Indian Journal of Fibre & Textile Research
Vol. 49, December 2024, pp. 408-415
DOI: 10.56042/ijftr.v49i4.3017

Impact of fire retardant finish on the mechanical and comfort properties of cotton fabric

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Received 21 June 2023; revised received and accepted 26 December 2023

The present study evaluates the hand value of cotton fabric treated with a newly developed fire-retardant (FR) finish with Ammonium Sulfamate and Sodium Stannate with the help of the Kawabata Evaluation System (KES). The analysis reveals that the FR treatment reduces fabric tensile energy (39%) and bending rigidity (13%) while increasing shear stress at 5^0 angle (34%) and coefficient of friction (438%). These changes indicate that the FR treatment makes the fabric stiffer, less capable of withstanding external stress, and rougher in texture, resulting in less comfort to the wearer. Consequently, the FR-treated fabric demonstrates less potential for the tailoring and garment industry.

Keywords: Bending rigidity, Fire-retardant finish, Hand value, Kawabata System, Shear stress

1 Introduction

Comfort is essential for fabrics used in garments, especially undergarments and leisurewear. Cotton, with its inherent properties such as excellent comfort, breathability, texture, hygroscopic nature and good drapeability[1,2], is mainly used for creating comfortable garments. Traditionally, comfort is measured in terms of drape, air permeability, moisture transmission property, and thermal resistance. However, these evaluations often overlook human sensory comfort factors such as tactile sensation, shape retention, multi-directional stretch and thermal response[3,4]. These sensory comfort properties, collectively referred to as “handle” or “hand value of fabric/ garment” or “sensorial comfort”[5], are critical to understanding a fabric's performance. These are broadly divided into four major sub-components – sensorial (tactile), thermal, psychological and body movement comfort[6].

Tactile comfort is a complex sensory phenomenon associated with the shape or size change after the application of low force like shear, tensile, bending, stretching, and shearing, in addition to surface characteristics (friction, smoothness, softness), surface feel (coolness or warm), mechanical sensation during direct touching of fabric etc.[7] Tactile comfort mainly depends on the textile material like fibre composition, yarn characteristic, fabric structure, chemical treatment, finishing etc.[8]

Efforts to objectively measure fabric hand value date back to Peirce's early work in the 1930s, though his definition excluded physical clothing properties. Later, Kawabata developed the Kawabata Evaluation System (KES), an instrumental method used to measure fabric tensile, shearing, bending, compression, and surface attributes[9-15]. Researchers have extensively applied KES to study the effects of fibre blends, finishing treatments, and fabric construction on comfort[16-19]. For instance, KES has been utilized to evaluate the comfort properties of denim made from various cellulose-based regenerated fibres[18]. Although KES for fabric helps interpret results to assess comfort[20-21], it cannot provide the perception of touch.

A preliminary study by the present authors explored the application of Ammonium Sulfamate (AS), Sodium Stannate (SS), and Zinc Acetate (ZA) as fire-retardant (FR) chemicals on cotton fabric[21]. This study revealed that the stiffness of the fabric, as indicated by its bending length, increased after FR treatment. The optimal fire-retardant performance was achieved using 16% AS, 8% SS, and 8% ZA. Building on this earlier work, the present study investigates cotton fabric’s total hand value and low-stress mechanical properties after applying the optimal concentration of a new fire-retardant finish.

2 Materials and Methods

A peroxide-bleached 100% cotton plain-woven lightweight fabric was used as the control fabric. The fabric had the following specifications: EPI

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(Ends/inch) – 72, PPI (Picks/inch) – 50, thickness – 0.82 mm and aerial density– 126.2 g/m^2. The major chemicals used included sodium stannate (Na_2SnO_3, extra pure, analytical grade), ammonium sulfamate ($NH_4SO_3NH_2$, assay – 98.5%, analytical grade), and Zinc Acetate [$Zn(CH_3COO)_2$, analytical grade], all procured from Loba Chemie Pvt. Ltd.

2.1 Test Methods

All untreated (control) and chemically treated 100% cotton fabric samples were conditioned for 48h at temperature $(27 \pm 2)^0$C and relative humidity (65 ± 5) % before testing.

