Impact of ultraviolet radiation on thermal protective performance and comfort properties of firefighter protective clothing

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ABSTRACT – REZUMAT

Impact of ultraviolet radiation on thermal protective performance and comfort properties of firefighter protective clothing

In this study, the impact of ultraviolet radiation is studied on thermal protective performance and clothing comfort properties of firefighter protective clothing. Firefighter clothing assembly consists of the outer shell, moisture barrier and thermal barrier. In this research, two different outer shells were utilized. Outer shell O1 consists of inherently fire-retardant fibres mainly consisting of Conex (Nomex) and firefighter assembly having Conex as the outer shell was called specimen A. On the other hand, clothing arrangement which employed Proban coated outer layer (O2) was termed as specimen B. Both specimens were evaluated for tensile testing, air permeability, radiant heat transmission machine, bending moment and water vapour resistance before and after exposure to ultraviolet radiation. The tensile strength value of outer shell O2 was higher than that of O1 before and after exposure to UV radiation. Tensile strength values of both outer shells O1 and O2 decline after exposure to ultraviolet radiation. Air permeability values of both outer shell O1 and O2 increase after being exposed to ultraviolet radiation. It was noted that specimen A has better thermal protective performance as compared to specimen B, before and after exposure to UV radiation. Also, radiant heat transmission index RHTI 24 values were greater for specimen A as compared to specimen B, before and after exposure to UV radiation. Moreover, bending moment values for both outer shell O1 and O2 decline after being subjected to UV radiation. Furthermore, Water vapour resistance values of outer shell O1 and outer shell O2 enhance after exposure to ultraviolet radiation.

Keywords: *thermal protective performance (TPP), ultraviolet radiation (UV), radiant heat transmission index (RHTI 24)*

Influența radiațiilor ultraviolete asupra performanței de protecție termică și proprietăților de confort ale îmbrăcămintei de protecție pentru pompieri

În acest studiu, s-a analizat influența radiațiilor ultraviolete asupra performanței de protecție termică și proprietăților de confort vestimentar ale îmbrăcămintei de protecție pentru pompieri. Ansamblul de îmbrăcăminte pentru pompieri este format din stratul exterior, barieră de umezeală și barieră termică. În această cercetare au fost utilizate două straturi exterioare diferite. Stratul exterior O1 este format din fibre ignifuge în mod inerent constând în principal din Conex (Nomex), iar ansamblul vestimentar al pompierilor având Conex ca strat exterior a fost numit proba A. Pe de altă parte, îmbrăcămintea care a folosit stratul exterior acoperit cu Proban (O2) a fost denumită proba B. Ambele probe au fost evaluate pentru rezistența la tracțiune, permeabilitatea la aer, transmiterea căldurii radiante, rezistența la încovoiere și rezistența la vapori de apă înainte și după expunerea la radiații ultraviolete. Valoarea rezistenței la tracțiune a stratului exterior O2 a fost mai mare decât cea a stratului O1, înainte și după expunerea la radiații UV. Valorile rezistenței la tracțiune ale ambelor straturi exterioare O1 și O2 scad după expunerea la radiații ultraviolete. Valorile permeabilității la aer, atât ale stratului exterior O1 cât și ale stratului O2, cresc după expunerea la radiații ultraviolete. S-a observat că proba A are o performanță de protecție termică mai bună în comparație cu proba B, înainte și după expunerea la radiații UV. De asemenea, valorile indicelui de transmitere a căldurii radiante RHTI 24 au fost mai mari pentru proba A în comparație cu proba B, înainte și după expunerea la radiații UV. În plus, valorile rezistenței la încovoiere atât pentru stratul exterior O1, cât și pentru stratul O2 scad după ce au fost supuse la radiații UV. Mai mult, valorile rezistenței la vapori de apă ale stratului exterior O1 și ale stratului exterior O2 se îmbunătățesc după expunerea la radiații ultraviolete.

