Flame retardant properties of fabrics designed to be used in military camouflage

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PELIN GÜRKAN ÜNAL
MEHMET KEMAL AKIN
TARKAN AYDIN
BESTE AYDIN

ABSTRACT – REZUMAT

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In this study, wool/aramid blended yarns, as well as viscose FR yarns, were used to produce flame-retardant woven fabrics. Many fire retardancy standards also include tear strength, abrasion resistance, tensile strength and dimensional change of the fabrics during fire hazards. Therefore, these tests were included to study the fire retardant performances of the fabrics produced with 100% wool/aramid blended fibres and viscose FR fibres in the warp and wool/aramid blended fibres in the weft direction. As a result of the study, no statistically significant differences were found in the mechanical properties of the fabrics. In contrast, the thermal protective performance of the fabrics produced with wool/aramid blended yarns was better than the ones produced with viscose FR warp yarns. On the other hand, the vertical flame-retardant performance of fabrics produced with viscose FR yarns was better than those produced with wool/aramid blended yarns in both directions. As a result of the study, it was found that the use of viscose FR fibre, which is a more accessible and comfortable alternative to the wool/aramid blend, in the warp or weft direction will minimize fabric costs while providing similar flame-retardant performance without losing fabric mechanical properties.

Keywords: *aramid**,** wool, viscose FR, flammability, thermal protective performance, dimensional change.*

Proprietăți ignifuge ale țesăturilor concepute pentru a fi utilizate în camuflajele militare

În acest studiu, au fost utilizate fire în amestec de lână/aramidă, precum și fire de viscoză FR, pentru a produce țesături ignifuge. Multe standarde de rezistență la foc includ, de asemenea, rezistența la rupere, rezistența la abraziune, rezistența la tracțiune și modificarea dimensională a țesăturilor în timpul riscurilor de incendiu. Prin urmare, aceste teste au fost incluse pentru a studia performanțele ignifuge ale țesăturilor produse cu fibre în amestec 100% lână/aramidă și fibre de viscoză FR pe direcția urzelii și fibre în amestec lână/aramidă pe direcția bătăturii. În urma studiului, nu s-au constatat diferențe semnificative din punct de vedere statistic în ceea ce privește proprietățile mecanice ale țesăturilor. În schimb, performanța de protecție termică a țesăturilor produse cu fire în amestec lână/aramidă a fost mai bună decât cea a țesăturilor produse cu fire de viscoză FR pe direcția urzelii. Pe de altă parte, performanța de ignifugare verticală a țesăturilor produse cu fire de viscoză FR a fost mai bună decât a celor produse cu fire în amestec de lână/aramidă în ambele direcții. Ca rezultat al studiului, s-a constatat că utilizarea fibrelor de viscoză FR, care reprezintă o alternativă mai accesibilă și mai confortabilă la amestecul de lână/aramidă, pe direcția urzelii sau a bătăturii, va minimiza costurile țesăturilor, oferind în același timp performanțe similare de ignifugare, fără a pierde proprietățile mecanice ale țesăturilor.

Cuvinte-cheie*: aramidă, lână, viscoză FR, inflamabilitate, performanță de protecție termică, modificare dimensională*

INTRODUCTION

Fire hazards are associated with a variety of properties of a material in a particular scenario. It is determined by a combination of factors, including the material ignitability, the rate at which heat is released from it when it burns, the total amount of heat that is released, the flame spread, the smoke production, and the toxicity of the smoke [1]. As it is so far known, no natural fibre – except asbestos – is meeting all the fire hazard needs. Therefore it is also essential to provide more escape time and to reduce burn injury levels during working [2] for protective clothing made of natural fibres that are sustainable, compatible with changing environmental needs, and have less carbon imprint [3]. Amongst natural fibres, wool fibre, with its superior properties of biodegradability and recyclability, warmth and coolness, breathability, high moisture absorption, resilience, low odour and high odour absorption, softness, and flame-resistance properties, make them used in apparel clothing as well as upholstery, carpeting etc. [4]. Wool is the most resistant fibre of all the commonly used textile fibres to burning, which has an ignition temperature of 750–800°C, a high limiting oxygen index (LOI 25–26%), does not melt or drip, and forms char [4]. However, the abrasion resistance and chemical resistance of wool fibres are insufficient to produce flame-retardant protective garments since rigid precautions should be taken for designing protective clothing [5]. For this reason, blending wool fibres with highly abrasive and chemical-resistant aramid fibres will ensure not only flame-retardant garments but also combine the high comfort properties of wool with high mechanical and temperature-resistant properties of aramid fibres together. These blends can be used in areas with less fire hazard odds but where fire protection is important. Flame-retardant viscose fibres with polyimide fibre, processed with dope dyeing technology, are combined in a 50/50 ratio blend. This fabric is extensively utilized as the primary material for specialized military uniforms in European nations. In Italy, firefighting suits, and in the UK and France, riot suits employ fabrics composed of polyimide blended with flame-retardant viscose fibres. Fabrics created from a 50/50 mixture of these fibres offer outstanding comfort and enduring flame retardancy [3]. For this reason, combining viscose FR fibres with high-technical fibres not only enhances the comfort properties of the fabrics but also decreases the production costs of a fabric consisting of aramid, polyimide, and other high-technical fibres.