2.1.1 Kawabata Evaluation System for Fabric 1 (KES-FB1)

The KES-FB1 system was used to evaluate low-stress mechanical properties, including tensile, bending, shearing, compression, thickness, and weight[22]. Fabric strips (20 cm x 5 cm) were subjected to unidirectional forces of up to 500 gf/cm under tensile testing mode using the Auto Tensile and Shear Tester (2012). The instrument was allowed to return to its original position with a constant rate of strain after reaching maximum force. The fabric deformation, primarily biaxial, was recorded during stretching and subsequent relaxation. In shear mode, a constant force of 10 gf/cm was applied initially, followed by superimposed traverse shear forces up to a maximum angle of 8º. The shear angle was gradually returned to 0°, and corresponding deformation was measured.

The stress-strain curve or load-extension curve was generated from these experiments, and the extent of the Linearity-extensive curve (LT) was measured. In addition, Tensile Energy (WT) or work done for tensile deformation in J/m^2 and Tensile Resilience (RT) or percentage recovery of energy from tensile deformation could be obtained from the stress/ strain curve. LT (Eq. 1), WT (Eq. 2) and RT (Eq. 3) are calculated using the following equations:

$$LT = \int_0^{Em} F\, dE / 0.5\, Fm.\, Em \quad \ldots(1)$$

$$WT = \int_0^{Em} F\, dE \quad \ldots(2)$$

$$RT = \left(\int_0^{EM} F\, dE / WT\right) \text{X } 100 \quad \ldots(3)$$

where *Em* is the extensibility at 500 gf/cm; and *Fm*, applied force.

Physical parameters in the shear test are calculated by following equations:

Shear stiffness/ rigidity (G) = Avg. slope of shear hysteresis between $\phi = 0.5^o$ and 5^o …(4)

2HG = Hysteresis at $\phi = 0.5^o$ …(5)

2HG5= Hysteresis at $\phi = 5^o$ …(6)

2.1.2 Kawabata Evaluation System for Fabric 2 (KES-FB2)

The bending behaviour of fabric was analyzed using the Bending Tester (1996) with strips (20 cm × 1 cm) to a standard curvature (± 2.5 cm^{-1}). The bending and recovery behaviour were tested for both warp and weft directions and on both sides (face and back) of the fabric.

Key parameters measured included:

Bending rigidity (B) = Avg. slope in between 0.5 cm^{-1} and 1.5 cm^{-1}

Bending hysteresis (2HB) = hysteresis width at ± 0.5 cm^{-1}

2.1.3 Kawabata Evaluation System for Fabric 3 (KES-FB3)

Compression properties of the fabric were assessed using the Auto Compression Tester (2012) by applying a compressive load of 50 g/cm^2 on the fabric (20 cm × 20 cm) and gradually withdrawing with the help of a movable plunger. From this experiment, fabric thickness at a low compressive load of 0.5 g/ cm^2 (TO), fabric thickness at a maximum compressive load of 50 g/cm^2, work done in compression (WC) and Compressive resilience (RC%) were calculated.

2.1.4 Kawabata Evaluation System for Fabric 4 (KES-FB4)

Surface characteristics, such as surface roughness and friction, were calculated using the Surface tester (1996). The fabric was subjected to forward and backward movements under a preset stress, and geometric roughness, as well as the coefficient of surface friction, were recorded by electronic sensors. From this experiment, characteristic values are: -

Mean Frictional Co-efficient (MIU) = $\frac{1}{x}\int_0^x \mu dx$

where μ is co-efficient of friction; and x is displacement of sensor

Mean deviation of friction Co-efficient (MMD) = $\frac{1}{x}\int_0^x |\mu - \bar{\mu}| dx$

where maximum of x = 2 cm

Index of surface roughness (SMD) = $\frac{1}{x}\int_0^x |T - \bar{T}| dx$

where T is thickness (cm)

2.2 Water Vapour Transmission

Water vapour transmission was measured as per ASTM E 96-95 standard. Samples were sealed in containers with a drying agent, exposed to controlled humidity and temperature for 24 h. and periodically weighed to calculate the transmission rate.