Cuvinte-cheie*: performanță de protecție termică (TPP), radiații ultraviolete (UV), indice de transmitere a căldurii radiante (RHTI 24)*

INTRODUCTION

Firefighter clothing is a multilayer garment that is manufactured from high-performance fibres. In multi-layer firefighter protective clothing, there are normally three layers i.e., outer shell, moisture barrier and thermal barrier. The outer shell consists of those materials which don't burn or degrade on having contact with heat and flame. A moisture barrier is a microporous membrane that is impermeable to water but permeable to water vapours. The thermal barrier supports the body of a firefighter by blocking the amount of heat from reaching the firefighter's body [1]. The primary purpose of this firefighter protective garment is to protect the body of firefighter clothing from hazardous working atmospheres like flash fire, chemical spillage and radiant heat flux density [2–5]. The location of firefighters' bodies and kinds of action performed by firefighters are contingent on exposure of multilayer protective clothing to different conditions. It is almost impossible to comprehend the useful life of firefighter clothing assembly. In general, normally 10 years are given to firefighter protective clothing. After this tenure, this multilayer clothing is not applicable for utility as it did not comply with National Fire Fighter Protective Clothing, NFPA 1851 standard [6]. The pertinent element in weathering is sunlight [7]. The interaction of sunlight with organic polymers caused irreversible changes and polymer degradation due to photo-oxidation caused brittleness and reduction in textile strength parameters. There are two conditions that are essential for the light of a specific wavelength to cause deterioration of polymers. Firstly, a polymer must be able to absorb light rays. Secondly, the energy of light must be strong enough to break chemical bonds. The ageing of chemicals takes place through three main reactions i.e., breakage of chain, cross-linking and depolymerisation. Chain breaking leads to the polymer ageing process [8]. Scission of the chain is seldom accompanied by oxidation, causing self-sustained procedure inculcating production of extremely reactive free radicals. Weathering can take place naturally and artificially [9]. Firefighter protective clothing is generally made from high-performance fibres which are made from combination meta-aramid and para-aramids. The high-performance fibres are inherent absorbers of ultraviolet light. UV light causes degradation in these fibres due to primary photoreactions resulting in the breakage of the main chain bond. Para-aramids fibres (Kevlar) have a more ordered crystalline structure than meta-aramid fibres. Chemical degradation occurs more easily within disordered regions, which in para-aramids is only a small fraction of polymer and hence less susceptible to photodegradation [9–16]. Carlsson et al. [17] mentioned that stability in para-aramids is more as compared to meta-aramids are due to enhanced conjugation and delocalization of absorbed energy through the enol form of the amide group.

Mechanical properties of multilayer protective clothing play a pivotal role in the performance of firefighter protective clothing. In recent years, it has been found that high-performance fibres can absorb ultraviolet radiation and suffer photolytic deterioration instigated by crucial photo reactions causing the scission of main chain bonds. In the case of polyaramids, photo-oxidation is very acute. The factors that impact the protective performance of firefighter clothing are thermal exposure, washing, moisture absorbing, laundering and abrasion [10–14].

In this study impact of artificial weathering of ultraviolet radiation on thermal protective performance and comfort properties of firefighter protective clothing was investigated. Two different outer shells Nomex and Proban coated outer layers were utilized. At first, tensile strength, air permeability, radiation heat flux density, bending moment and water vapour resistance values were evaluated. Afterwards, these specimens were exposed to ultraviolet radiation in Atlas weathering machine UV 340 for continuous thirteen days and later on aforementioned properties were also calculated.

EXPERIMENTAL WORK

Materials

All specimens were provided by Vochoc Company, Czech Republic. Two different combinations were made from these specimens. Each specimen consists of an outer shell layer, moisture barrier and thermal barrier. The specification of materials is mentioned in table 1 and the combination of specimens is revealed in table 2.