Heat resistance and flammability of high-performance fibres were reviewed according to literature, and high-performance fibres such as Poly(p-phenylene-2,6-benzobisoxazole) (PBO), Poly p-phenylenediamine - terephtalamide fibres (PPTA), Poly(2,6-diimidazo[4,5-b:4´,5´-e]pyridinylene-1,4(2,5-dihydroxy)phenylene) (PIPD), phenolic fibres, melamine fibres, and polyimide fibres were evaluated using cone calorimeter as well as were examined in terms of heat resistance using combined TGA/DSC. PBO and PIPD fibres exhibited the best performance [6]. In another study, PBO, PPTA, and wool-spun yarns were used to produce knitted fabrics in different blend ratios to study the heat and fire resistance of fabrics. It was found that blends of wool with p-aramids improved the FR performance of the fabrics, while blends of wool with PBO did not enhance the FR properties of the fabrics [7]. FR performance of the knitted fabrics made of blends of wool with PPTA fibres was examined and it was found that even with low percentages of PPTA of at least 30% in the blends compared to the previous study in which the blend was processed yarn by yarn, better FR results were obtained [8]. The effect of yarn count (10, 20, 30 Ne) and fibre type (para-aramid, meta-aramid, and flame-retardant polyester (FR PES) staple fibres) on the mechanical and flammability properties of the woven fabrics were investigated [9]. P-aramid fibres were found to be thermally more stable than m-aramid and FR PES fibres as the 100% p-aramid fabrics produced smaller carbonized areas and no holes or cracks [9]. The burning behaviour of woven fabrics produced from flame-retardant (FR) viscose fibres with m-aramid fibres in 3 different ratios as well as nylon 6.6 fibre with FR viscose and m-aramid fibres again in 3 different ratios was studied. It was found that blending viscose fibre with m-aramid fibres improved the limiting oxygen index, contact, radiation and convective heat index properties of the fabrics compared to that of the fabrics made of 100% FR viscose or m-aramid fibres [10].

This study was performed to produce flame-resistant camouflage fabrics that can be used in protective clothing for soldiers who need extra protection due to their job definitions. However, high flame-resistant textile materials produced from highly technical fibres to be used in protective clothing are not only sufficient by themselves. Besides, the comfort properties of the textile material during a field operation are also important. Different fibres should be blended in fibre form to produce a flame-resistant fabric having good mechanical and comfort properties. Blends of aramid fibres with wool staple fibres exhibit good mechanical properties and comfort properties, resulting in high flame-resistant textile products. This study differs from the previous studies in blending wool fibres with m-aramid/p-aramid/antistatic fibres in the form of fibre, which is very difficult since it is difficult to find long staple p-aramid fibres. Using viscose FR fibres and combining them with polyimide fibres are very popular in Europe in the production of military uniforms. Therefore, blends of wools with m-aramid/p-aramid/antistatic fibres were used to produce woven fabrics, the mechanical and flame retardancy tests were measured, and the results were examined in detail. Viscose FR fibres were also used in warp direction as an alternative to wool/m-aramid/p-aramid/anti-static fibres to evaluate the performance of viscose FR fibres, which are easily accessible and low-priced.

MATERIALS AND METHOD

Blends of m-aramid, p-aramid, and anti-static fibres with wool were used to produce single and plied yarns. These yarns were then used in the production of woven fabrics.

Foremost, the manufacturer performed the blending of m-aramid/p-aramid/anti-static fibre, and the combed fibre blend in the form of tops was supplied by the manufacturer. Aramid fibres exhibit high mechanical properties, flame retardancy, and resistance to chemicals. Anti-static fibres are somehow different in structure from the other fibres. These fibres consist of a carbon core and an insulating sheath of nylon 6. These fibres and the supplied blend are presented separately in figure 1. These

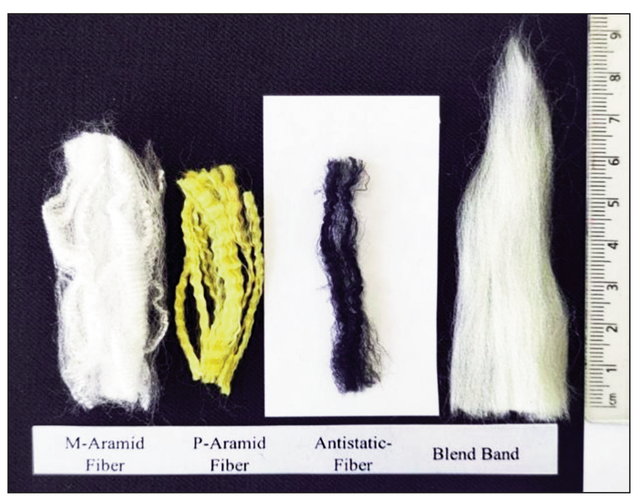

Fig. 1. M-aramid, p-aramid, antistatic fibre and the supplied blend from the right to the left

Table 1

FIBRE PROPERTIES USED WITHIN THE STUDY					
Fibre properties	**Wool**	**M-Aramid fibre**	**P-Aramid fibre**	**Antistatic fibre**	**Viscose FR**
Diameter (micron)	20	14.25	12.25	18.50	12.02
Diameter (dtex)	4.28	2.2	1.7	3.1	1.7
Variation of diameter (CV%)	19.63	-	-	-	11.76
Length (mm)	75	75	51	76	40
Variation of length (CV%)	42	-	-	-	5
Strength (g/den)	1.22–1.55	3.95	23	2.1	2.83
Elongation (%)	25–35	29.7	3.6	44.6	13

combed tops were blended in the mélange stage of wool yarn production with wool fibre in 50/50 ratios.

The properties of wool, m-aramid, p-aramid, and antistatic fibres were presented in table 1 (diameter, diameter variation, fibre length, variation of length, sliver cv). The following equation was used to convert the values between micron and dtex to compare the fineness of each fibre. For m-aramid, p-aramid, and antistatic fibres, 1.38 g/cm^3, 1.44 g/cm^3, and 1.15 g/cm^3 densities can be used, respectively. Besides, the standard deviation of diameter for synthetic fibres is very small and can be ignored. For wool fibres, 1.314 g/cm^3 for density and the standard deviation of 3.926 were used, and fineness in dtex was calculated.

$$dtex = 0.007854\,(d^2 + s^2) \times density \qquad (1)$$

Easy accessibility, low price, and high comfort properties of viscose FR fibres make them a good alternative for flame-resistant textile products. Therefore, yarns made for woven fabrics were produced with wool/aramid blended fibres, and an alternative to wool/aramid fibres was viscose FR yarns, which were also used. For yarn production, wool/m-aramid/p-aramid/anti-static fibre blend was processed on Zinser 451 ring machines with 9000 rpm spindle speed in the yarn count of Nm 50/1 with 650 turns/meter (T/m). After conventional yarn production, doubling and twisting of the yarns were performed simultaneously on Savio two-for-one machines, and yarns with Nm 50/2, 650 T/m in the S direction were produced. Viscose FR fibres were supplied from another yarn manufacturer and these yarns were doubled with the exact yarn count and twists and then dyed for camouflage fabrics.