2.3 Air Permeability

The air permeability of the fabric was tested using the Shirley Air Permeability Tester, following IS 11056:2013 standards. The rate of airflow through a defined area was calculated under a specific pressure difference.

2.4 SEM Analysis

The surface morphology of the fabric was analyzed using a scanning electron microscope. Samples were coated with a gold-palladium alloy to prevent charging and examined at 1000x magnification or higher.

2.5 Preparation of Samples

A FR fabric sample was prepared using a double bath process. During the first bath, the control fabric was dipped in a 16% solution of AS for 60 min at room temperature (approx. 30 ºC). Then, the chemically treated fabric was transferred to a second bath of 8% SS aqueous solution for 60 min at room temperature (Approx. 30 ºC). 8% ZA was added to the second bath, and the solution pH was maintained at 10–12 for another 60 min at room temperature (approx. 30 ºC). After treatment, the fabric was padded for 100% wet pick up, dried in a hot air dryer at 100 ºC for 5 min, cured at 150 ºC for 4 min, and finally washed with NaOH solution. The chemically treated fabric was then washed with water and dried in open air.

3. Results and Discussion

3.1 Fabric Properties

The control and fire-retardant (FR) fabrics were evaluated for their low-stress mechanical properties using the KES-FB. Fabric physical characteristics are summarized in Table 1.

The results show a slight increase in fabric thickness and a 15.61% increase in fabric weight following the application of FR chemicals, attributed to the deposition of AS, SS and ZA on the fabric's surface and interlacements.

Tensile properties for the control and FR-treated fabrics are presented in Table 2. The FR-treated fabric exhibits a 39.11% reduction in tensile energy (WT), suggesting a decreased capacity to withstand external stress during extension, making the fabric less stretchable. Tensile resilience (RT) and tensile elongation (EMT) also decline by 22.70% and 28.31%, respectively. Reduced RT indicates the fabric's diminished ability to regain its original shape after tensile stress removal, while lower EMT highlights decreased extensibility under applied stress.

Statistical analysis confirms that load-extension differences are significant for both warp and weft directions at the 95% confidence level. Stress-strain curves (Fig. 1) further illustrate reduced tensile resilience (RT) and elongation (EMT) after FR treatment.

Bending properties results reveal that bending rigidity (B) and bending hysteresis (2HB) decrease by 13.36% and 9.33%, respectively, after FR treatment (Table 3). Reduced bending rigidity indicates the fabric bends more efficiently, while decreased bending hysteresis reflects improved recovery after bending. Statistical analysis shows significant changes in bending rigidity for warp but not weft. Bending curves (Fig. 2) confirm these observations.

Shear properties (Table 4) reveal a marginal reduction in shear rigidity (G) and hysteresis at ±0.5° (2HG). The lower G value suggests a softer fabric with a better drape. However, a slight decrease in 2HG value and an increase in 2HG5 value indicates reduced fibre slippage, leading to stiffness. Statistical analysis suggests significant warp-wise but not weft-wise changes in shear rigidity. Shearing curves (Fig. 3) show increased 2HG5 after FR treatment.

Table 1 — Fabric physical characteristics

Fabric	Thickness mm	Thickness at max. pressure mm	Fabric weight mg/cm^2
Control	0.811	0.623	12.62
FR-treated	0.832	0.609	14.59

Table 2 — Tensile properties of control and FR-treated fabrics

Fabric		LT	WT, gf.cm/cm^2	RT, %	EMT, %	Significant (95%)
Control	Warp	0.860	1.17	25.72	2.72	---
	Weft	0.847	21.23	18.68	12.53	---
	Avg.	**0.854**	**11.20**	**22.20**	**7.63**	
FR-treated	Warp	0.799	0.60	11.11	1.88	Yes
	Weft	0.823	13.03	23.22	9.06	Yes
	Avg.	**0.811**	**6.82**	**17.16**	**5.47**	

LT- Linearity of load-extension curve, WT- Tensile energy, RT- Tensile Resilience, EMT- Tensile elongation

