(REFEREED RESEARCH)

BURNING BEHAVIOUR AND MECHANICAL PROPERTIES OF FABRICS WOVEN WITH RING SPUN ARAMID AND FLAME RETARDANT POLYESTER YARNS

ARAMİD VE GÜÇ TUTUŞUR POLİESTER RİNG İPLİKLERİYLE DOKUNMUŞ KUMAŞLARIN YANMA DAVRANIŞLARI VE MEKANİK ÖZELLİKLERİ

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ABSTRACT

In recent years, demand for flame resistant fibres and fabrics has been growing rapidly in the market, especially for the manufacture of garments for protection in environments where there are hazards such as electric arc discharge, molten metal splashes and fire. In this study, para-aramid, meta-aramid and flame retardant polyester (FR PES) staple fibres were spun on the ring frame to produce the woven fabrics especially for the applications where protection against heat and flame is important. For the production of woven fabrics, three different yarn counts (10, 20, 30 Ne) of para-aramid, meta-aramid and FR PES yarns were spun as weft yarns and 2-ply spun para-aramid yarns (30/2 Ne) were used as warp yarns. The effect of yarn count and fibre type on the mechanical and flammability properties of the woven fabrics were investigated and evaluated statistically. Furthermore, to compare the carbonized areas on the flame spread test samples, binarization technique was employed by image analysis software.

Key Words: Flame resistant fibres and fabrics, Aramid fibres, Flame retardant polyester fibres, Burning behaviour of fabrics, Image analysis.

ÖZET

Son yıllarda tekstil pazarında özellikle yangın, erimiş metal sıçraması ve ark boşalması gibi tehlikelerin bulunduğu ortamlarda kullanılan koruyucu giysilerin üretiminde kullanılan aleve dayanıklı lifler ve kumaşlara olan talep hızla artmaktadır. Bu çalışmada, ısı ve alevden korunmanın önemli olduğu uygulamalarda kullanılmak üzere, ring iplik makinesinde üretilmiş para-aramid, meta-aramid ve güç tutuşur poliester ipliklerle kumaşlar dokunmuştur. Kumaşların üretiminde para-aramid, meta-aramid ve FR PES esaslı üç farklı lif tipinden üç farklı numarada (Ne 10, 20, 30) atkı iplikleri üretilmiş; çözgü ipliği olarak ise Ne 30/2 para-aramid iplikleri kullanılmıştır. İplik numarasının ve lif tipinin kumaşların yanma davranışı ve mekanik özellikleri üzerindeki etkisi istatistiksel olarak incelenmiştir. Ayrıca alev yayılma testi sonrası kumaşlar üzerindeki karbonlanmış alanları karşılaştırmak için iki renkli resim haline getirme yöntemi kullanılmıştır.

Anahtar Kelimeler: Aleve dayanıklı lifler ve kumaşlar, Aramid lifleri, Güç tutuşur poliester lifleri, Kumaşların yanma davranışı, Görüntü analizi.

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1. INTRODUCTION

Aramid and flame retardant polyester (FR PES) fibres are widely used in different areas of protective textiles. The products which are made of aramid fibres provide protection against flames and high temperatures for car racing, high risk industries and army. FR PES fibres are generally used for curtains, upholstery fabrics and bedding equipment.

The term ‘‘aramid’’ is designated for the fibres of the aromatic polyamide type in which at least 85% of the amide linkages (─CO─NH─) are attached directly to two aromatic rings (Fig.1a,b). Para-aramid fibres are commercially available as in various types of continuous filament yarns, staple, pulp, chopped fibre compounds, and elastomeric master batch for specific end uses. The end uses cover a broad spectrum of industrial, aerospace, military, and civilian applications. A major end use of para-aramid fibre is in protective clothing. Other major uses include bullet-resistant body armour, hard armour composites, high strength to mass ratio applications (ropes and cables), rubber reinforcements, cut through protection in safety gloves, aprons, work wear and shoes for high risk jobs and pulp-reinforced friction products. Para-aramid fibres exhibit no melting point, high limiting oxygen index for combustion, excellent structural integrity at elevated temperatures, and a high strength to weight ratio. Decomposition temperature of para-aramid fibre is above 590°C. The combination of high strength, non-flammability and high temperature resistance of the para-aramid fibre makes it suitable for thermal protective applications. The commercial products include Kevlar® by DuPont, Twaron® and Technora® by Teijin. (1,2,3).

