Factors Affecting the Thermal Insulation and Abrasion Resistance of Heat Resistant Hydro-Entangled Nonwoven Batting Materials for Use in Firefighter Turnout Suit Thermal Liner Systems

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ABSTRACT

This paper describes a study on heat resistant nonwoven batting materials used as components in the construction of thermal liners systems in firefighter turnout suits. It examines relationships between the fiber composition and construction of hydroentangled nonwoven battings and properties that can affect their performance when used in this application. Relationships between batting porosity, weight, thermal insulation, bulk and abrasion resistance are examined in hydroentangled constructions made with oxidized PAN, para-aramid and meta-aramid fibers. Correlations observed between the insulation of batting materials components and the thermal protective performance of integrated multilayered fabric systems used in firefighter turnout suits are described.

INTRODUCTION

The materials used in the primary construction of firefighter turnout suits consist of three distinct layers: a heat resistant outer shell fabric, a moisture barrier, and a thermal liner system *Figure 1*. The thermal liner component consists of a multilayered fabric system typically incorporating an air-encapsulating nonwoven batting material quilted to a woven fabric face cloth.

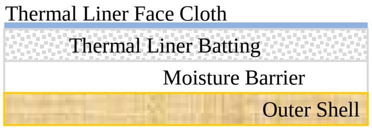

FIGURE 1. Turnout composite system with nonwoven thermal liner batting.

The thermal liner component contributes a significant portion of the thermal protective insulation of the turnout garment ensemble. The thermal liner component also contributes significantly to the turnout garment's weight and bulk. Firefighter heat stress could, therefore, be reduced by developing lighter, thinner, and more flexible thermal liners that also provide durable thermal protection against fire exposure. The objective of this research was to examine how the composition and construction of hydro-entangled batting materials affect properties important to the performance of thermal liner components used in fire fighter turnout suits.

THERMAL INSULATION IN NONWOVEN BATTING MATERIALS

Woo and Barker found that nonwoven batting materials typically possess sufficiently small void spaces to prevent the development of convective boundary layers in the entrapped air [1]. As a result, except for very thick or extremely low density battings, the convective component of heat transfer can usually be neglected in these materials. Consequently, fiber and entrapped air conduction and radiation through the fabric are the primary mechanisms for heat transfer. Farnsworth's model defines the relationship between the fabric fiber volume fraction and conductive heat transfer as follows:

$$k = (1 - f)k_a + fk_f \qquad (1)$$

Where k is fabric thermal conductivity, f is the volume fraction of component fibers; ka is the conductivity of air and kf is the conductivity of component fibers in the fabric [2].

Although this simple model does not account for fiber orientation, or for pore size and pore size distribution, it does indicate that lower density batting materials can be expected to provide higher thermal insulation due to a higher volume fraction of entrapped air. At the same time, researchers have shown that thermal insulation in very low density battings can actually increase with batting density. Dent indicated that in low density batting, increase in thermal insulation with density can be attributed to an increase in component fibers that absorb and/or scatter radiation within the batting [3]. Ankara and Barker likewise found that component fiber properties, specifically fiber fineness and cross sectional shape, can influence thermal insulation in low density nonwoven batting [4]. Their work shows very low density nonwovens, or nonwoven batting in the density range of battings that incorporate finer fibers are more effective thermal insulators. This is attributed to reduction in conductive and radiative heat transfer due to the increased surface area associated with finer fibers and fibers with non-round cross-sectional shapes.

Anjaria and Barker, and others, have found that thermal insulation of nonwoven batting materials increases with batting thickness [4,5-7]. The increase in thermal insulation as a function of thickness is caused the reduction in conduction and radiation heat transfer. Conduction through the entrapped air is reduced by the increasing the total amount of entrapped air within thicker webs. Fiber to fiber conduction is reduced by the more tortuous path created by the fibers of thicker webs. The "tortuous path" or smaller mean free path created by the fibers reduces the radiative component by increasing the radiative absorption and scattering by the component fibers within the batt [4]. The basis weight of batting materials is also positively correlated with the thermal insulation. For most nonwoven batts, basis weight cannot be considered independently of the thickness and the density.

EXPERIMENTAL PROCEDURES

Test Materials

The experimental batting materials for this study were produced as follows: Carded webs were formed by cross lapping, followed by a hydroentanglement step. Hydroentanglement was selected as an ideal method for producing thermally insulating batting because of the high void volume and three dimensional structure that typically results from this process [8].

Experimental battings were produced to examine the effects of fiber composition on the thermal insulation and abrasion resistance of hydroentangled constructions having different thicknesses, weights, and bulk densities. They were produced using three different heat resistant fibers: oxidized PAN, para-aramid, and meta-aramid fibers. As shown in *Table I*, fibers used to form the experimental battings embody different deniers and cross-sections including round, dog bone and kidney bean shapes.