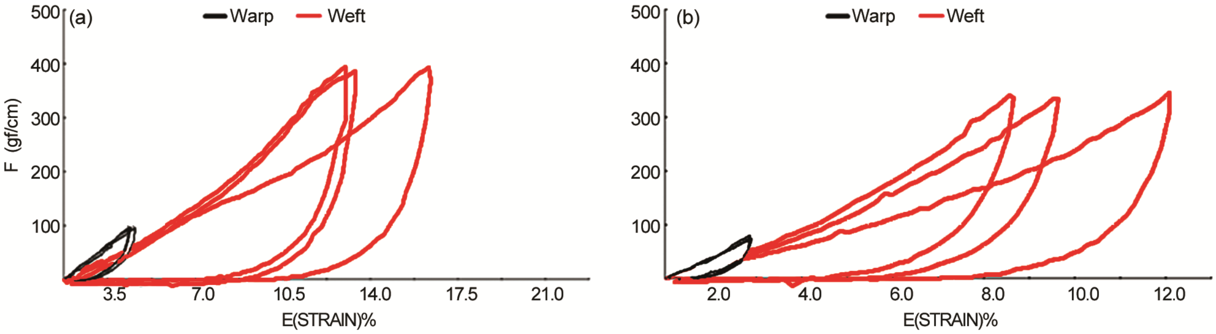

Fig. 1 — Warp-wise and weft-wise stress strain curve of (a) control fabric and (b) FR treated fabric

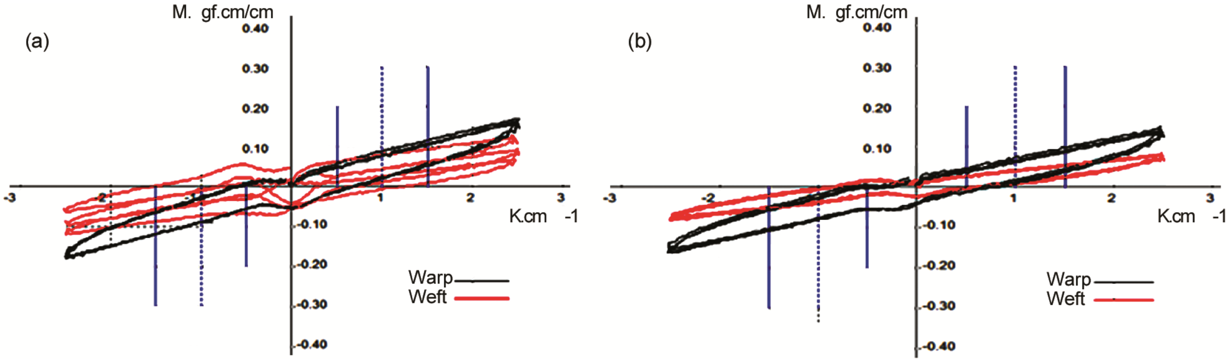

Fig. 2 — Warp-wise and weft-wise bending curve of (a) control and (b) FR-treated fabrics

Table 3 — Bending properties of control and FR-treated fabrics

Fabric		Bending rigidity gf. cm^2/cm	Bending hysteresis gf.cm/cm	Significant (95%)
Control	Warp	0.0609	0.0565	----
	Weft	0.0319	0.0336	----
	Avg.	**0.0464**	**0.0450**	
FR-treated	Warp	0.0505	0.0508	Yes
	Weft	0.0298	0.0309	No
	Avg.	**0.0402**	**0.0408**	

Table 4 — Shear properties of control and FR-treated fabrics

Fabric		G, gf/cm. deg	2HG, gf/cm	2HG5, gf/cm	Significant (95%)
Control	Warp	1.03	2.05	3.48	----
	Weft	0.97	1.42	3.22	----
	Avg.	**1.00**	**1.74**	**3.35**	
FR-treated	Warp	0.97	1.98	4.53	Yes
	Weft	0.97	1.32	4.47	No
	Avg.	**0.97**	**1.65**	**4.50**	

G- Shear rigidity, 2HG- Hysteresis at shear force at ±0.5^0 shear angle, 2HG5- Hysteresis at shear force at ±5^0 shear angles

Compression properties (Table 5) show negligible changes following FR treatment. However, a slight reduction in compression resilience (RC) indicates reduced compressibility of the treated fabric. Statistical analysis shows no significant differences in compression properties. Compression curves (Fig. 4) highlight minimal differences between control and FR-treated fabrics.