Outer shell 1 (O1) is made from a combination of inherently flame-resistant materials like meta-aramids and para-aramids. Outer shell 2 (O2) is Proban coated cotton/polyester fabric. Two different

Table 1

SPECIFICATION OF SAMPLES

Sample no.	Name of sample	Code	Material specification	Weave design	Thickness	GSM (g/m²)
1	Outer shell (1)	O(1)	70% Conex, 23% Lenzing FR, 5% Twaron, 2% Beltron	Rip stop weave	0.44±0.01	225±2.1
2	Outer shell (2)	O(2)	79% Proban, 20% polyester and 1% antistatic	Twill	0.6±0.01	260±2.2
3	Moisture Barrier	MB	Face fabric, 50%/50% Kermel/ viscose FR, PTFE membrane	Non-woven	0.55±0.01	120±1.8
4	Thermal Barrier	TB	Thermo: Para Aramid Inner futter: 50% Meta aramid, 50% viscose	Non-woven	1.8±0.02	200±2.3

Table 2

COMBINATION OF SPECIMEN

Sample no.	Fabric assembly	Fabric code	GSM (g/m^2)	Thickness (mm)
1	O(1)+MB+TB	A	545±2.1	2.79±3.1
2	O(2)+MB+TB	B	580±2.9	2.95±2.9

outer shells were selected to compare thermal protective performance and thermal comfort properties of firefighter protective clothing before and after exposure to Ultraviolet light.

CHARACTERIZATION OF SPECIMEN

Weathering machine

Weathering of outer shell O1 and outer shell O2 was performed in artificially accelerated weathering chambers (Atlas Weathering machine UV 340) for 13 days of continuous exposure nearly equal to 6.6 years of firefighter clothing exposure to UV radiation in natural conditions of utility [9]. ASTM G154-06 standard was used. According to this standard, test specimens (outer shells) were exposed to fluorescent Ultraviolet light under controlled conditions. The approximate wavelength of absorbed Ultraviolet radiation was maintained around 340 nm and energy distribution in the form of spectral irradiance was 0.89 $W/m^2/nm$.

Evaluation of tensile strength

Tensile strength was evaluated from a tensile testing machine called Tensile Testometric M350-5CT as per EN ISO 13934-1 standard.

Evaluation of air permeability

Air permeability tester FX 3300 Labotester III (Textest Instruments) was employed to evaluate air permeability as per CSN EN ISO 9237 standard. The test pressure was kept at 200 pascals on an area of 20 cm^2 ($l/m^2/sec$).

Evaluation of radiation heat flow through tested fabrics

The X637 B machine utilizes ISO 6942 standard to evaluate the transmission of heat through the textile substrate or material assembly. The size of the specimen was 230 mm × 80 mm and shall be taken from the area more than 20 mm away from the edge of the textile substrate and must be free from defects. Specimens were conditioned for at least 24 hours at a temperature of (20±2)°C and had a relative humidity of (65±2)%. The room in which the test was performed must be freed from any current of air. The temperature of the room was maintained between 15°C and 35°C. The results are mentioned in the form of radiant heat transmission index (*RHTI* 12 and *RHTI* 24) and the percentage heat transmission factor (percentage $TF\ Q_o$) and transmitted heat flux density Q_c. Three specimens are required for testing at each level of heat flux density. A schematic diagram of the radiant flux density machine is shown in figure 1 [15]. Incident heat flux density is evaluated from the following equation [15]:

$$Q_o = \frac{C_p R M}{a A} \quad (1)$$

where A is the area of the copper plate in m^2, a – the absorption coefficient of the painted surface of the calorimeter, M – the mass of copper plate in kg, C_p – the specific heat of copper 0.385 (kJ/Kg°C), R – rate of rise of the calorimeter temperature in the linear region in °C/s.

The transmitted flux density, Q_c in kW/m^2 is evaluated by the following equation:

$$Q_c = \frac{M C_p}{A} \times K \quad (1)$$

$$K = \frac{12}{(RHTI\ 24 - RHTI\ 12)} \quad (3)$$

where K is the mean rate of escalation of the calorimeter temperature in °C/s in the region between a 12°C and 24°C rise, *RHTI* 12 is threshold time in seconds, when the temperature of the calorimeter increases in 12°C, *RHTI* 24 is threshold time in seconds, when the temperature of calorimeter increases in 24°C.

Percentage age heat transmission factor, Percentage $TF\ Q_o$ for incident heat flux density level is explained by equation 4 [15]:

$$TF\ Q_o\ (\%) = 100 \cdot \frac{Q_c}{Q_o} \quad (4)$$

Evaluation of bending resistance moment

TH-4 (Tuhomer) device was employed to calculate the bending moment of firefighter clothing specimen. This device measures the bending moment of firefighter clothing specimen according to CSN 80 0858 standard. The specimen was cut into 5 cm × 2.5 cm.