TABLE I. FIBERS USED TO MANUFACTURE THERMAL LINER BATTS

Fiber Type	Linear Density (dTex)	Cross Section Shape	Fiber Density (gm/cm^3)
Meta-Aramid	1.7	Dog bone	1.38 [9]
Meta-Aramid	2.2	Dog bone	1.38 [9]
Oxidized PAN	2.0	Kidney Bean	1.35 - 1.4 [10]
Oxidized PAN	5.0	Circular	1.35 - 1.4 [10]
Para-Aramid	0.9	Circular	1.44 [11]
Para-Aramid	1.7	Circular	1.44 [11]

Sample batting materials were produced with the blend ratios described in *Table II.*

Web consolidation in the hydroentanglemant step was optimized by varying water jet pressure to achieve the optimum level of web integrity and strength. Single layer webs thus produced were subsequently made up into one, two and three layer hand samples for testing and analysis. Details of the procedures used to produce these nonwoven materials can be found in reference [12].

TABLE II. EXPERIMENTAL BATTS

Batting	Component Fiber 1	Component Fiber 2	Blend Ratio Fiber1/Fiber2
OM1	2.2dTex Oxidized PAN	1.7dTex Meta-Aramid	25% / 75%
OM2	2.2dTex Oxidized PAN	1.7dTex Meta-Aramid	50% / 50%
OM3	5.0dTex Oxidized PAN	1.7dTex Meta-Aramid	50% / 50%
OM4	5.0dTex Oxidized PAN	1.7dTex Meta-Aramid	75% / 25%
PM	0.9dTex Para-Aramid	2.2dTex Meta-Aramid	40% / 60%
PP	0.9dTex Para-Aramid	1.7dTex Para-Aramid	50% / 50%
M	1.7dTex Meta-Aramid		100% Fiber 1

BULK PROPERTIES MEASUREMENT

Test Methods

The weight of each batting sample was determined using a precision electronic balance. The weight of each sample was divided by the area of each sample in square meters to determine the basis weight in grams per square meter (gsm). Batting thickness was measured, at an applied 10 gf/cm^2 pressure using the KES-FB3 compression tester. Batting aerial density was calculated by diving measured basis weight by measured batting thickness. Batting porosity was calculated as:

$$P = 1 - \frac{\rho}{\rho_f} \qquad (2)$$

where,

P: porosity of the batting sample

ρ : density of fabric sample

ρ_f : density of component fibers

The density of the component fibers was calculated based on a weighted average as follows:

$$\rho_f = w_a \rho_a + w_b \rho_b \qquad (3)$$

where,

w_a : weight fraction of component fiber a

w_b : weight fraction of component fiber b

ρ_a : density of component fiber a

ρ_b : density of component fiber b

Multiple readings of each sample were taken and averaged to determine the thickness of each sample. At least five replicate measurements were made on each batting sample.

Measurement of Batting Performance Properties

Batting thermal insulation and abrasion resistance were measured to assess the effects of the batting designs on properties important to thermal liner performance in firefighter turnout clothing. Thermal insulation is of obvious importance to the thermal protective performance of firefighter turnout systems. Abrasion resistance is an important factor affecting the functionality and use durability in turnout suits. The abrasion resistance of the batting component can be expected to affect the ability of the thermal liner to maintain physical integrity over the wear life of the firefighter garment.

Thermal insulation was measured using a guarded hot plate using procedures described in ASTM D 1518 [13]. These procedures were modified to measure heat loss from a 12.7cm x12.7cm heated guarded plate at 35^{o}C to a controlled environmental chamber maintained at 21^{o}C and 65% relative humidity. Thermal insulation was calculates in clo units. Three samples of each batting construction were tested in one, two, and three layer batting constructions.

A modified Martindale Abrasion Test was used to evaluate the abrasion resistance of the experimental batting materials [14]. The Martindale method was modified for this study to better simulate the effects of wear abrasion on batting integrity as it may occur in the wearing of firefighter turnout suits. Therefore, since the batting layer is in direct contact with the moisture barrier membrane of turnout composite system, a fabric PTFE membrane was used as the abradant material in the Martindale test. Abrasion testing was conducted for 10,000 to 50,000 cycles, or until a tear or hole was visible in the batting sample. Each experimental batting was tested as a single layer with at least three testing repetitions.

RESULTS AND DISCUSSION

Batting Thermal Insulation

Figure 2 shows that the thermal insulation of nonwoven battings is highly correlated with their bulk thickness.

These data demonstrate that layering thin single layer webs to form thicker multilayered systems is an effective means to increase batting insulation. They indicate that the correlation between thermal insulation and batting thickness is independent of the type of heat resistant fiber used in the batting construction. On the other hand, the fiber composition of the batting does influence the relationship between measured insulation and the basis weight of these materials. *Figure 3* shows the direct correlation observed between measured thermal insulation and batting basis weight.