Surface properties (Table 6) demonstrate a notable increase (438%) in friction coefficient (MIU) and deviation (MMD) for FR-treated fabrics, suggesting increased roughness and frictional interaction due to the surface chemicals. Statistical analysis confirms significant differences in MIU for both warp and weft directions. Increased roughness is evident in the surface curves (Fig. 5).

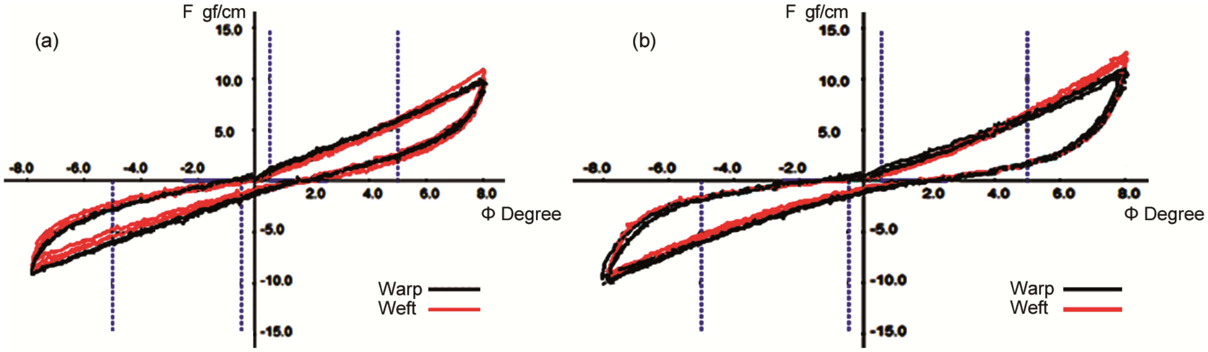

Fig. 3 — Warp-wise and Weft-wise shearing curve of (a) control and (b) FR-treated fabrics

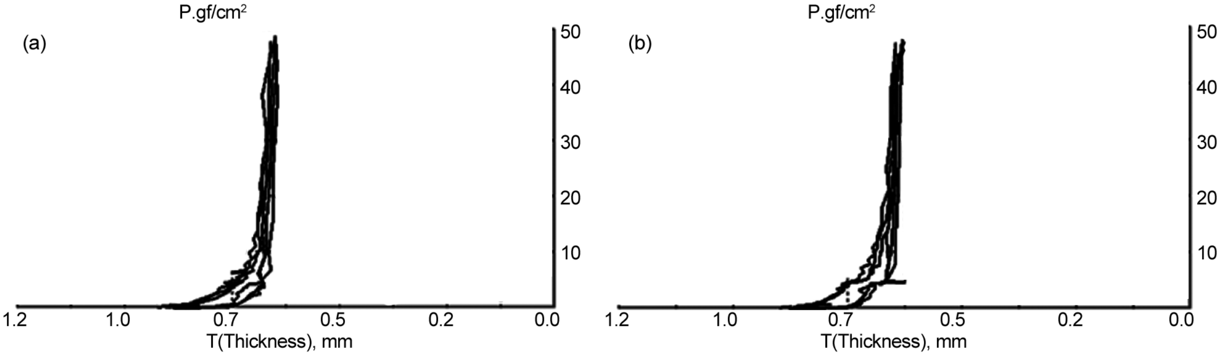

Fig. 4 — Compression curve of (a) control and (b) FR-treated fabrics

Table 5 — Compression properties of control and FR-treated fabrics

Fabric		LC	WC, g.cm/cm^2	RC, %	Significant (95%)
Control	**Avg.**	0.296	0.154	35.61	----
FR-treated	**Avg.**	0.296	0.150	33.42	No

LC- Linearity of load-extension curve, WC- Compression energy, RC- Compressional resilience

Table 6 — Surface properties using KES-FB4 by surface tester

Fabric		MIU	MMD	SMD, μm	Significant (95%)
Control	Warp	0.135	0.0099	5.072	----
	Weft	0.118	0.0119	2.377	----
	Avg.	**0.127**	**0.0109**	**3.724**	
FR-treated	Warp	0.601	0.0402	5.700	Yes
	Weft	0.764	0.0353	2.948	Yes
	Avg.	**0.683**	**0.0378**	**4.324**	