Meta-aramid fibre, poly(m-phenylene isophthalamide) (MPDI), is commercialized in several product forms: continuous filament yarns, staple, and paper. In industrial processes, meta-aramid is spun and collected in the form of continuous filament yarn. Filament yarn is used in woven fabrics for applications such as industrial filtration media and reinforcement of automotive hose. It can also be cut into staple products for use in spun yarn for thermal protective apparel. Meta-aramids have low flammability and have been found to be self-extinguishing when removed from the flame. On exposure to a flame, a meta-aramid fabric hardens, starts to melt, discolours, and chars thereby forming a protective coating. An outstanding characteristic is also low smoke generation on burning. They have moderate tenacity and low elasticity modulus but excellent resistance to heat; thermal degradation starts at 375°C. The most popular brand is Nomex® (Du Pont); other brands are Conex® (Teijin), Apyeil® (Unitika), Fenilon (former USSR), and Kermel® (Rhone-Poulene, now Rhodia Performance Fibers). Meta-aramid fibres can resist up to 250°C for long periods (3,5).

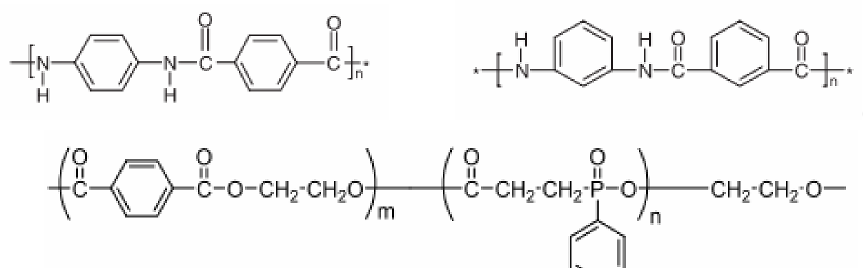
Polyester fibres are the main synthetic fibres used in the industrial manufacturing sector and can be found in several application areas. As polyester fibres are easily flammable, flame retardancy is a significant issue. One of the common solutions to flame retarding polyester is to incorporate 2-carboxyethyl (methyl) phosphinic acid, 2-carboxyethyl (phenyl) phosphinic acid (Fig.1c)., or their cyclic anhydrides unit into the PET polymeric chain such as Trevira GmbH (Trevira CS®), Invista (Avora®) and Toyobo (Heim®) (7). A phosphorus content of 0.7–1% is sufficient to achieve satisfactory levels of flame retardancy. The mechanism of flame retardant action of these phosphorus compounds may be due to reduction in melt viscosity caused by acid hydrolysis (8). These fibres do not promote any char formation. Flame retardancy is not lost through use, washing or ageing; but rather the flame-resistant properties are permanently built into the molecular chain of the fibre and cannot be removed. The positive technical properties of the polyester fibre remain the same. The entire raw material is flame retardant, not just the surface, as is the case with the treated product (9).

Flame resistant fabrics can be manufactured by using inherently flame resistant fibres or incorporating flame retardant chemicals into conventional fibres and fabrics. These fibres are typically blended to balance protection, comfort, durability, cost of the fabric based on intended end use. Para-aramids have been shown to be an excellent blending partner to reduce thermal shrinkage. This is also true of meta-aramid blends where para-aramid is used to offset the inherent thermal shrinkage of the meta-aramid fibre. They can also be blended with Lenzing FR, Polybenzimidazole (PBI), wool and modacrylic (10-18).

Studies concerning the spinning of aramid fibres by using the technology of short-staple spinning are relatively few. Flambard et al. studied blends of wool with Poly(ρ-phenylene terephthalamide) (PPTA) fibres in spun yarns for investigating better synergistic effects due to the intimate contact between fibres (10). Zhao et al. investigated the flame retardant property of Nomex/Lenzing Viscose FR fabric with different blend ratios. They stated that, the blended fabric of two fibres have better flame retardant property than that of pure fabric of each fibre. The advantages of Nomex/Lenzing Viscose FR blended fabric include the enhancing of the flame retardant property, improvement of the spinnability of yarn and reduction of cost (11). Ferreira et. al. produced knitted fabrics with compound yarns (wool and PPTA) and analysed on the properties such as resistance to UV, fire, cutting, dyeing and abrasion (18). In all previous studies, yarns were produced by blending these fibres in yarn preparation processes such as blowroom or drawframe. In this study, it is aimed to produce 100% para-aramid, meta-aramid and FR polyester yarns with conventional ring spinning system and investigate the mechanical and burning behaviours of fabrics after they are woven into a plain woven blend fabric structure.

2. MATERIALS AND METHODS

The fibres used within the context of the study have the properties listed in Table 1. Mean fibre length and fineness values were given by the manufacturers. Tensile strength and elongation properties of the fibres were measured according to TS EN ISO 5079 standard. Para-aramid, meta-aramid and FR PES fibres were supplied as roving which were spun into final counts of 10, 20 and 30 Ne. A conventional ring spinning frame (Pinter-Merlin) (Fig.2) was used to spin the yarns. All yarns were spun with a twist factor of α_e= 3.5.