The fabrics were produced in plain and twill 2/1 patterns on Dornier rapier weaving machines with dobby mechanisms. To produce plain fabrics, 20 warps and 19 wefts per cm were used, while 28 warps and 24 wefts per cm were used for twills. Viscose FR yarns were also used as warp yarns as an alternative to wool/aramid blended yarns. As a result, using two different patterns with two different warp yarns produced four types of woven fabrics. The properties of the woven fabrics and the blend ratios of the final fabrics are presented in table 2. All fabrics were treated with same processes such as open width washing, continuous pressing (100 °C, 15 m/min), stenter (130 °C, 40 m/min), singeing, open width washing, stenter (130 °C, 40 m/min), shearing of both sides, stenter (120 °C, 25 m/min with 20 g/l extrasoft + 10 g/l sotycel), continuous decatizing under pressure (backside, 20 m/min), decatizing and finally stenter (130 °C, 40 m/min) under the same conditions.

The properties of the woven fabrics under laboratory conditions were measured for each fabric after 24 hours of conditioning at 20±2 °C and 65±2% relative humidity. The mass per unit area and widths of the fabrics were measured according to ISO 3801:1977 and ISO 3932 standards, respectively. Tensile and tear strength of the fabrics were performed based on the ISO 13934-1 and ISO 13937-2 standards, respectively, both in warp and weft directions. Seam slippage measurements were performed according to ISO 13936-1. The fabrics' abrasion resistance

Fig. 2. Measurement of thermal protective performance on the left and vertical flammability on the right

Table 2

FABRIC PROPERTIES USED WITHIN THE STUDY				
Fabric properties	**Viscose FR_Plain**	**Viscose FR_Twill**	**Wool_Aramid_Plain**	**Wool_Aramid_Twill**
Pattern	Plain	Twill 2/1	Plain	Twill 2/1
Warp density (threads·cm^{-1})	20	28	20	28
Weft density (threads·cm^{-1})	19	24	19	24
Warp threads	Nm 50/2 Plied 650S 100% Viscose FR	Nm 50/2 Plied 650S 100% Viscose FR	Nm 50/2 Plied 650S 50% Wool 20 μ wool tops 50% blend of M. Aramid P. Aramid Antistatic fibre	Nm 50/2 Plied 650S 50% Wool 20 μ wool tops 50% blend of M. Aramid P. Aramid Antistatic fibre
Weft yarns	Nm 50/2 Plied 650S 50% Wool 20 μ wool tops 50% blend of M. Aramid P. Aramid Antistatic fibre	Nm 50/2 Plied 650S 50% Wool 20 μ wool tops 50% blend of M. Aramid P. Aramid Antistatic fibre	Nm 50/2 Plied 650S 50% Wool 20 μ wool tops 50% blend of M. Aramid P. Aramid Antistatic fibre	Nm 50/2 Plied 650S 50% Wool 20 μ wool tops 50% blend of M. Aramid P. Aramid Antistatic fibre
Fabric blend	52/24/24 52% Viscose FR 24% Wool 24% blend of M. Aramid P. Aramid Antistatic fibre	54/23/23 54% Viscose FR 23% Wool 23% blend of M. Aramid P. Aramid Antistatic fibre	50/50 50% Wool 50% blend of M. Aramid P. Aramid Antistatic fibre	50/50 50% Wool 50% blend of M. Aramid P. Aramid Antistatic fibre

and pilling tendency were measured based on ISO 12947-2 and ISO 12945-2, respectively. Determination of dimensional change of the fabrics with steaming on ironing machines was performed according to ISO 53984-2. Dry-rubbing, wet-rubbing, and dry-cleaning fastness of the fabrics were also measured according to ISO 105-D01, ISO 105-X12, and ISO 105-X12 standards, respectively.

Thermal protective performances and vertical flammability of the fabrics were measured according to ISO 17492:2003 and ASTM D 6413-08:2015. Fabric samples should be pretreated according to ISO 6330:2012 before vertical flammability of the fabrics. Fabric samples were washed at 60±3 °C with ECE reference detergent of (20±1 g) 5 times and dried with a tumble dryer 5 times.

Analysis of variance was performed for the observed measurements. Based on the experimental design and data type, variance analysis with one factor, two factors, and Friedman non-parametric analysis was performed. Obtained p-values less than 0.05 mean that the effect of that specific factor has a statistically significant effect on that fabric property.

RESULTS AND DISCUSSION

The yarns were produced in the yarn count of Nm 50/2 as a plied yarn. To compare the flame-resistance performance of different fabrics that are inherently FR, such as wool/aramid/anti-static fibre blend and an FR viscose yarn, which are accessible and less costly, Nm 50/2 viscose FR double-plied yarns were also produced. The properties of produced single and plied yarns of wool/aramid/anti-static fibre blends and doubled viscose FR yarns before and after dyeing processes are given in table 3.