MIU- Co-efficient of friction, MMD- Deviation in Co-efficient of friction, SMD- Geometrical roughness

Table 7 presents the total hand value (THV) of the control and FR-treated fabrics based on the primary data using the Kawabata Evaluation System. The data indicate minimal changes in stiffness; however, the smoothness value and fullness & softness value decrease significantly by approximately 50% and 24%, respectively. This reduction implies that the FR-treated fabric is less suitable for tailoring and offers diminished comfort for the wearer. Consequently, the treated fabric demonstrates limited potential for application in the ready-to-wear garment sector. The THV (KN-302-Summer) for both fabrics is below 3.5, suggesting their suitability for winter-autumn garment applications.

The snake charts and THV diagrams for the control [Fig. 6 (a)] and FR-treated fabrics [Fig. 6 (b)] show average values and deviations for various hand properties. These visualizations aid in assessing fabric

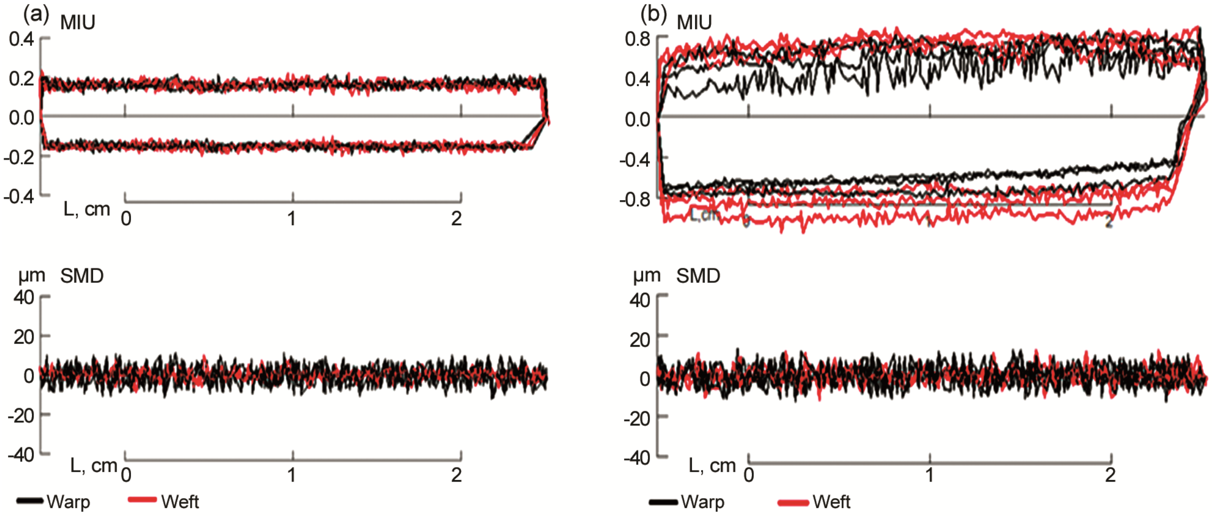

Fig. 5 — Surface properties of (a) control (b) FR-treated fabrics.