Evaluation of water vapour resistance

Water vapour resistance *Ret* (m^2Pa/W) and relative water vapour permeability (*RWVP* %age) under steady-state conditions was evaluated by Permetest (non-destructive method) which was developed by Sensora company as per ISO 11092 standard.

Evaluations are based on the principle of heat flux sensing. The test was carried out under isothermal conditions; the temperature of the measuring head was regulated at room temperature. When water passed through the measuring head, some amount of heat is lost due to evaporation. The equipment determines the evaporation of the "uncovered" head as well as that of the head when sheltered with the test fabric. The full test is accomplished when the exchange of water from the measuring head to the atmosphere reaches a steady-state (usually within two to three minutes).

Relative water vapour permeability (*RWVP*) (or relative cooling effect) is the relative heat flow responsible for the cooling of the body:

$$RWVP\ (\%) = \frac{q_v}{q_o} \cdot 100 \quad (5)$$

where q_v is the heat flow in W/m^2, passing through the measuring head covered by the sample, and q_o is the heat flow passing through the uncovered measuring head in W/m^2.

Plan of experimental work is shown in figure 2.

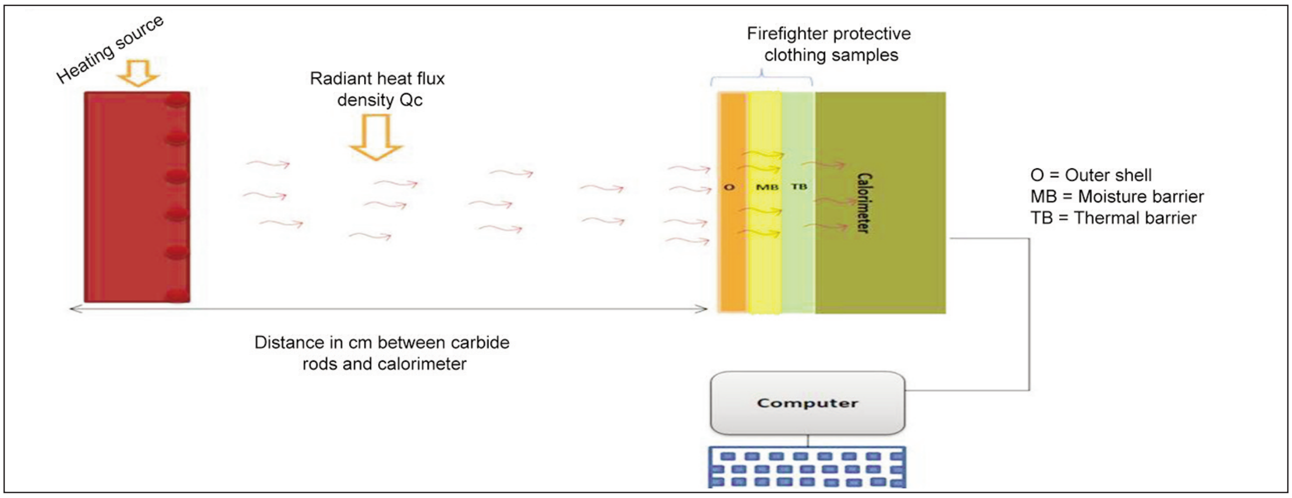

Fig. 1. Schematic diagram of radiant heat flux density machine

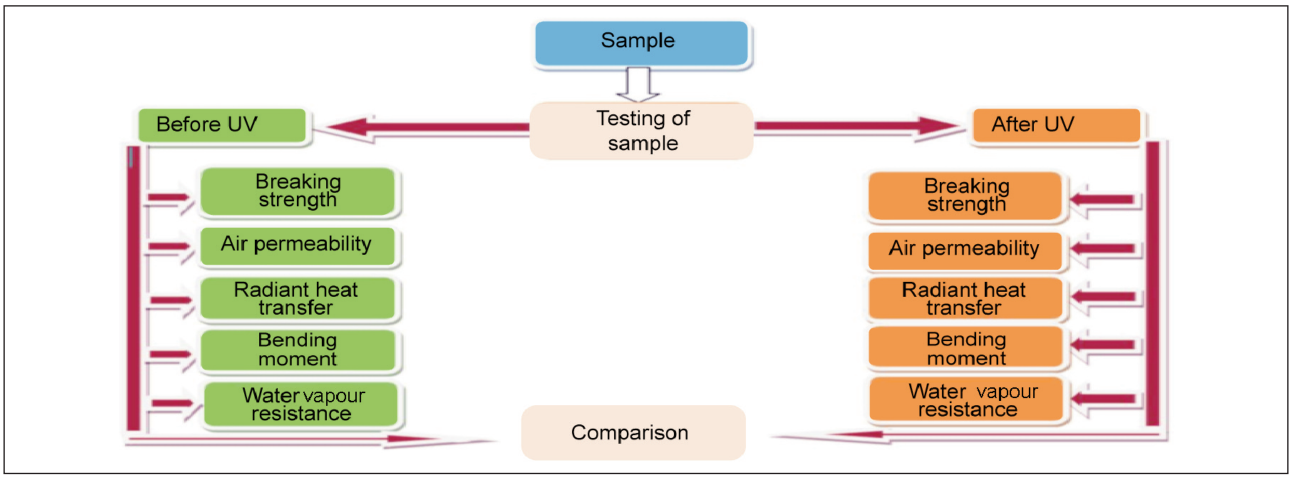

Fig. 2. Schematic diagram of experimental work

RESULTS AND DISCUSSION

Evaluation of tensile strength

