹¹⁻¹³, such as limited flame spread test, convective heat, radiant heat, contact heat, and molten metal splash(iron) tests, were evaluated using standard test methods for various mechanical, heat and flame retardant, and comfort properties after giving 5 cycles of wash followed by a tumble dry by ISO 6330-2A as per the requirement of ISO 11612 standard.

In all the experiments, woven fabric samples were tested for radiant, convective and conductive heat resistance as per ISO 6942, ISO 9151 and ISO12127-1 respectively. As per ISO 11612, in the case of radiant heat for performance levels, C1, C2 and C3 the mean radiant heat resistance index (RHTI_{24}) should be 7.0 to <20 s, 20.0 to <50 s, 50.0 to <95.0 s and 95s or above respectively, while for convective heat test, the mean heat transmission index (HTI_{24}) should be 4.0 to <10.0 s for B1 level, 10.0 to <20.0 s for B2 level and 20.0 or above for B3 level. For contact heat tests the performance levels are F1(5.0 to<10.0s), F2(10.0 to<15.0 s) and F3(15.0 s or more).

The molten metal splash test was carried out as per ISO 9185. The method is used to assess the heat penetration resistance of materials intended for use in clothing to protect against large splashes of molten metal. In this method, the fabric sample is tested by pouring quantities of molten metal onto the test specimen supported at an angle to the horizontal on a pin frame. The specimen angle to the horizontal in the

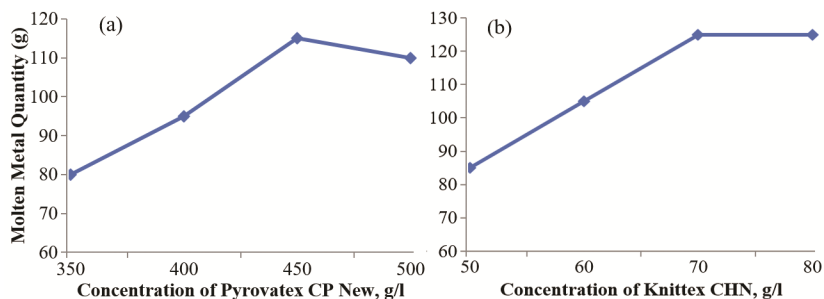


Fig. 1 — (a) Effect of concentrations of Pyrovatex CP New and (b) Knittex CHN on quantity poured molten metal (iron)

case of iron is kept at $75\pm 1^\circ$ and for aluminium, $60\pm 1^\circ$. In both cases, the molten metal pour height is kept at 225 ± 5 mm. The pouring temperature for iron and aluminium was kept at $1400 \pm 20^\circ\text{C}$ and $780 \pm 20^\circ\text{C}$ respectively. Damage is assessed by placing an embossed thermoplastic PVC sensor film (skin) directly behind and in contact with, the test specimen and noting the change in film after pouring. Any adherence of the metal to the test specimen surface is also noted. As per ISO 11612, the performance level for molten metal splash iron is E1= 60g to <120g, E2= 120g to <200g, and E3 \geq 200g. In the case of molten metal splash aluminium, the performance level is D1= 100g to <200g, D2 200g to <350g, and D3 \geq 350 g. In all the cases, the starting amount of molten metal was 50g.

3 Results and Discussion

3.1 Optimization of FR Finish

Pyrovatex CP New and Knittex CHN concentrations are optimized by keeping the concentration of phosphoric acid (22 g/L) and Invadine PBN (10 g/L) constant in all the studies. The scoured, bleached sample coded as JC1 is taken for the optimization study. The finished samples are evaluated for their molten metal splash (iron) properties after 5 wash cycles.