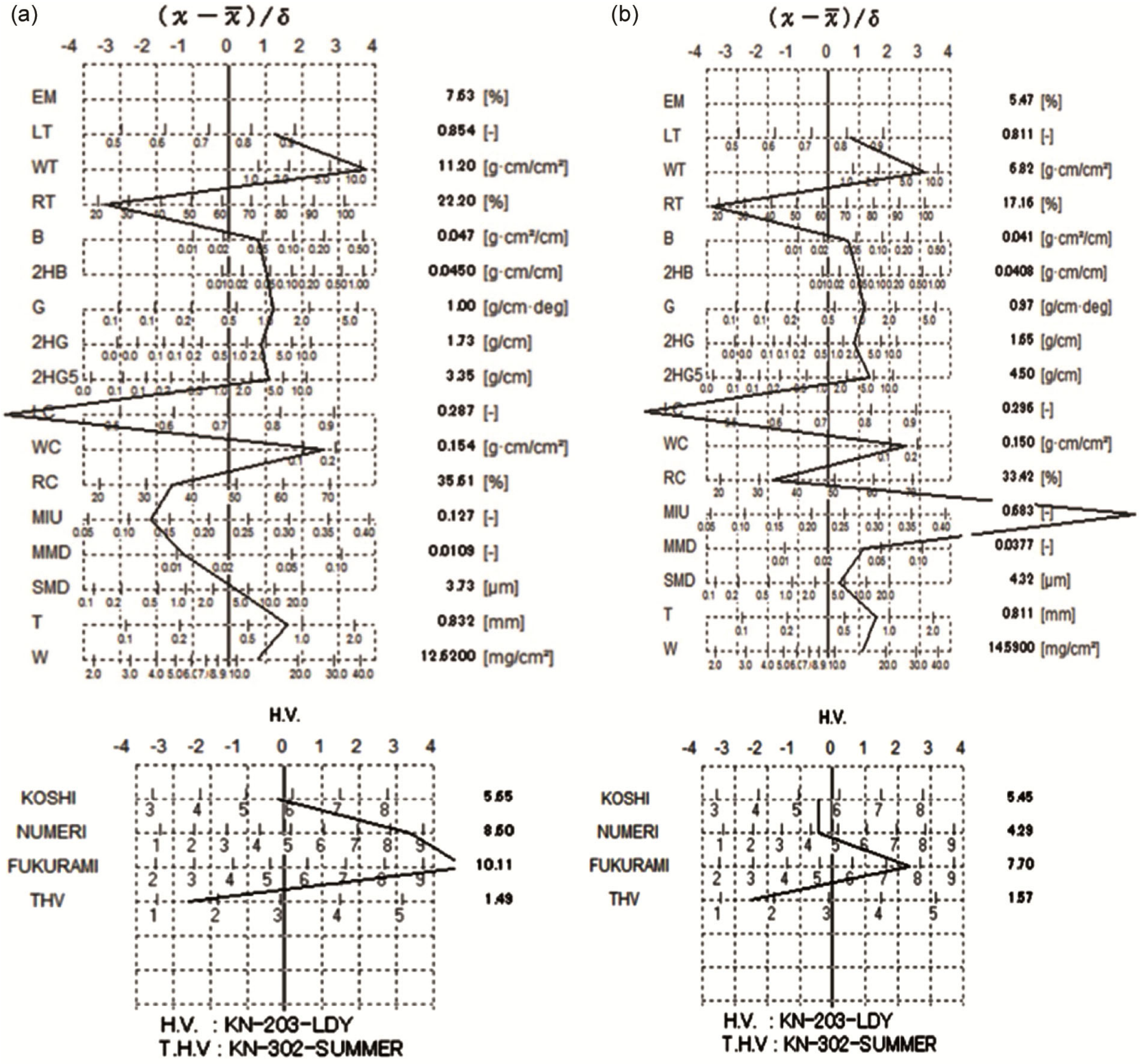

Fig. 6 — Snake diagram and THV of (a) control and (b) FR-treated fabrics

Table 7 — Total hand value of control and FR-treated fabrics

Fabric		Koshi (Stiffness)	Numeri (Smoothness)	Fukurami (Fullness & softness)	THV(KN-302-Summer)
Control	Warp	5.65	8.60	10.11	1.49
FR-treated	Warp	5.45	4.29	7.70	1.57

Table 8 — Water vapour transmission rate and air permeability of control and FR-treated fabrics

Fabric	GSM, g/m^2	Thickness mm	Water vapour transmission g/h/m^2	Air permeability ft^3/ft^2/min
Control	126.20	0.811	25.65	440.4
FR-treated	145.90	0.832	25.14	401.8