It can be seen from figure 3, that the tensile strength of outer shell O1 was more before exposure to ultraviolet radiation. This clearly indicates that exposure to UV radiation impacts the mechanical properties of fibres by decreasing the strength of fibres which might be due to a decline in the breaking strength of fibres and as a result, there was a 13.06% decline in tensile strength after exposure to UV radiation. A similar pattern of tensile strength was observed in figure 4 for outer shell O2. However, the decline in breaking strength of the O2 shell was 9.67%.

After exposure to UV radiation, there was a considerable decline in the strength of outer shell O1 and O2. This indicates that there was deterioration in fibres due to which their breaking strength is decreased and as a result, the breakage of fibres takes place at low force.

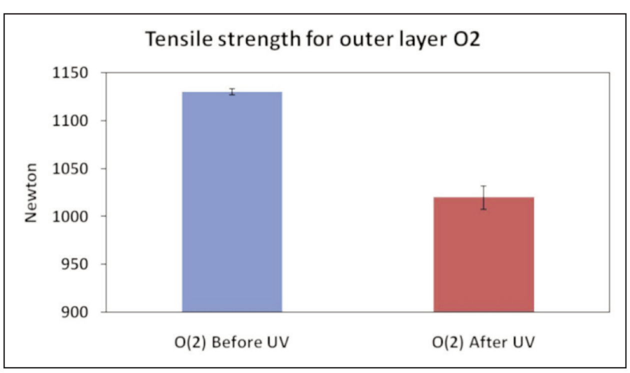

Fig. 3. Tensile strength of outer layer 1 before and after UV exposure

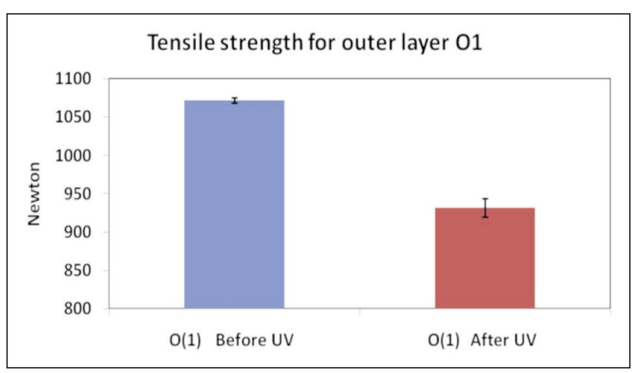

Fig. 4. Tensile strength for outer layer 2 before and after UV exposure

Evaluation of air permeability

It can be witnessed from figure 5 that there was a considerable decline in air permeability values for both specimen and outer shell O2. This might be due to fact that damage of fibres after exposure to UV radiation might further close the air gapes between fibres due to which less amount of air was passed through both outer shells. It was also witnessed that air permeability values of outer shell O1 were more as compared to outer shell O2 which might be due to the high thickness of outer shell O2.