Figure 3 shows that the relationship between thermal insulation and batting weight is distinctly different for battings made from oxidized PAN and battings made with aramid fibers. Oxidized PAN battings provide more insulation per unit weight than do aramid fiber battings. This finding can be attributed to the greater thickness and lower density of oxidized PAN battings: Thicker battings are more insulating than thinner battings of equivalent weight, because of additional air trapped in these structures. This result indicates that, as batting weight increases, bulk density plays a more significant role determining batting thermal insulation.

Figure 4 shows the relationship between thermal batting insulation and density for multilayered constructions.

As predicted by simple models, thermal resistance is higher in low density nonwoven webs. Regression analysis of these data shows that the correlation between batting density and thermal insulation improves as the bulk density of the batting increases in one to three layered constructions. These effects are corroborated by the relationship observed between batting porosity and thermal resistance. *Figure 5* show that thermal resistance increases as the batting porosity increases. It also shows that the correlation between batting porosity and thermal resistance (clo) is best for multilayered batting constructions.

These results can be attributed to increased air entrapped in more porous batting, and to the dominant effect of air insulation in low density nonwoven structures. They corroborate the finding of other research that has indicated the complex relationship between thermal insulation and the bulk density in nonwovens [4].

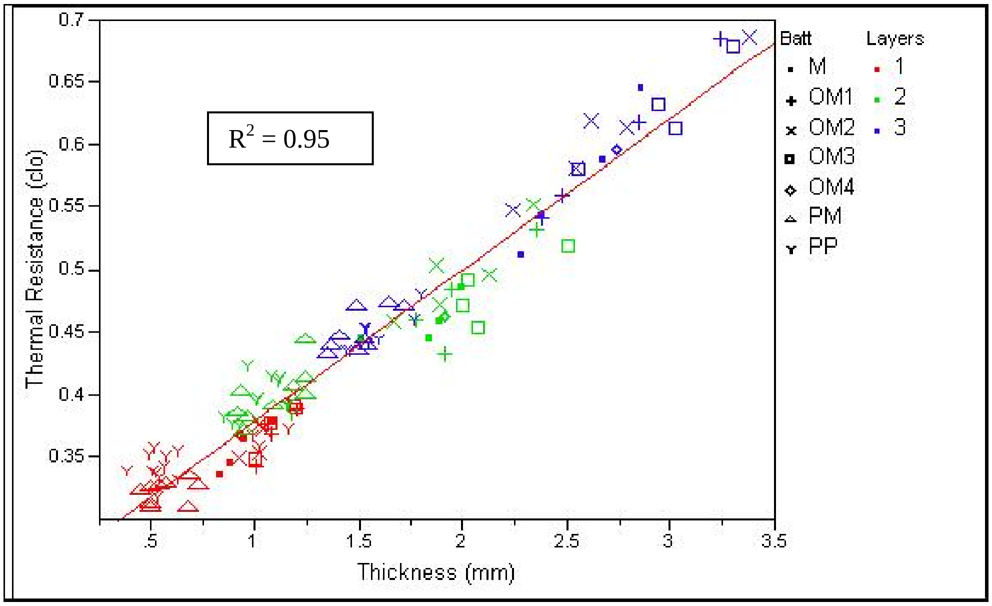

FIGURE 2. Relationship between batting thickness and thermal insulation.

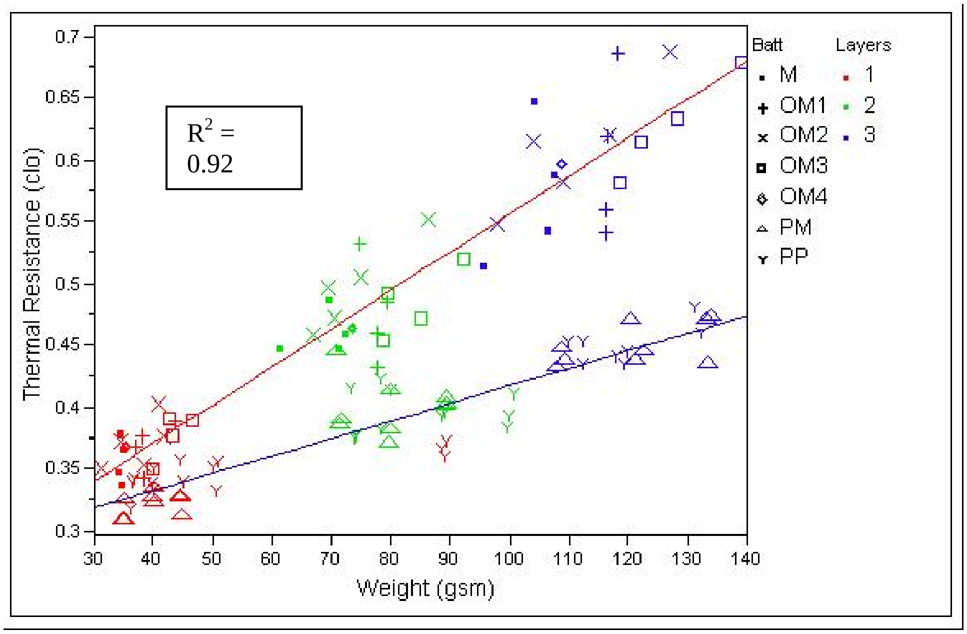

FIGURE 3. Relationship between batting basis weight and thermal insulation.