The mean values of yarn count and turns per meter were observed to be similar for viscose FR and wool/aramid blended yarns. However, yarn quality parameters such as yarn evenness (U%), coefficient variation of yarn evenness (CVm), thin, thick places, and neps values were better for raw viscose FR yarns compared to those of the wool/aramid blended yarns. This is due to the nature of wool fibre because wool is a natural fibre; it consists of a high coefficient of variation values for fibre properties of fineness, length, etc. Therefore, this property during the conversion of fibres to yarns is reflected in yarns. The effect of doubling could easily be seen when the results of the wool/aramid blended or raw viscose FR yarns were observed. Yarn doubling enhanced the yarns' properties, resulting in better U%, CVm, thin, thick places and neps. In addition to quality parameters, yarn doubling improved the tenacity and elongation properties of the yarns and decreased the hairiness of these yarns regardless of fibre type. When the results of the tenacity values of doubled wool/aramid blended and viscose FR yarns were examined, the tenacity values of wool/aramid blended yarns were 35% higher than that of the viscose FR yarns. This is due to the nature of aramid fibres, which have high tenacity properties. On the other side, the effect of package dyeing can easily be seen from the results of the yarn quality parameters of viscose FR yarns. Thick places and neps values

Table 3

MEASURED PROPERTIES OF THE YARNS USED WITHIN THE STUDY											
Fibre blend	**Nominal count**	**Count (Nm)**	**T/m**	**U%**	**CVm**	**H (S3)**	**Thin –50%/km**	**Thick +50%/km**	**Neps +200%/km**	**Tenacity (cN/tex)**	**Elongation (%)**
Wool-Aramid	Nm 50/1	50.74	656.40	17.12	23.30	2207.88	243.16	781.32	4538.58	14.00	15.12
Plied Wool-Aramid	Nm 50/2	25.61	642.80	12.88	17.61	1536.60	4.75	320.50	2843.70	17.49	24.31
Raw Viscose FR	Nm 50/1	50.67	905.00	11.40	14.45	1101.00	10.00	75.00	112.00	10.77	7.10
Plied Raw Viscose FR	Nm 50/2	26.13	649.10	8.44	10.67	572.60	0.00	1.75	10.50	12.64	11.87
Dyed Viscose FR	Nm 50/2	25.08	641.80	8.44	11.23	971.00	0.00	1.00	3.00	11.31	15.45

increased after package dyeing due to the movement of the dye solution from inside to outside and vice versa. Furthermore, the hairiness of the dyed yarns almost doubled, and the tenacity of the yarns was affected negatively, as expected.

The mass per unit area results of the fabrics are presented in figure 3. Weft and warp densities were fixed considering the weaving patterns of the fabrics on the weaving machine. The effect of the weaving pattern on the mass per unit area results can easily be seen from the results. Twill fabrics had higher mass per unit area results regardless of fibre type used in the warp direction since high warp and weft densities were used during the production of twill fabrics as well and higher fabric shrinkages occurred compared to that of plain fabrics due to the higher capacity of free moveable yarns in the twill structure. Based on the results, using viscose FR yarns in the warp direction of plain fabrics did not change mass per unit area results compared to the plain fabrics made of wool/aramid blended yarns in the warp direction. However, the situation is different for twill fabrics. Based on two-factor variance analysis without replications, there was no statistically significant difference between the mean values of each group ($p > 0.05$).

The tensile strength values of the fabrics are given in figure 4. The first bars in each group represented the tensile strength values of the fabrics in the weft direction. As mentioned in the materials and method section, wool/aramid blended yarns were used in the weft direction of all fabrics. As the values in the weft direction were observed in detail, no difference was found except due to the effect of weaving pattern differences. In twill fabrics, the tensile strength values of the fabrics were higher than that of the plain fabrics based on the higher weft densities used to produce twill fabrics. Based on the analysis of two-factor variance without replication, no significant differences between mean values of either yarn type or pattern type were found ($p > 0.05$).

The second bars in each group represented the tensile strength values in the warp direction. Using wool/aramid blended yarns in the warp direction increased the tensile strength values of the fabrics compared to that of the fabrics produced with viscose FR yarns due to lower tenacity values of viscose FR yarns compared to that of wool/aramid blended yarns (wool/aramid blended plied yarns had 54.6 % higher tenacity values). This difference in yarn tenacity values was reflected directly in the results of plain and twill fabrics produced with either viscose FR warp yarns or wool/aramid blended warp yarns. Based on the statistical analysis of two factors without replication, no significant difference was found in terms of different yarns and pattern use ($p > 0.05$ both for yarn type and pattern type).

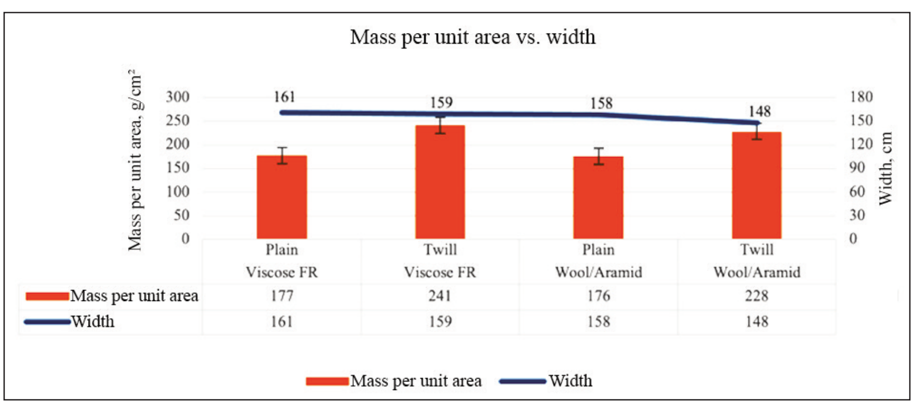

Fig. 3. Mass per unit area results of the fabrics based on the fabric width values

Tear strength is one of the essential mechanical tests that the fabrics meet the requirements of flame-retardant standards. Generally, tear strength mainly depends on free movable yarns and the capacity of yarns packing together. Thus, these two parameters are influenced by the weaving pattern and related yarn density of fabrics, which are measured in that direction. Along with these parameters, the constituent yarn tenacity of the fabric is one of the most critical factors. When the results were evaluated in this context, weaving patterns, warp/weft densities, and viscose FR instead of wool/aramid blended yarns were the factors that affected the tear strength results of the fabrics.