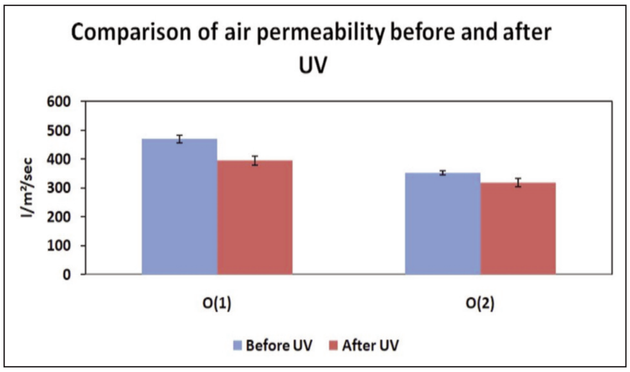

Fig. 5. Air permeability values before and after exposure to UV

After exposure to UV radiation in the outer shell, there was a 15.8 % decline in air permeability values in the case of outer shell O1. However, in the scenario of outer shell O2, there was a 9.67% decline in air permeability values.

Evaluation of radiation heat flow through tested fabrics

A perusal of table 3 reveals that specimen A has lower transmitted heat flux density values as compared to specimen B. The lesser the value of transmitted heat the better will be thermal protective performance as less amount of heat is transmitted towards the calorimeter. It is also evident from greater values for radiant heat transmission factor RHTI 24 which means the rate of rise of 24 degree centigrade is greater for specimen A as compared to specimen B.

However, it was witnessed from table 3 that after exposure to UV radiation, transmitted heat flux density values of both specimens A and B respectively have increased. This might be due to the deterioration of constitutional fibres present in the fabric layer.

It is evident from figure 6 that before exposure to UV radiation, the pattern of the curve was flat. However, after exposure to UV radiation, the flatness of the curve decreases and it becomes slightly steep. This is a clear indication of a decline in thermal protective performance after exposure to UV radiation due to which lower values of RHTI 24 were acquired. Till the first 3 seconds, both curves are superimposed over each other. Later on, the curve of specimen A before exposure to UV radiation starts to slacken and the gaps between the two curves go on increasing till the end of the experiment.

A perusal of figure 7 reveals that the curve of specimen B before UV radiation exposure was much flat as compared to the curve of specimen B after exposure. Till the first three seconds, both curves superimposed each other. Later on, the curve before exposure started to become flat and the gap between

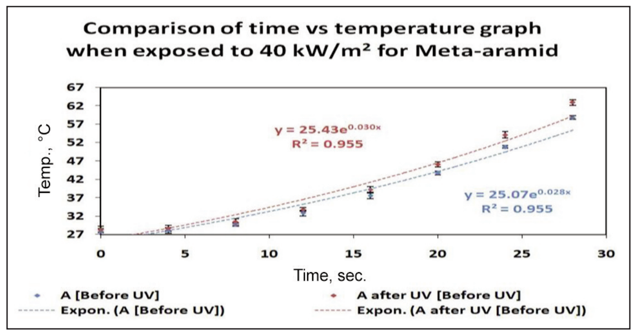

Fig. 6. Time vs temperature graph when exposed to UV for specimen A before and after UV exposure

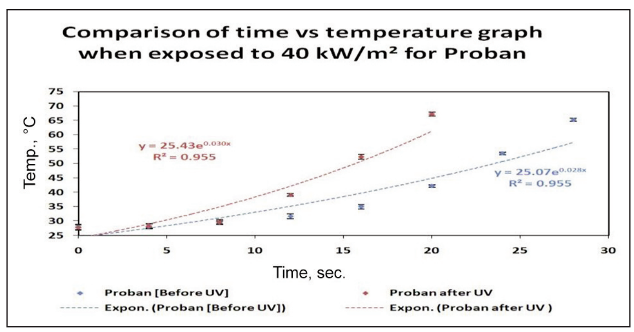

Fig. 7. Time vs temperature graph when exposed to UV for specimen B before and after UV exposure