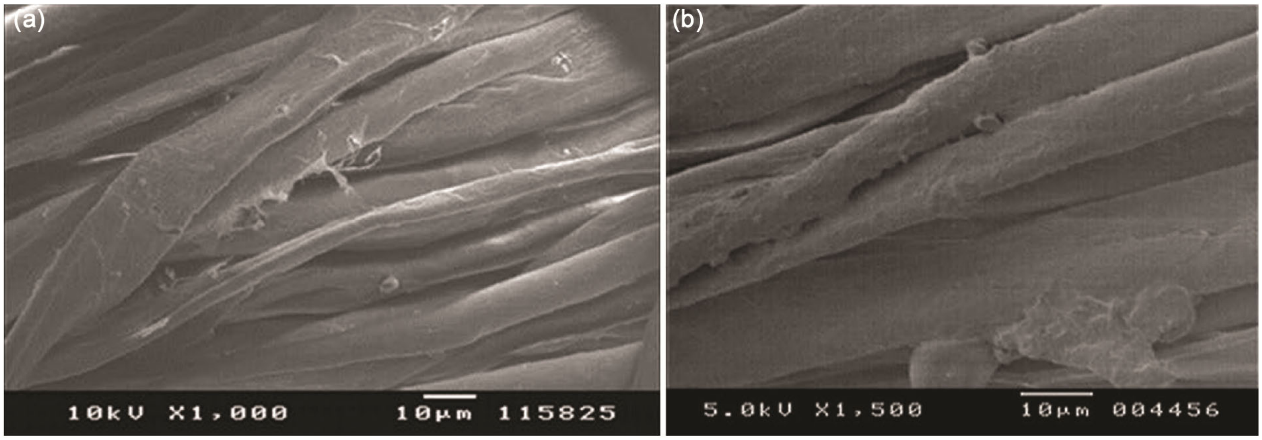

Fig. 7 — SEM images of (a) control and (b) FR-treated fabrics

elasticity, softness, smoothness, surface friction, and overall wearer comfort, providing insights into their suitability for garment applications[23].

3.2 Comfort Properties

The comfort properties of control and FR-treated fabrics (Table 8) reveal that the application of FR chemicals (16% AS + 8% SS + 5% ZA) results in a 15.61% increase in GSM (from 126.2 to 145.9) and a 2.59% increase in thickness (from 0.811 mm to 0.832 mm). This increase confirms the deposition of FR chemicals on the fabric surface.

Water vapour transmission decreases by 1.99%, while air permeability reduces by 8.76% compared to the control fabric. These reductions are attributed to the blockage of fabric pores by the FR chemical combination, impacting the fabric's breathability and moisture management properties.

3.3 SEM Analysis

SEM images of the control and FR-treated fabrics show that the control fabric exhibits a smooth surface with visible hairline cracks, which may have formed due to the oxidative effects of the bleaching process [Fig. 7 (a)].

In contrast, the FR-treated fabric shows a smooth and uniform deposition of chemicals on the surface, effectively masking the hairline cracks [Fig. 7 (b)]. Random agglomerated precipitations of zinc compounds, identified as Zinc Hydroxy Stannate, are also observed on the treated fabric. This deposition alters the surface morphology, further corroborating the chemical treatment's impact on fabric characteristics.

4 Conclusion

The study reveals that the application of FR chemicals significantly alters the physical and mechanical properties of the fabric. The treatment results in a 15.61% weight gain and notable changes in key parameters, including a 39% reduction in tensile energy and a 13% decrease in bending rigidity, indicating diminished ability to withstand external stress and reduced flexibility. Additionally, the FR treatment causes a 34.33% increase in shear stress at 5^0 angle and a 438% increase in the coefficient of friction, reflecting increased stiffness and surface roughness due to the chemical deposition.

Statistical analysis shows that tensile properties, bending rigidity (warp direction), shear rigidity (warp direction), and the coefficient of friction (both warp and weft directions) are significant at a 95% confidence level. However, bending rigidity (weft direction), shear rigidity (weft direction), and compression properties are not statistically significant.

The reduction in water vapour transmission and air permeability confirms decreased wearer comfort, attributed to the restriction of heat and moisture flow caused by the surface deposition and agglomerated precipitates observed in SEM images. The THV assessment further indicates that the FR-treated fabric is less suitable for tailoring and has limited potential for application in the garment industry. So, there would be less comfort for the wearer. However, despite these limitations, the treated fabric may be appropriate for winter-autumn garments where enhanced thermal insulation and fire resistance are desirable.

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