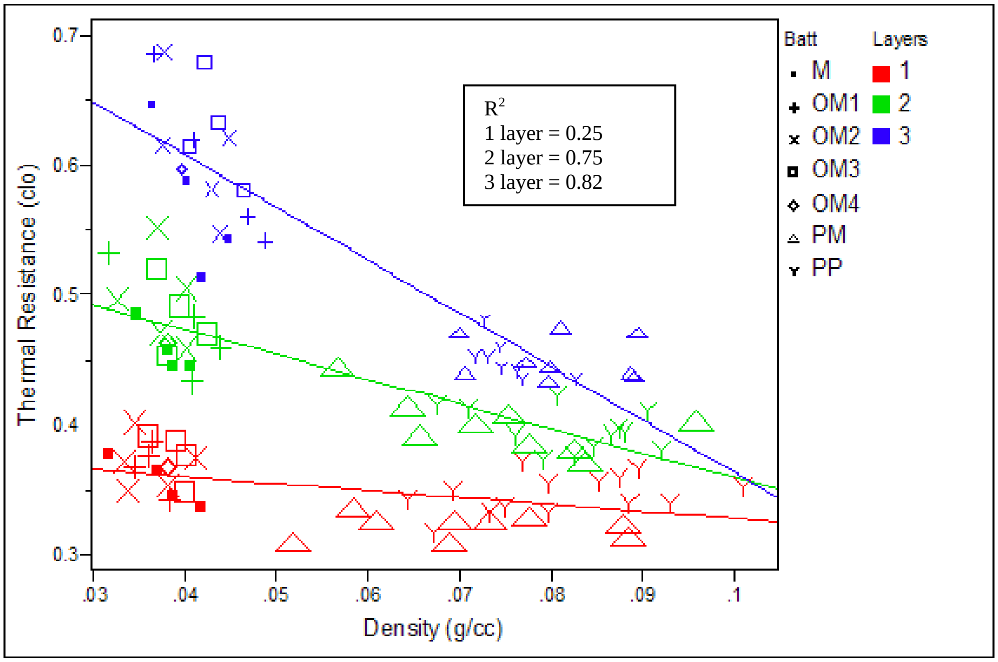

FIGURE 4. Relationship between batting bulk density and thermal insulation.

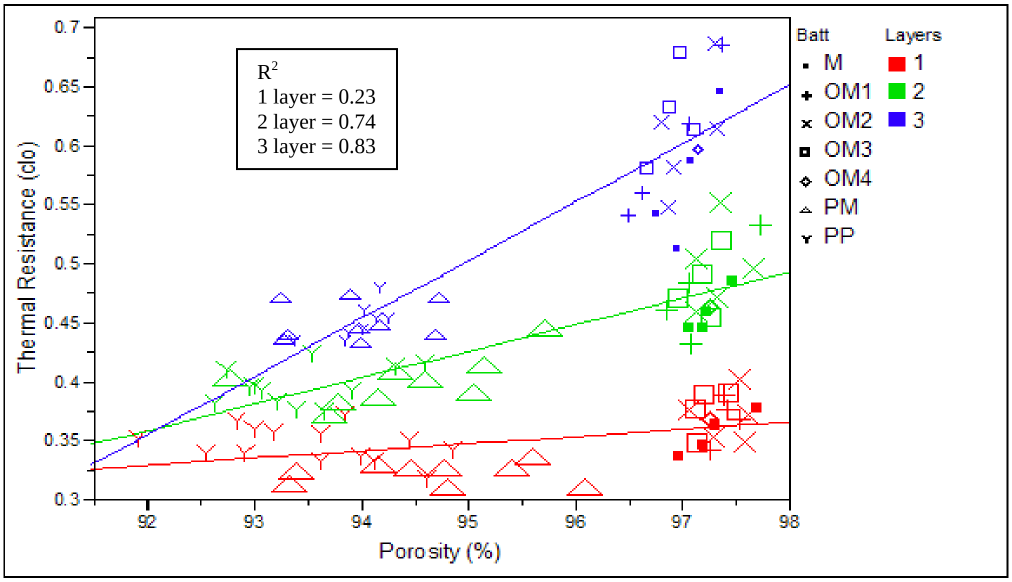

FIGURE 5. Relationship between batting porosity and thermal insulation.