Table 3

INCIDENT HEAT FLUX DENSITY, TRANSMITTED HEAT FLUX DENSITY AND PERCENTAGE TRANSMISSION FACTOR

Sample no.	Name of material	Incident heat flux density Q_o (kW/m²)	UV exposure	RHTI12 (sec)	RHTI24 (sec)	RHTI24 – RHTI12 (sec)	Transmitted heat flux density Q_c (kW/m²)	Percentage TF Q_o
1	A	40	**Before UV**	17.4	24.31	6.9	9.71	24
2	B			19.15	23.4	4.25	15.67	39
3	A	40	**After UV**	17.0	23.6	6.6	**10.089**	**25**
4	B			16.3	19.9	3.6	**18.48**	**46.2**

curves started to increase till the end of the experiment. This clearly depicts there was a decrease in thermal protective performance after exposure to UV radiation.
It can be witnessed from figures 6 and 7, the gap between curves of specimen B before and after UV radiation was much greater than the gap between curves of specimen A before and after UV radiation.
The greater the thickness of the fabric, the lesser the amount of heat passed through the fabric. However, the constituent fibre and construction of fabric and porosity also plays important role in the thermal protective performance of firefighter protective clothing. It is evident from figure 8, that specimen A has a larger value of time for rise of 24°C (RHTI 24) as compared to specimen B. This clearly indicates the better thermal protective performance of specimen A as compared to specimen B. RHTI 24 sec value of specimen A was greater than that of specimen B by 2.92%. This might be due to the fact that specimen A consist of Nomex fibre which are inherently flame resistant. Specimen B is coated with flame retardant chemical Proban on a mixture of cotton and polyester.
The decrease in thermal protective performance is a clear indication of a decrease in thermal protective behaviour of specimen because of structural changes or deterioration of outer shell of specimen B due to the swift rate of decomposition of cellulosic fibres as the incident temperature at the surface of specimen for Q_o of 40 kW/m^2 is 495°C. Consequently, specimen A had better thermal protective behaviour.

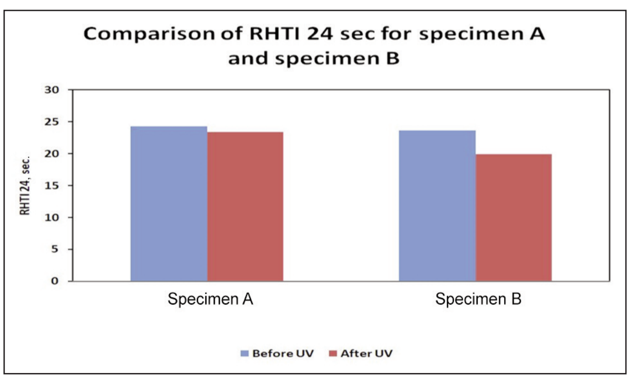

Fig. 8. Comparison of Radiant Heat Transmission Index RHTI 24 sec

It can be seen from figure 8, that in the case of specimen A, the decline in RHTI 24 sec before and after UV radiation was 3.74% when exposed to 40 kW/m^2. However, the declining percentage in specimen B was 15.67%. This clearly indicates that transmission of heat flow in the specimen takes place in a greater amount of time. The rate of heat flow in specimen A occurs at a slower rate as compared to specimen A. In consequence, specimen A has greater thermal protective performance as compared to specimen B.

Evaluation of bending resistance moment through tested fabrics

It can be noted from figure 9 that after exposure to ultraviolet (UV) radiation, there was a negligible