3.1.1 Optimization of Concentration of Pyrovatex CP New

The sample JC1 is finished with different concentrations Pyrovatex CP New with a constant 50 g/L concentration of Knittex CHN [Fig. 1(a)]. It is observed that the fabric finished with a 450 g/L concentration of Pyrovatex CP New provides more protection from molten metal (iron) than other finished samples with lower concentrations (350 g/L and 400 g/L) of Pyrovatex CP New. In the case of fabric finished with 450 g/L concentration of Pyrovatex CP New, the PVC skin does not damage up to 115g of molten iron poured on the PVC skin placed behind the sample JC1. At higher concentrations

Table 3 — Various properties of FR-treated fabric samples

Sample code	Areal density g/m ²	Tensile strength N		Tear strength N	
		Warp	Weft	Warp	Weft
100J1	380	608	735	31	60
100J2	393	622	447	32	25
100J3	368	595	488	33	48
100J4	410	603	661	26	25
100J5	488	696	491	33	28
100J6	374	485	840	22	47
100J7	400	608	553	41	43
JC1	450	848	933	42	72
JC2	580	887	960	45	75
JC3	470	869	954	44	72

(500 g/L), there is not much change in protection from molten metal (iron) observed. Earlier studies have also confirmed that 450 g/L concentration of Pyrovatex CP New provides the best results of the LOI^{14,15}.

3.1.2 Optimization of Concentration of Knittex CHN

The JC1 sample is finished with different concentrations of Knittex CHN with a constant 450 g/L concentration of Pyrovatex CP New [Fig. 1(b)]. The study reveals that the PVC skin remains undamaged up to 125 g of molten iron when the concentration of Knittex CHN is 70 g/L. However, at lower concentrations (50 g/L and 60 g/L), the damage to PVC skin occurs at a lower amount of molten metal. As Knittex CHN is a cross linking agent, if the quantity of this agent is not appropriate relative to the concentration of Pyrovatex CP New, the cross linking is affected. No change is observed on increasing the concentration of Knittex CHN to 80 g/L. Therefore, a concentration of 70 g/L Knittex CHN is used in all the studies.

3.2 Mechanical Properties

All the samples are desized (except JC1, JC2 and JC3), scoured, and bleached using Jigger. All fabric samples are finished with FR finish and tested for tensile strength, tear strength and areal density after 5 wash cycles (Table 3). JC2 exhibits higher tensile

(warp, 887N; weft, 960N) and tear strength (warp, 45.21N; weft, 75.35N) compared to the JC1 and JC3 samples. In JC1 to JC3 samples, the tensile and tear strength of weft-wise are found to be higher than warp-wise. The main reason for higher weft-wise strength is due to the coarser count of jute yarn used in the weft-wise direction. This yarn has more strength than cotton yarn used in the warp direction. The areal density (mass) of the JC2 sample is found to be higher (580 g/m²) than the JC1 and JC3 samples. All samples meet the minimum requirements outlined in ISO 11612 for work wear fabric, with a minimum tensile strength of 300 N and a minimum tear strength of 10 N in both directions after 5 wash cycles.

3.3 Evaluation of Thermal Properties

Only JC1, JC2 and JC3 samples are analysed for differential scanning calorimetric (DSC) and thermal gravimetric analysis (TGA) studies. DSC thermograms for untreated and FR-treated jute-cotton union fabric samples are investigated (Fig. 2). The thermogram of untreated jute-cotton union fabrics (plain, twill, and mockleno weaves) shows two endothermic peaks at 99 to 112°C and 375-386°C and one exothermic peak around 275 to 320°C. The relatively low-temperature endothermic peak at 99-112°C is attributed to the usual evaporation of absorbed moisture from hygroscopic jute-cotton union fabric. A weak broad exotherm over the range of 275-

