Aging of firefighter outer shell fabrics under accelerated conditions

Md. Saiful Hoque, Patricia I. Dolez*

Department of Human Ecology, University of Alberta, Edmonton, AB, Canada
* Corresponding author hoque1@ualberta.ca

Keywords
fire-protective fabrics, accelerated aging, degradation, thermal aging, ultraviolet radiation, hydrothermal aging, residual strength

Introduction
Firefighters, workers in the oil and gas industry, electricians, and military personnel, for example, wear protective clothing made of fire-resistant fabrics constructed from high-performance fibers (1). For firefighters' protective clothing, the outer shell is generally a blend of different fibers such as para-aramid, meta-aramid, polybenzimidazole (PBI), and polybenzoxazole (PBO). These high-performance fibers are known for their exception resistance to heat and flame when new. However, the corresponding fabrics may be affected by long-term exposure to heat (2), ultraviolet (UV) radiation (3), abrasion (4), and moisture (5). This study aims to explore how firefighters' outer shell fabrics respond to thermal, UV, and hydrothermal accelerated aging. After exposure to various aging conditions, the residual mechanical performance of the fire-protective fabrics was evaluated. Eventual morphological and chemical changes were also identified.

Methods
This study involves three fire-protective fabrics used as outer shell in firefighters' protective clothing. They are composed of blends of Technora®, para-aramid, meta-aramid, PBI, and PBO fibers (Table 1). To prevent any unintentional damage, the fabrics were stored in the dark in controlled laboratory conditions after reception.

Fabric specimens were exposed to thermal, hydrothermal, and UV accelerated aging conditions selected considering the conditions encountered by firefighters while in service. Thermal aging involved subjecting the specimens to temperatures ranging between 90 and 320°C for up to 1200 hours in an air oven. For the UV aging, the specimens were exposed to UV irradiances between 0.35 to 1.35 W/m^2 at temperatures between 40°C and 80°C for up to 600 hours. Fabric specimens were subjected to hydrothermal aging by keeping them in hot water between 60 to 90°C for up to 1200 hours. For a comparison, the hydrothermal aging was also performed at room temperature. The fabrics' residual tensile strength after aging was assessed using the raveled strip method (ASTM D5035). Additionally, Scanning Electronic Microscopy (SEM) was used to analyze the eventual morphological changes in the fabrics. The chemical changes were analyzed using attenuated total reflection-Fourier transform infrared spectroscopy (ATR-FTIR).

Table 1. Characteristics of the fabrics used in this study.

Fabric Code	Fabric Composition	Fabric Structure	Mass (g/m^2)	Fabric Count (yarn/cm)		Warp yarn		
				Warp	Weft	Fiber content	Yarn type	Linear density (tex)
SA	60% Technora® & 40% PBO	Plain (Rip-stop)	247	22	19	Technora®/ PBO	Spun	57
SB	65% para-aramid & 35% meta-aramid	Broken twill	244	23	23	Para-aramid/meta-aramid	Spun	43
						Para-aramid	Filament	46
SC	65% para-aramid & 35% PBI	Twill weave	219	19	19	Para-aramid & PBI	Spun	58
						Para-aramid	Filament	71

Results and discussions
It was observed that the strength of all fabrics decreased for elevated aging temperatures and long exposure times, even when the accelerated aging was done at 190°C, which is equal to or below the continuous operating temperature of the high-performance fibers used to make these fabrics. The time-temperature superposition principle (TTSP) was applied to the residual tensile strength data to construct a master curve for each fabric (Figure 1). In the case of Fabric SA and SB, an Arrhenius plot could be constructed with the shift factors and was used to calculate the activation energy (Figure 2). In the case of Fabric SC, the breaking force was observed to initially increase before eventually decreasing. Fiber breaking was observed in aged specimens. It is thought to be the cause of the fabrics' decreased tensile strength. Chemical changes in aged specimens were also detected by ATR-FTIR analysis under the most extreme thermal aging conditions.