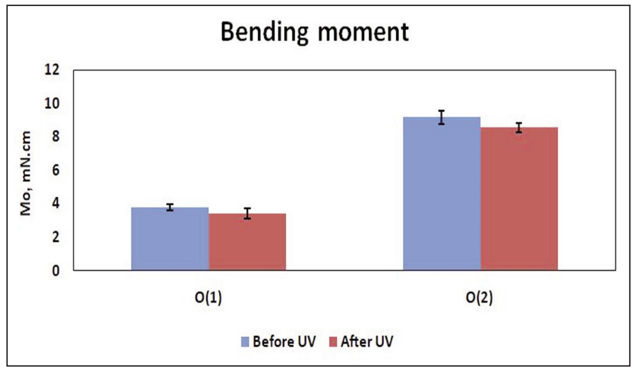

Fig. 9. Bending resistance moment values before and after UV

decline in bending moment values of both outer shell O1 and outer shell O2. Bending moment is related to the flexibility of fibres.
The greater the bending moment values, the greater will be the force required to bend the fibre. After exposure to UV radiation, there was a considerable decline in the strength of fibres as witnessed from the textile strength tester, due to which less amount of force was required to bend the fibres. In the case of outer shell O1, there was a 9.785 t decline in bending moment values after UV radiation exposure. Also, there was a 6.95% decline in bending moment values for outer shell O2 after being subjected to UV radiation.

Evaluation of water vapour resistance

The breathability of the textile substrate is related to the water vapour permeability of the fabric. The greater the water vapour permeability, the better will be comfort property of the fabric. Permeation of water vapour is one the most important aspect of the textile substrate. The greater the water vapour permeability, the lesser will be water vapour resistance values. If the permeation of water vapour is not good, it may accumulate inside the fabric and may cause an uncomfortable feeling.
It can be witnessed from figure 10 that water vapour resistance of both outer shells enhanced after exposure to UV radiation which might be due to degradation of constituent fibres which might be able to block the flow of water vapour through the exposed fabric to UV radiation. There was a 10% enhancement in water vapour resistance for outer shell O1 after exposure to

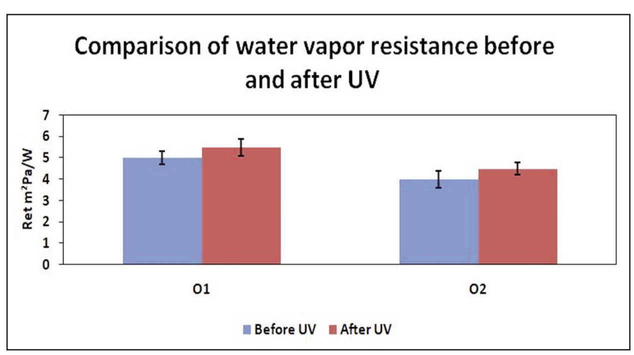

Fig. 10. Comparison of water vapor resistance before and after exposure to UV

ultraviolet radiation. In the case of O2, there was a 12.5% increment in water vapour resistance values when subjected to ultraviolet radiation.

CONCLUSION

It can be witnessed that the breaking strength of both outer shells declines after exposure to ultraviolet radiation. In the case of outer shell O1, there was a 13.06% decline in tensile strength after exposure to UV radiation and for outer shell O2, the decline in breaking strength of the O2 shell was 9.67%. Air permeability values of outer hell O1 was higher than air permeability values of outer shell O2. After exposure to UV radiation in the outer shell, there was a 15.8% decline in air permeability values in the case of outer shell O1. In the case of outer shell O2, there was a 9.6% decline in air permeability values. However, air permeability values of both specimens increase after exposure to UV radiation because of the deterioration of fibres.

Specimen A delivers better thermal protective performance as compared to specimen B. Radiant heat transmission index of both specimens A and B declines after exposure to UV radiation. RHTI 24 sec values of specimen A were greater than that of specimen B by 2.92%. For specimen A, there was a 3.74% decline in RHTI 24 sec before and after UV radiation when exposed to 40 kW/m². Whereas, the declining percentage in specimen B was 15.67%. Bending moment values of both outer shell O1 and O2 decline when subjected to UV radiation. This might be due to the loss of strength in fibres. Outer shell O1 depicts a 9.78% decline in bending moment values after UV radiation exposure. However, in the case of outer shell O2, a 6.95% decline in bending moment values was witnessed after being subjected to UV radiation. Water vapour resistance of both outer layers increases after being exposed to UV radiation. For outer shell O1, there was a 10% increment in water vapour resistance values after exposure to ultraviolet radiation. For outer shell O2, there was a 12.5% improvement in water vapour resistance values when subjected to ultraviolet radiation.

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