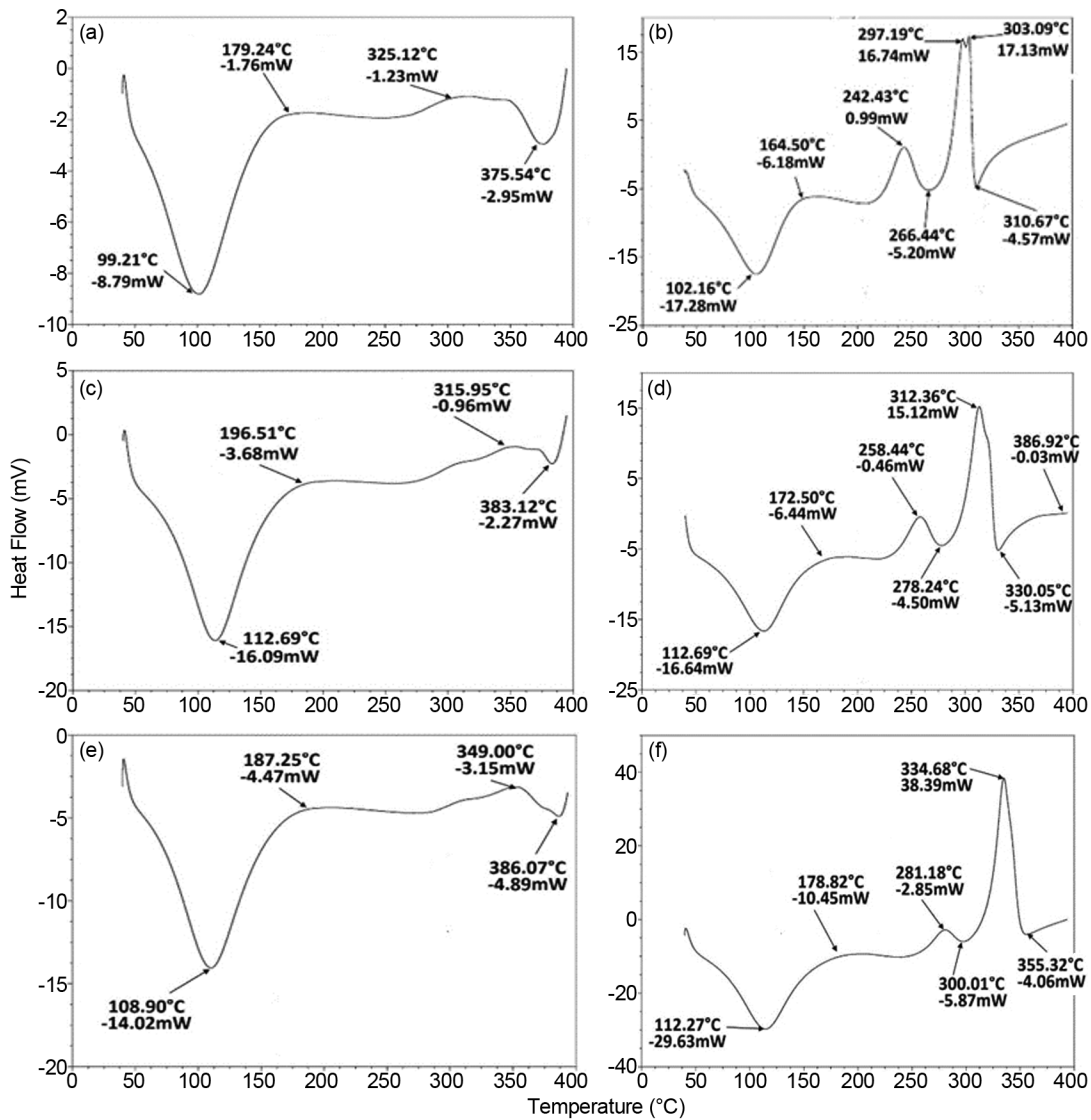


Fig. 2 — DSC thermograms (a) untreated plain jute-cotton union fabric(JC1), (b) FR-treated plain jute-cotton union fabric (JC1), (c) Untreated twill jute-cotton union fabric(JC2), (d) FR-treated twill jute-cotton union fabric(JC2), (e) untreated mockleno jute-cotton union fabric (JC3) and (f) FR treated mockleno jute-cotton union fabric(JC3)