They support the hypothesis that the dominant mechanism of heat conduction is through entrapped air, in multilayered hydroentangled battings produced in densities ranging from 0.03 to 0.1 g/cc. They indicate that these batting densities are sufficient to minimize convective and radiant transfer.

No significant correlations with thermal batting insulation were observed that could be directly related to fiber size or shape in these blends of oxidized PAN or meta-aramid and para-aramid heat resistant fibers. This finding is further imperial indication that absorption of radiant heat is not an important factor contributing to heat transfer in batting with bulk densities exceeding about 0.03 g/cc.

BATTING ABRASION RESISTANCE IN THERMAL LINERS

Figure 6 shows the effects of 10,000 cycles of abrasion in a modified Martindale abrasion test on the visual appearance of experimental battings made from blends of oxidized PAN and meta-aramid fibers.

These photographs show significant degradation in batting integrity in all battings that contain blends of oxidized PAN and meta-aramid fibers (Samples OM1-4). Easily observable holes and tears in the fiber web structure were visually apparent before 10,000 abrasion cycles in the abrasion test. Abrasion in the oxidized PAN/meta armid blends is obvious in comparison 100% meta-aramid batting (Sample M). Furthermore, the deterioration in abrasion resistance increased with the percentage of oxidized PAN fibers used in the batting. The poorer abrasion resistance exhibited by oxidized PAN containing battings can be attributer to their poor mechanical strength and toughness of in comparison with meta-aramid fibers. This is why abrasion resistance is somewhat better in the oxidized PAN/ meta-aramid batting that used larger denier oxidized PAN fibers (Sample OM3). The relative stiff and brittle nature of oxidized PAN fibers may also contribute to less effective web consolidation and fiber entanglement in the hydro entangling process.

Figure 7 show the effects achieved by blending para armid and meta-aramid fibers on batting abrasion resistance after 50,000 cycles in the modified Martindale test.

This comparison shows that the abrasion resistance of aramid blend battings is improved with the addition of stronger para-aramid fibers to the batting structure. The best abrasion resistance was achieved by the 100% micro denier para-aramid batting (Sample PP). This can be attributed to the tensile strength characteristic of para-aramid fibers. It can also be explained by the lower denier para-aramid sample which contribute to increased fiber flexibility that appears to translate to improved integrity of the hydro- entangled web structure.

EFFECT ON BATTING PROPERTIES ON THERMAL PROTECTIVE PERFORMANCE OF MULTILAYERED TURNOUT COMPOSITES

Because of the demonstrably poor abrasion resistance exhibited by all the batting constructions containing oxidized PAN fibers, this research focused on studying relationships between batting insulation and the thermal protective performance of thermal liner systems that use aramid fibers in their construction. For this part of the study, hydroentangled aramid fiber webs were formed into one, two and three layer hand samples to produce layered batting basis weights ranging from 35 to 135 grams per square meter, and batting thicknesses ranging from 0.4 to 1.8 millimeters. Each of these experimental battings was combined with the same moisture barrier, outer shell fabric and face cloth fabric to make up an experimental group of multilayered firefighter turnout composites for testing and analysis. The firefighter suit materials used to make up the experimental composites were selected to represent state of the art commercially available heat resistant materials. They incorporated a 6.0 oz/yd2 woven para-aramid/PBI outer shell fabric, a moisture barrier component consisting of a PTFE membrane laminated on a pajama check woven substrate, and a face cloth fabric woven from spun and filament meta-aramid yarns.

Turnout composite samples were evaluated to determine thermal protective performance (TPP) using testing procedures described in NFPA Standard 1971 [15]. The TPP test reports an index of thermal protective performance measured in thermal exposures of 84 kW/m^2 (2.0 cal/cm^2sec) 50/50 convective and radiant heat. The turnout composite is configured in the TPP test such that the heat exposure is incident on the outer shell of the turnout composite test sample.

Figure 8 shows the strong correlation observed between turnout composite TPP and the thermal insulation, or clo rating, of the nonwoven batting layer used in the thermal liner component. *Figure 9* shows that bulk thickness of the nonwoven batting is also a strong predictor of the thermal resistance of these turnout composites to intense heat exposures in a TPP test.