The first bars in each group represent the values of the tear strength in the weft direction. In the weft direction of all fabrics, the same yarns, wool/aramid blended yarns, were used. Thus, in the first pair, the difference was related to the weaving pattern and the weft density. These two parameters inversely affect the tear strength of the fabrics. As it is well known, increasing the movement ability of yarns in the fabric structure increases the tear strength of the fabrics. While the twill pattern causes yarns to be grouped and acted together and increasing the weft yarn density causes the yarns to be packed in a denser structure and makes their movement difficult, on the one hand, using twill instead of plain increased the tear strength values on the other hand, increasing the weft density decreased the tear strength values of the fabrics. As a result, a 7.25% increment in the tear strength in the weft direction occurred in the twill fabrics produced with viscose FR warp yarns. However, a 3.75% decrement had occurred in the weft tear strength values of the fabrics based on the pattern change produced with wool/aramid blended warp yarns, which was insignificant and was under the acceptable quality limits. Another significant result obtained from the weft tear strength of the fabrics produced with viscose FR warp yarns and wool/aramid blended warp yarns was that higher weft tear strength values were obtained with the fabrics produced with 100% wool/aramid blended yarns due to higher tenacity values of wool/aramid blended compared to that of viscose FR yarns. However, no statistically significant difference was found between the mean values of fabric groups based on the two-factor ANOVA without replication ($p > 0.05$).

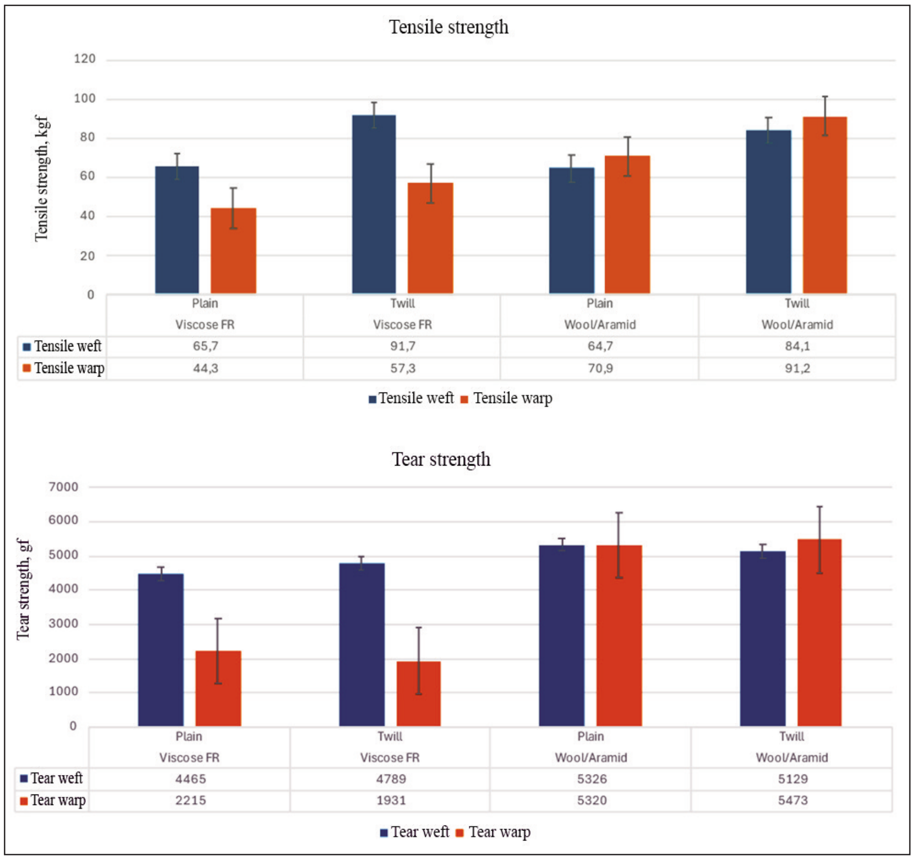

Fig. 4. Tensile and tear strength of the fabrics in both directions

The most significant difference occurred in the warp tear strength values. Using viscose FR in the warp direction led to low tear strength values due to lower tenacity values of viscose FR yarns compared to wool/aramid blended yarns. Using twill patterns and high warp densities in the fabric construction affected the warp tear strength similarly as explained in the weft tear strength. Based on the statistical analysis, except for the yarn parameter in warp direction results, no significant difference was found for mean differences ($p = 0.041$ for different warp yarn use in warp direction results).

Seam slippage is another crucial mechanical property that should be measured for most flame-retardant standard tests. The observed measurements of the fabrics in weft and warp directions are presented in figure 5. Seam slippage is defined as the slippage of weft threads on the warp or slippage of warp threads on the weft, the value of which depends on the fabric structure and the finishing applied when the stitch is subjected to a particular load. This not only results in partial or complete deterioration of the appearance of the garment but also reduces the lifespan of the garment. The fabrics' mechanical properties have a great impact on seam slippage; for example, increasing fabric thickness results in decreasing seam slippage. As skips increase in the texture structure, thread slippage becomes easier, and weft density has a greater effect on stitch slippage than warp density. When the results were evaluated within the relevant factors, the weft direction seam opening strength values were similar because the same weft yarns of wool/aramid blended yarns were used. On the other hand, seam slippage strength results in warp direction were all the same despite using viscose FR yarns in the warp direction. No statistically significant difference was found between the means based on the use of different warp yarns and patterns.