386°C, showing a broader hump, is attributed to the thermal degradation of the hemicellulose fraction of cellulosic fibres. The relatively sharp endotherm showing a sharp endothermic peak at 375-386°C is attributed to the thermal degradation of the major cellulose component of untreated jute-cotton union fabric. This study shows that hemicellulose is least thermal resistant compared to cellulose. On the other hand, FR-treated jute-cotton union fabric samples show three endothermic peaks at 102 - 112°C due to evaporation of absorbed moisture, 310 - 355°C, and 266-299°C and two exothermic peaks at 225-240°C and 297-334°C. All the FR-treated samples show lower heat flow compared to untreated jute-cotton union fabrics. The results demonstrate a lower

thermal decomposition temperature in the case of FR-treated fabric.

TGA is performed in an open platinum sample pan, with measurements conducted in an aerobic atmosphere. Figure 3 shows the TGA curves of jute-cotton union fabrics without the FR treatment (control samples) and FR-treated jute-cotton union fabrics.

The thermal decomposition of the jute-cotton union fabrics occurs in multiple stages. The first stage involves the release of adsorbed water, which begins at around 100°C. The second stage involves fast weight reduction where decarboxylation and dehydration reactions deliver flammable gasses such as ketones, aldehydes, ethers, etc. The third stage, beginning around 500°C, relates to the decomposition