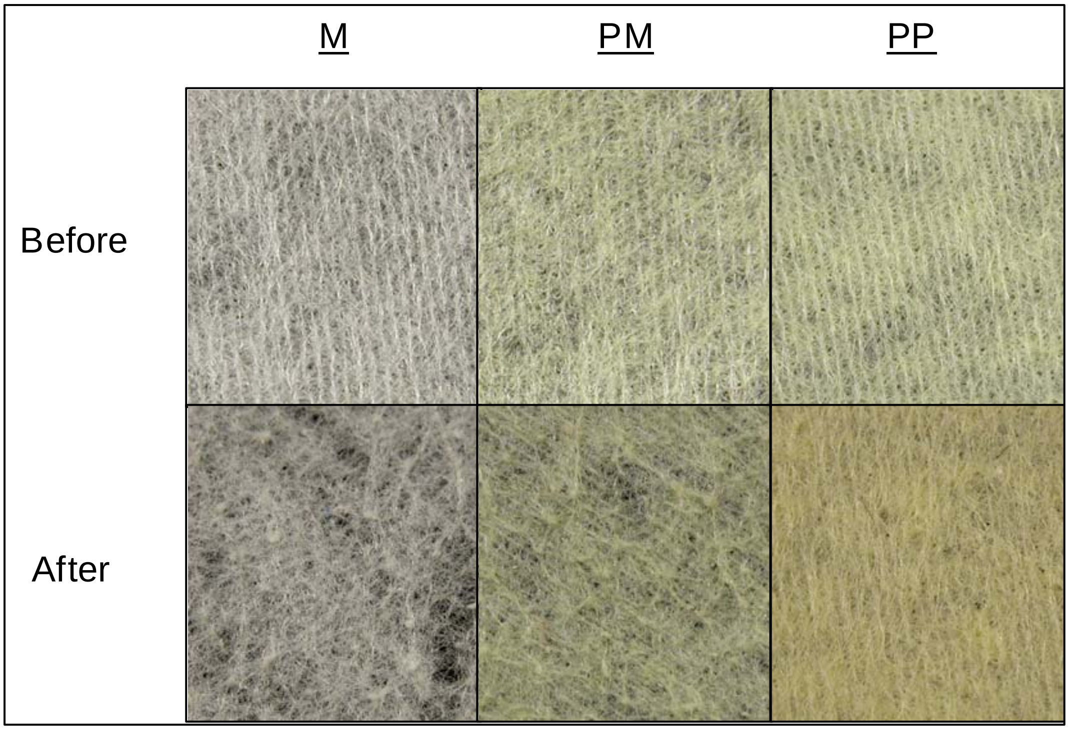

FIGURE 6. Effect of abrasion on hyrdoentangled webs made with oxidized PAN blends compared to 100% meta-aramid fibers.

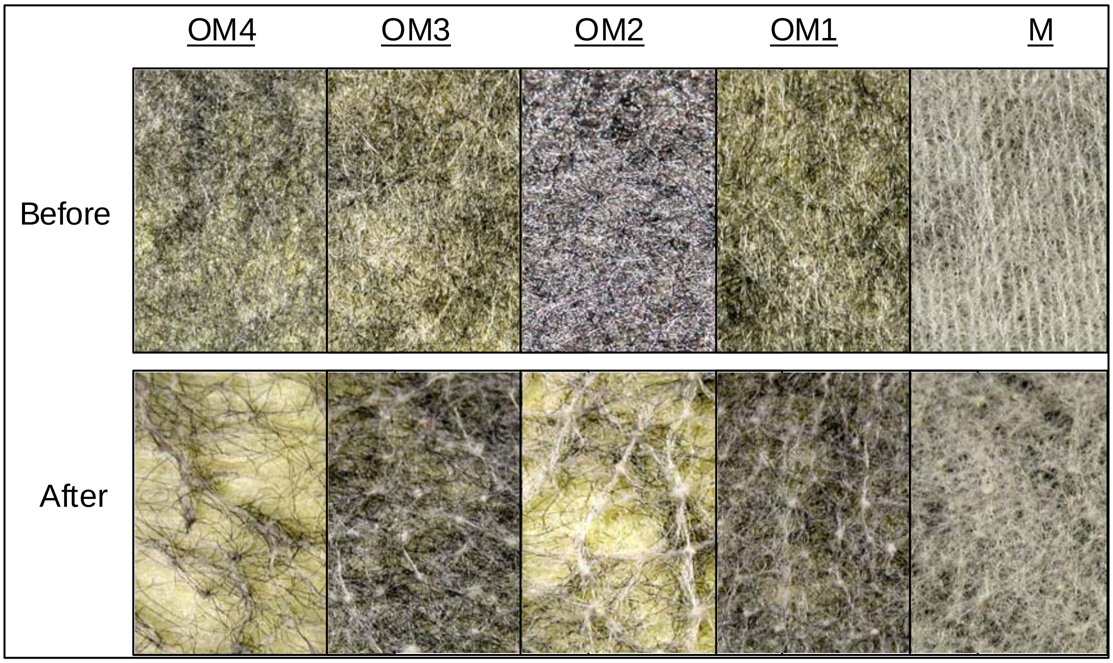

FIGURE 7. Effects of abrasion on Para- and meta-aramid battings (50,000 in Martindale cycles).