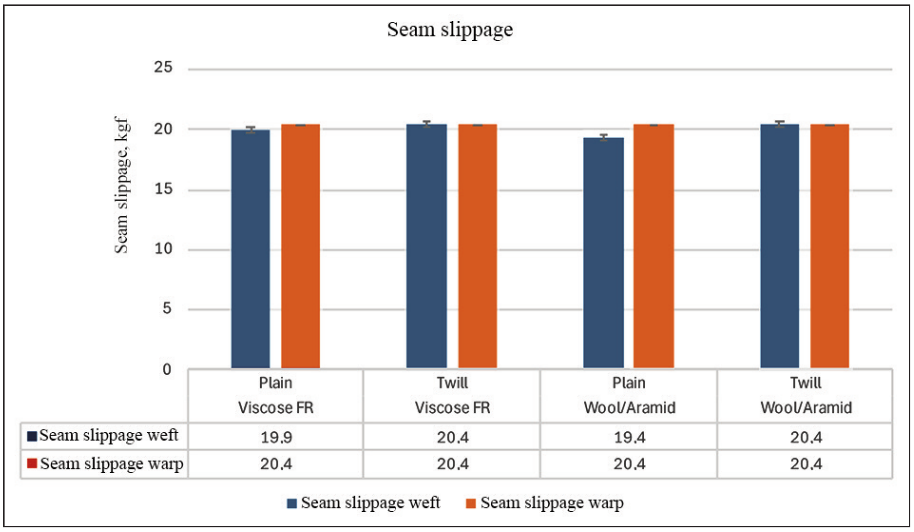

Fig. 5. Seam slippage of the fabrics in both directions

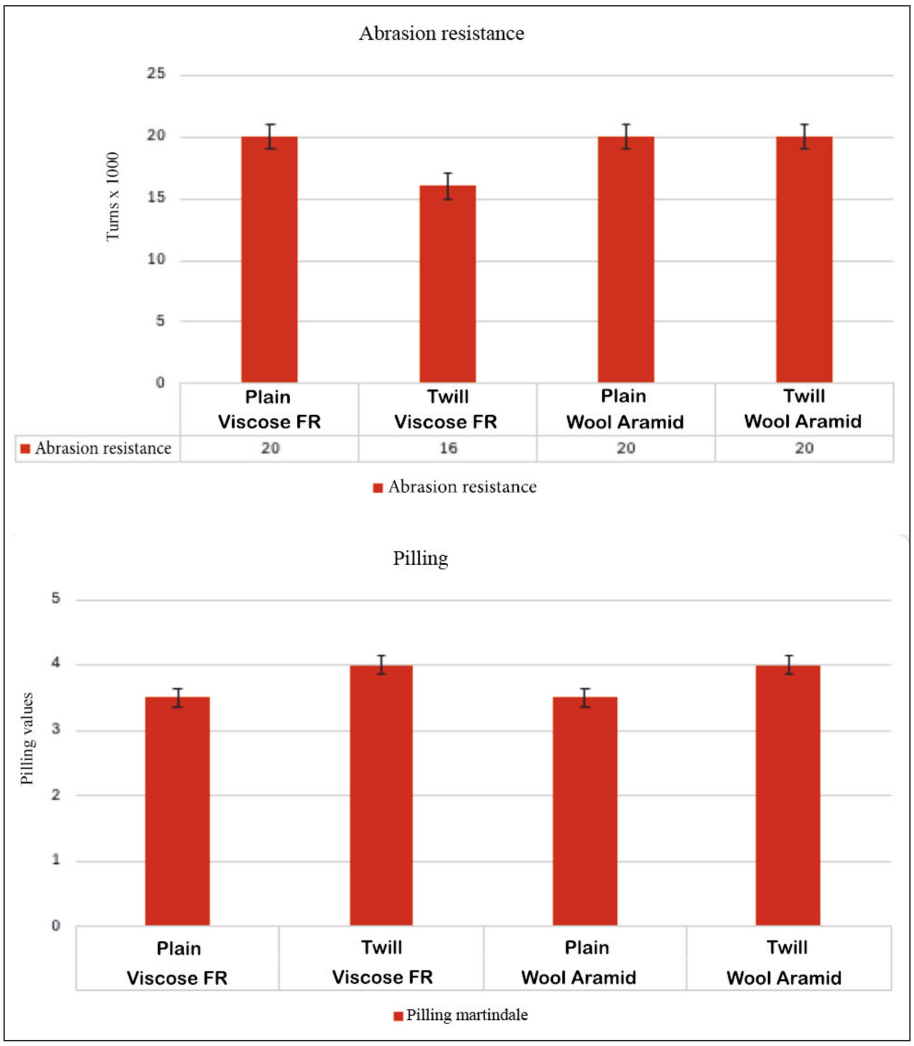

Fig. 6. Abrasion resistance and pilling properties of the fabrics

Abrasion properties of the fabrics affect the garment's appearance during usage. Abrasion of the fabric can lead to a reduction in weight and thickness, and eventually, the fabric will fail, with a hole forming, which exposes the wearer directly to an electric arc or fire threat [11]. Thus, some parts of the garments must endure abrasive forces, such as the crotch area for pants and armpits for shirts. Uniforms, especially for police forces or firemen, must meet these requirements as well as they can allow different body movements and withstand extreme conditions.

Therefore, the abrasion resistance of the fabrics was measured and presented in figure 6. All fabrics had the same abrasion values except twill fabrics produced with viscose FR warp yarns. According to statistical analysis of two factors without replication, no statistically significant difference was found between the means based on different warp yarn and pattern use ($p > 0.05$).

The pilling property is another important fabric property that affects the garment's appearance during usage. The pilling results of the fabrics were measured and presented in figure 6.

Commonly, the pilling property of a fabric is affected by fibre type, yarn property, especially hairiness, and fabric construction (warp/weft densities, weaving pattern). When results were evaluated in this context, it can easily be seen that all the fabrics had similar piling results. There was no difference observed regarding the yarn type since the expectation was that using viscose FR yarns would cause less pilling in the fabrics since viscose FR yarns had less hairiness; on the other hand, wool/aramid blended fibres are long staple fibres, which would cause less pilling. These two factors reconciled, and the fabrics had the same pilling values. On the contrary expectation, the twill pattern improved the pilling results of the fabrics compared to the plain fabrics. In twill fabrics, yarn floats are more compared to plain fabrics in which yarns would be more exposed to friction forces and cause more pilling on the fabric surface. However, this situation is valid for fabrics with the same densities. In this study, twill fabrics had higher densities of warp/weft which would result in denser structure and less exposure to friction forces per unit yarn. Pilling values are ordinal values; therefore, based on Friedman's non-parametric test results, there were no statistically significant differences between fabric groups. Dimensional changes after the Hoffman press in both directions were presented in figure 7. Fabric shrinkage is essential, especially for woollen fabrics. However, shrinkage is another important property, and a flame-retardant fabric should meet the requirements of related standards since nobody wants his/her clothing to shrink under fire conditions. Low shrinkage values mean that the dimensional change of fabrics is low and fabrics are stable or set. All dimensional changes, both in weft and warp directions, were low for all fabrics. For the weft direction, dimensional change in twill fabrics was 0.3%, while for plain, this value was 0.5%. For warp direction, no trend was observed regarding different yarn composition and weaving patterns. Based on a statistical analysis of two factors without replication, no statistically significant difference was found between the means based on different warp yarn and pattern use ($p > 0.05$).