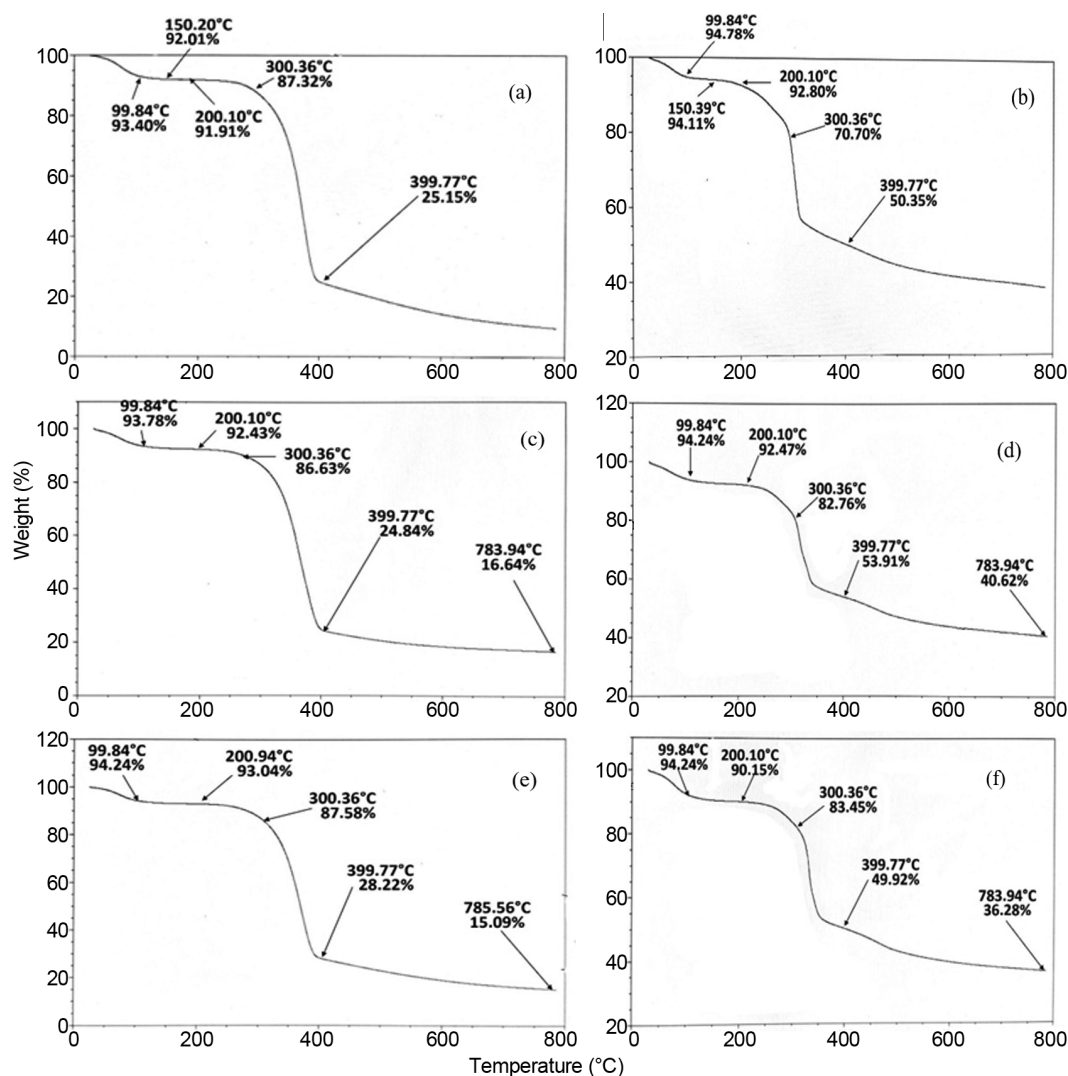


Fig. 3 —Thermogravimetric analysis (a) untreated plain jute-cotton union fabric(JC1), (b) FR-treated plain jute-cotton union fabric (JC1), (c) Untreated twill jute-cotton union fabric(JC2), (d) FR-treated twill jute-cotton union fabric(JC2), (e) untreated mockleno jute-cotton union fabric(JC3) and (f) FR treated mockleno jute-cotton union fabric(JC3)

(conductive heat) test. Other samples, 100J4, JC2 and JC3, meet the requirement of the highest level F3.

3.6 Molten Metal Resistance Tests

Table 5 displays the results of the molten metal splash (iron and aluminium) of all samples. Samples 100J1, 100J2, 100J3 and 100J6 meet the requirements of E1 and samples 100J4, 100J5, 100J7, JC1, and JC3 pass the E2 level of a molten metal splash(iron), while only sample JC2 pass the E3 level. This may be because of the weave and areal density of the fabric samples as higher areal density of fabric provides better protection from molten metal splash (iron). Fabric JC2 has a twill weave, and the areal density is 580 g/m², higher than the others. Only JC1, JC2 and JC3 samples pass the D1 level.

3.7 Colour Fastness Properties

The colour fastness properties of all the samples are the same as these samples are dyed with the same colour. The change in colour and staining on cotton fibre are found to be 4 and 4-5 respectively, in all the samples after washing. The colour fastness to light in all the samples is 4. The colour fastness to rubbing in the dry state is found to be a rating of 4; in the wet state, the rating is 3-4. The colour fastness to perspiration results show a rating 4 for the change in colour and staining on cotton fibre for all the samples for acidic and alkaline media.

4 Conclusion

Sample JC2 (2/2T will weave) possesses higher tensile, tear and areal density than samples JC1 (plain weave), and JC3 (mock leno). The areal density of the JC2 sample is found to be high erthan the JC1 and JC3 samples. Differential scanning calorimetric (DSC) thermo-grams for untreated and FR-treated jute-cotton union fabric samples demonstrate a lower thermal decomposition temperature in the case of FR-treated fabric. TGA study shows higher residue remains at 400°C of FR-treated fabric compared to

untreated jute-cotton fabric samples. Samples 100J1, 100J2, 100J3 and 100J6 meet the requirements of E1 and samples 100J4, 100J5, 100J7, JC1 and JC3 pass the E2 level of a molten metal splash (iron), while only sample JC2 pass the E3 level. Only JC1, JC2 and JC3 samples pass the D1 level. The colour fastness properties such as colour fastness to washing, light, rubbing, and perspiration are found to be satisfactory.

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