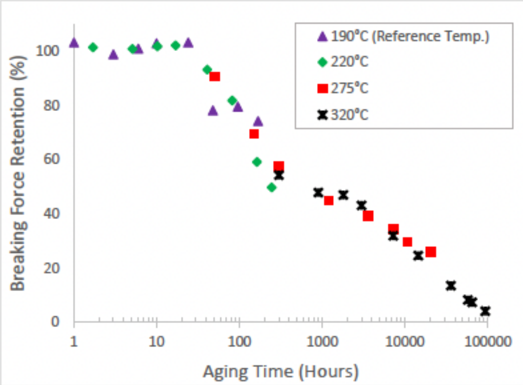

Figure 1. TTSP master curve at 190°C for the thermal aging of Fabric SB

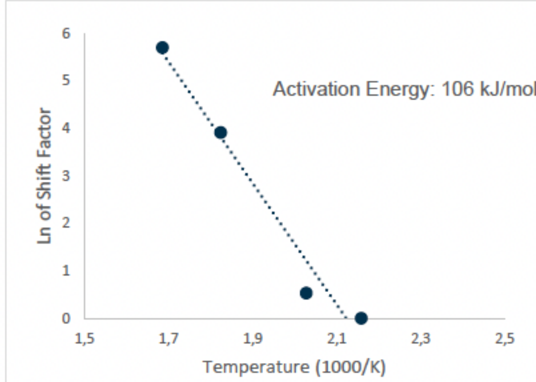

Figure 2. Arrhenius plot for the thermal aging of Fabric SB

Findings from the hydrothermal aging indicate a severe loss in Fabric SC's tensile strength while the tensile strength of Fabric SA and SB was not affected significantly, even after 1200 hours of water immersion at 90°C. Further analysis revealed that the residual sulfur coming from the PBI fibers in Fabric SC was the cause of the premature hydrothermal aging of the fabric, which is potentially attributed to the hydrolysis of the para-aramid fibers in acid conditions (5). On the other hand, no evidence of change was detected on the fiber morphology and chemical structure of the hydrothermally aged specimens.

UV aging severely affected the tensile strength of Fabric SA and SB, while Fabric SC showed comparatively good resistance to UV conditions. However, evidence of changes in fiber morphology due to UV aging was observed for all the fabrics. No chemical changes were observed in the UV aged specimens.

Conclusions

This study explores how different aging conditions affect firefighters' outer shell fabrics. Depending on the type of aging and the fiber content in the fabrics, different behaviours were observed. In some instances, the decrease in tensile strength observed was very large. However, this decrease in strength of the aged fabrics was not always associated with morphological or chemical changes in the fibers. The findings of this work will support the development of predictive aging models and end-of-life sensors for fire-protective fabrics.

Acknowledgements

This research has benefitted from funding from the Natural Sciences and Engineering Research Council of Canada (NSERC). The authors also want to thank Dr. Jane Batcheller and PCERF for support for the testing.

References

1. Song G, Wang F, editors. Firefighters' Clothing and Equipment: Performance, Protection and Comfort. 1st edition. CRC Press, Taylor & Francis Group; 2018.
2. Dolez PI, Tomer NS, Malajati Y. A quantitative method to compare the effect of thermal aging on the mechanical performance of fire protective fabrics. J Appl Polym Sci. 2019;136(6):1–15.
3. Arrieta C, David É, Dolez P, Vu-Khanh T. Hydrolytic and photochemical aging studies of a Kevlar®-PBI blend. Polym Degrad Stab. 2011 Aug;96(8):1411–9.
4. Rezazadeh M, Torvi DA. Assessment of factors affecting the continuing performance of firefighters' protective clothing: A literature review. Fire Technol. 2011;47(3):565–99.
5. Hoque MS, Saha A, Chung HJ, Dolez PI. Hydrothermal aging of fire-protective fabrics. J Appl Polym Sci. 2022 Aug 10;139(30):e52666.