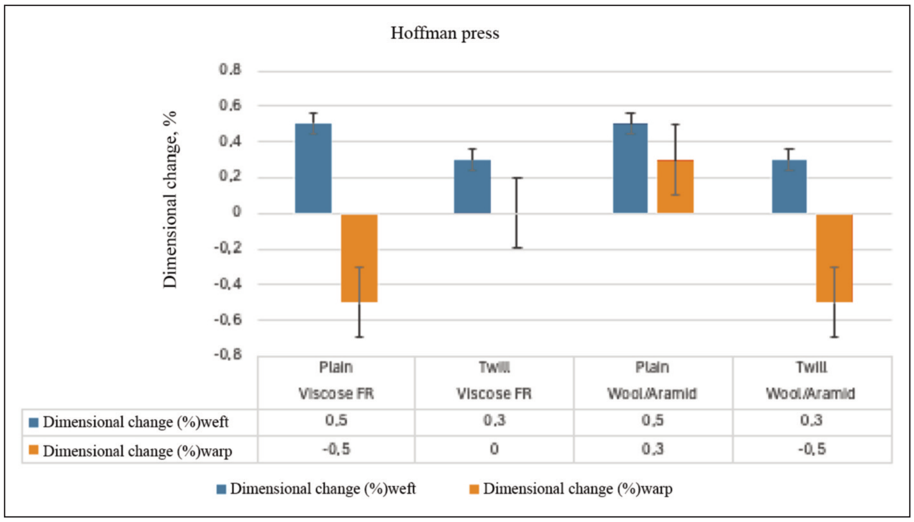

Fig. 7. Dimensional changes of the fabrics after Hoffman press in both directions

Flammability characteristics and thermal barrier performance are important for a garment to provide flame and thermal protection [12]. The thermal protection, or thermal barrier performance, of a fabric, can be evaluated by benchtop tests that expose the outside surface of the fabric to a heat source and measure the heat flux transmitted on the back side of the fabric. A standard version of a thermal protection test, commonly called the Thermal Protective Performance (TPP) test, is described by ISO 17492 [12], which simulates typical fire conditions through the combination of convective heat and radiant heat. Therefore, a specimen is exposed to typical fire conditions: The heat source consists of 50% convective heat and 50% radiant heat. The heat flow adds up to 84 kW/m^2 (approximately 2 cal/cm^2/sec.). The test determines the time and applied heat energy per unit area (TPP) on the back of the textile which would result in second-degree burns on the skin. Higher TPP values mean the product will provide more insulation to the wearer from outside exposures. In other words, higher values of TPP mean that the product will increase the amount of time available before a burn at a known exposure. TPP is calculated with the equation of *TPP = time to second – degree burn × exposure*. When the results were evaluated, plain fabrics produced with 100% wool/aramid blended yarns had higher values of both TPP and time to record pain. Statistical analysis was performed, and it was found that differences between these fabrics regarding TPP variables were statistically meaningful. However, for flame-resistant fabrics, the minimum limit for TPP rating is 35 cal/cm^2, which means that all fabric samples failed to pass.

The results of the vertical flammability test are shown in table 5. Ten specimens were evaluated for vertical flame testing (five samples from each direction of the fabric). Each sample was exposed to a controlled flame for a specified amount of time before the source of the flame was removed. Measurements were taken as after flame time – the length of time for which a material continues to burn after the ignition source has been removed; after glow time – the time afterglow continues after the removal of the ignition source and the cessation of flaming, and char length-in measuring flame resistance of textiles, the distance from the fabric edge, which is directly exposed to the flame to the furthest point of visible fabric damage after a specified tearing force has been applied.

Table 4

THERMAL PROTECTION PERFORMANCES OF PLAIN FABRICS

Warp	Weft	Time to record pain (s)	Time to 2nd degree burn (s)	TTP rating (cal/cm^2)	Fabric Failure Factor
Viscose FR	Wool/Aramid	3.80	5.17	10.37	5.87
Wool/Aramid	Wool/Aramid	4.83	6.50	13.00	5.63
p (sig. value)		0.00	0.00	0.00	0.00

Table 5

RESULTS OF VERTICAL FLAMMABILITY TESTS OF PLAIN FABRICS						
Parameter	**Weft**	**Wool/Aramid**	**Wool/Aramid**	**Wool/Aramid**	**Wool/Aramid**	**p (sig.value)**
	Warp	**Viscose FR**	**Viscose FR**	**Wool/Aramid**	**Wool/Aramid**	
	Pre-treatment	**No**	**5w-5d**	**No**	**5w-5d**	p1/p2
After flame time (s)	warp	$0.00^1/0.00^2$	$0.00^1/0.00^2$	$0.00^1/0.00^2$	$0.22^1/1.10^2$	0.33/0.33
	weft	$0.00^1/0.00^2$	$0.00^1/0.00^2$	$0.56^1/2.80^2$	$0.00^1/0.00^2$	0.33/0.33
After glow time (s)	warp	$0.00^1/0.00^2$	$0.00^1/0.00^2$	$2.92^1/3.40^2$	$3.98^1/4.30^2$	0.00/0.00
	weft	$0.00^1/0.00^2$	$0.00^1/0.00^2$	$2.96^1/3.90^2$	$5.08^1/7.50^2$	0.00/0.01
Char length (mm)	warp	$46.20^1/51.00^2$	$49.40^1/53.00^2$	$77.60^1/101.00^2$	$68.40^1/80.00^2$	0.00/0.54
	weft	$142.20^1/182.00^2$	$125.20^1/132.00^2$	$89.88^1/101.00^2$	$63.20^1/88.00^2$	0.00/0.00
Melting/dripping	warp	No	No	No	No	-
	weft	No	No	No	No	-

Note: [1]First values are averages and [2]the second are maximum values observed during tests. p1 stands for the possibility of the mean difference between the fabrics made of viscose FR and wool/aramid blended yarns. p2 stands for the possibility of the mean difference between the non-treated and treated yarns.