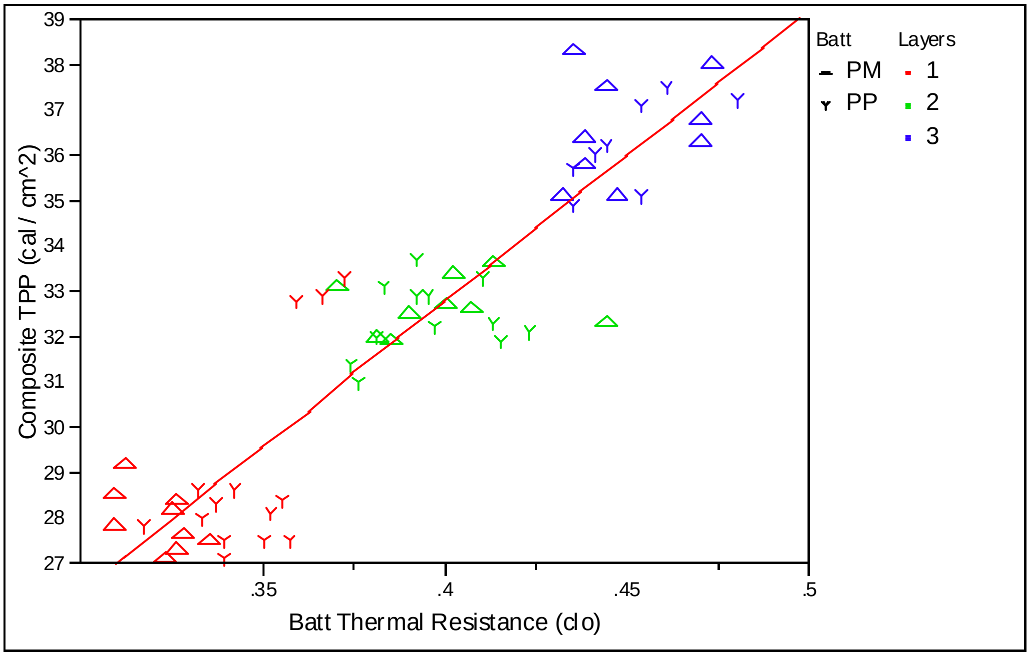

FIGURE 8. Relationship between thermal liner batting thermal insulation and turnout composite TPP.

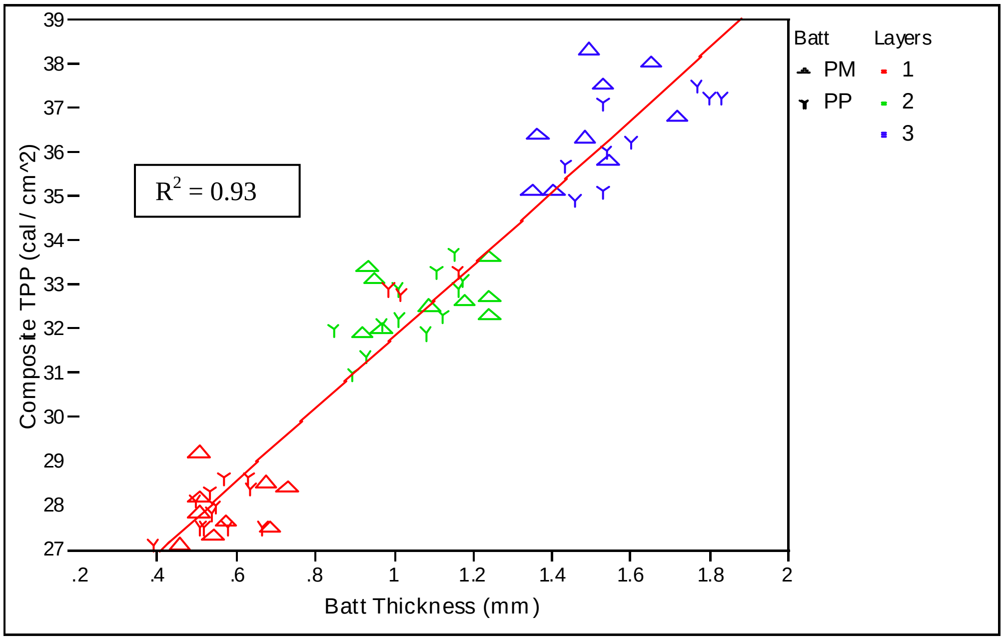

FIGURE 9. Relationship between thermal liner batting thickness and TPP of model turnout composite system.