Observations include any melting and/or dripping that may occur during testing [13].
It was observed that both the "after flame" and "after-glow time" of the fabrics produced with viscose FR warp yarns and wool/aramid blended weft yarns was less than the plain fabrics produced with wool/aramid blended yarns both used as warp and weft yarns. Most protective clothing standards, such as in ASTM F 1506-22, and NFPA 2112, after the flame time of the protective clothing, should be less than 2 seconds. When the results were evaluated in this context, all fabrics had less than 2 seconds on average after flame time. According to the Standard on Emergency Services Work Apparel of the National Fire Protection Association, Massachusetts, USA (NFPA 1975), it is recommended that the char length should not be more than 150 mm [14]. Based on this result, the fabrics produced with viscose FR warp yarns and wool/aramid blended yarns passed the test with average values of char length. However, the non-treated fabrics produced with viscose FR warp yarns and wool/aramid blended weft yarns failed to pass the char length in the weft direction since the maximum result of the tests was 182.00 mm. During this test, melting/dripping of the samples was also noted, and there was no observation, including any melting/dripping.
Fastness results of the fabrics are presented in table 6. All fabrics had the same dry and wet rubbing fastness results. Nevertheless, the fastness of dry-cleaning values of fabrics produced with viscose FR yarns was less than that of the fabrics produced with wool/aramid blended yarns.

Table 6

RESULTS OF DIFFERENT FASTNESS RESULTS OF THE FABRICS				
Warp	**Viscose FR**	**Viscose FR**	**Wool/ Aramid**	**Wool/ Aramid**
Pattern	Plain	Twill	Plain	Twill
Dry rubbing	4.5	4.5	4.5	4.5
Wet rubbing	4.5	4.5	4.5	4.5
Dry-cleaning	3	3	4	4

CONCLUSION

In this study, flame-resistant camouflage fabrics to be used in military operations were produced by using the yarns of wool fibres blended with m-aramid, p-aramid, and antistatic fibres and the yarns of viscose FR fibres. The fabrics were produced in two different patterns, resulting in four different fabrics. Thermal protective performance and vertical flammability of the fabrics, as well as tear strength, seam slippage, shrinkage, and abrasion resistance, which are found in many flame retardancy standards, were also measured. As a result of the study, the mechanical performances of the fabrics did not show significantly different results, while results of TPP and vertical flammability tests of the fabrics led to different conclusions.
Plain fabrics produced with 100% wool/aramid blended fibres had better results than those produced with viscose FR warps and wool/aramid blended weft yarns in terms of TPP results. However, the results of vertical flammability tests of the fabrics produced with viscose FR warp yarns and wool/aramid blended weft yarns were better than those produced with 100% wool/aramid blended yarns. Blending aramid fibres with wool fibres in 50/50 ratios decreased the flammability performance of aramid fibres relatively compared to using 100% viscose FR. As a result, fabrics with viscose FR yarns may be used in which the wearer may be subjected to direct flame, not for a prolonged time; on the other hand, fabrics made of wool/aramid blended fibres may be a good alternative for the wearer subjected to severe radiant and convective heat.
As it is well known, these flammability standards and tests aim for real-life situation simulation. However,

under actual conditions, fabrics can behave differently from the results obtained from the measurements. At least these tests give a comparative idea of the produced fabrics, and these designed fabrics may be used, for example, in military field operations where neither direct flame nor radiant and convective heat for prolonged periods are exposed.

The most significant limitation of this study is to blend the wool fibres with p-aramid fibres, which are very difficult to find in long staples. Therefore, the blending of m-aramid/p-aramid/and antistatic fibre was performed in another professional fibre mill.

Another limitation is the cost of the designed fabrics. For this reason, viscose FR fibres, which are less costly and more comfortable compared to aramid fibres and are very popular in the production of military uniforms, were added to the study. Thus, using 100% viscose FR fibres in one direction of the fabric improved the vertical flammability properties of the fabrics compared to wool/aramid blended yarn usage. Meanwhile, the mechanical properties of the fabrics under examination differed slightly from each other which is also another plus for viscose FR fibres. Furthermore, the production costs of fabrics using viscose FR warp yarns were 30% less than the cost of fabrics made of 100% wool/aramid blended fibres. In future works, fabrics produced with 100% viscose FR, and 100% aramid blended yarns can also be added. In addition to the mechanical and flammability properties of the fabrics, comfort properties such as thermal insulation and air and water permeability of the fabrics can also be studied.

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Authors:

PELIN GÜRKAN ÜNAL[1], MEHMET KEMAL AKIN[2], TARKAN AYDIN[2], BESTE AYDIN[2]

[1]Tekirdağ Namık Kemal University, Çorlu Engineering Faculty, Textile Engineering Dept., Çorlu, Tekirdağ, Türkiye

[2]Altınyıldız Tekstil ve Konfeksiyon A.Ş. Tasarım Merkezi, Çerkezköy, Tekirdağ, Türkiye
e-mail: mehmet.akin@altinyildiz.com.tr, tarkan.aydin@altinyildiz.com.tr, beste.aydin@altinyildiz.com.tr

Corresponding author:

Prof. Dr. PELIN GÜRKAN ÜNAL
e-mail: pgunal@nku.edu.tr, https://orcid.org/0000-0001-8141-5627