These findings show that three layer thermal liner battings, with a minimum thickness of about 1.5 millimeters, are needed to achieve the TPP rating of 35 cal/cm2 required by the NFPA 1971 standard for these materials, when tested in combination with this outer shell fabric and moisture barrier system[15]. These results further demonstrate that the contribution of the batting layer to thermal protective performance is primarily determined by the bulk properties of the batting materials, specifically the batting weight and thickness. Differences in the batting composition related to differences between meta-aramid or par-aramid fibers, or to differences in fiber shape and dimensions are much less apparent. This finding confirms that heat conduction through trapped air is the main mechanism of heat transfer in turnout ensembles, even in exposures to the intense radiant and convective heat. It also indicates that outer shell and moisture barrier layers of the turnout composite effectively shield the thermal liner batting from most severe effects of the flame exposure.

CONCLUSIONS

This research confirms that air conduction is the primary heat transfer mechanism in hydroentangled battings produced with bulk densities exceeding about 0.03 g/cc. It shows that batting construction and thickness determine thermal insulation in these structures. It demonstrates that web layering is an effective means of enhancing insulation because it contributes air layers and thickness without adding proportionally to the weight or to the thickness of the batting. Differences related to fiber type are more apparent as they affect batting abrasion resistance than in the effect on batting thermal insulation. Constructions that incorporate brittle oxidized PAN fibers made up into thicker battings that exhibited poor performance in an abrasion test in comparison to aramid fiber battings. In aramid blends, the use of para-aramid fibers appears to increase web integrity and batting resistance to abrasion and wear.

This research shows that comparatively low bulk aramid fiber hydroentangled nonwovens can be produced that exhibit thermal insulation and abrasion resistance properties consistent with acceptable thermal protective performance and durability when integrated into thermal liner systems for firefighter suits. Three layered hydroentangled webs, made in thickness exceeding about 1.5 millimeters, provided optimum thermal protective performance when testing in a model turnout composite ensemble.

CAVEAT

This report describes the results of a limited laboratory study designed to provide a scientific basis for understanding the effects of nonwoven batting properties on thermal liner insulation and abrasion resistance. Care must be taken in drawing conclusions about the safety benefits from these data. The data describe the properties of selected fabrics in response to the controlled laboratory exposures and conditions that are specified. Study results must be weighed in light of the fact that no laboratory analysis can completely qualify complex fire fighting events, which can be physically complicated and unqualified. This study was not intended to recommend or exclude any materials from any particular application.

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REFERENCES

[1] Woo, S.S., I. Shalev, and R.L. Barker, Heat And Moisture Transfer Through Nonwoven Fabrics.1. *Heat-Transfer, Textile Research Journal*, 1994. 64(3): p. 149-162.

[2] Farnworth, B., The Mechanisms of Heat Flow Through Clothing Insulation. *Textile Research Journal*, 1983. 53: p. 717-724.

[3] Dent, R.W., Donovan, James G., and Skelton, John, Development of Synthetic Down-Alternatives, U.S. Army Natick RD&E Center, Technical Report Natick/TR-86/021L.

[4] Anjaria, M.K., Thermal Insulation Properties of Low Density Nonwoven Battings, in Textile Engineering and Science. 1988, North Carolina State University, Raleigh, North Carolina.

[5] Mohammadi, M., P. Banks-Lee, and P. Ghadimi, Determining Radiative Heat Transfer Through Heterogeneous Multilayer Nonwoven Materials. *Textile Research Journal, 2003*. 73(10): p. 896-900.

[6] Mohammadi, M., P. Banks-Lee, and P. Ghadimi, Determining Effective Thermal Conductivity of Multilayered Nonwoven Fabrics. *Textile Research Journal, 2003*. 73(9): p. 802-808.

[7] Lee, Y.M. and R.L. Barker, Thermal Protective Performance Of Heat-Resistant Fabrics In Various High-Intensity Heat Exposures. *Textile Research Journal*, Vol. 57, No. 3, pp. 123-132, March 1987.

[8] Acar, M.a.H., J.F., Textile composites from hydro-entangled non-woven fabrics. *Computers and Structures, 2000*. 76(1-3): p. 105-114.

[9] Nomex Aramid Staple Fiber. 1998, E I DUPONT NEMOURS& CO INC.

[10] Perepelkin, K.E., Oxidized (Cyclized) Polyacrylonitrile Fibers—Oxypan. A Review. *Fibre Chemistry*, *2003*. 35(6): p. 409-416.

[11] Twaron para-Aramid Pulp. 2004, TEIJIN CHEMICALS LTD.

[12] Heniford, R., "The Effects of Batting Materials on the Performance of Turnout Thermal Liners," December, 2005.

[13] ASTM D 1518-85 (Reapproved 2003) Standard Test Method for Thermal Transmittance of Textile Materials

[14] ASTM D 4966-98(2004) Standard Test Method for Abrasion Resistance of Textile Fabrics (Martindale Abrasion Tester Method).

[15] NFPA 1971 Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting.

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