(a) (b) (c)

Figure 1. Chemical structure of some (a) para-aramid, (b) meta-aramid, (c) flame retardant polyester (1,4,6)

Table 1. Fibre properties

Fibre type	Mean fibre length/Fineness (mm/dtex)	Tensile Strength (cN/tex)	Elongation (%)
Para-aramid	38 /1.7	134.5	4.2
Meta-aramid	50 /2.2	39	37
FR PES	40 /1.2	48	14

The yarns were then woven into plain fabrics on a sample weaving loom with a modified weft cutting system (Fig.2). The original weft cutter on the loom wasn't appropriate for technical yarns such as para-aramid yarns with high cut resistance and tensile strength; so a variac and a transformer with a resistor wire as the weft cutter is installed on the loom. Warp yarns were produced from para-aramid fibres in the yarn count of 30/2 Ne and remained same for all fabrics. After the preparation of 2-ply yarns, warping beam was prepared on a single end warping machine. Warp yarns were strong enough, therefore no sizing was employed. To investigate the effect of yarn count and fibre type, warp and weft densities were respectively kept constant as 22 ends/cm, 15 picks/cm during the weaving process.

All materials were conditioned for at least 24 h in an atmosphere with a temperature of 20 ± 2ºC and a relative humidity of 65 ± 5%. Tensile properties of the yarns and fabrics were measured on a Zwick Z010 Universal Tensile Tester in accordance with TS 245 EN ISO 2062 and TS EN ISO 13934-1 respectively. All the tests were processed with testXpert® software. Thickness of the fabrics was determined using SDL Thickness Gauge according to TS 7128 EN ISO 5084 standard.

To investigate the burning behaviour of the experimental fabrics, vertical flammability test was carried out in accordance with EN ISO 15025:2002 and evaluated as required in EN ISO 11612:2008 for code letter A1 on a SDL Atlas M233B AutoFlamm Tester. This method assesses the properties of textile fabrics in response to a short contact with a small igniting flame under controlled conditions. A flame with a height of 25 mm produced by a propane gas burner in height is exposed to the surface of the sample at a distance of 17 mm for 10 seconds. Afterflame and afterglow mean times are calculated and shall be ≤ 2 s. To meet the requirements for code letter A1, no flaming to the top or either side edge is allowed and no sample shall melt or give hole formation or molten debris.

To obtain the flame spread test results, the evaluations can be done by human eye observing. But even the samples meet the standard requirements; it would be useful to compare the samples with similar carbonized areas by using image analysis to see small differences. So carbonized areas on the flame spread test samples were measured using computerized image capture and image analysis software (Fig. 3). A ruler was also scanned with the test samples and 10 mm was set scale as the known distance. Binarization, which is to convert all pixels within a selected threshold values to red and those outside to white, is carried out and area inside the yellow line is calculated via the image analysis software (IAS).

(a)  (b)

Figure 2. (a) Pinter – Merlin lab ring frame, (b) CCI SL 8900s weaving loom with new weft cutting system

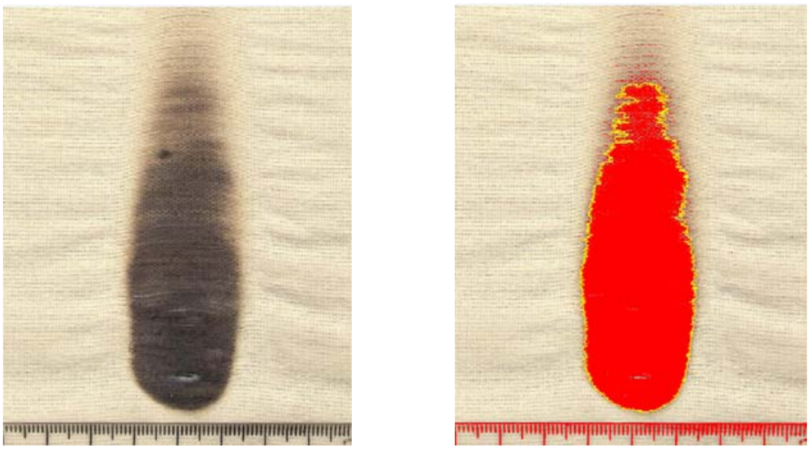
(a)  (b)

Figure 3. (a) Image of the carbonized area, (b) Image obtained after binarization

In this study, the importance of differences of results related to mechanical properties of yarns and fabrics were assessed by variance analysis in means by employing ANOVA analysis using SPSS software. To deduce whether a response was significantly influenced by the independent parameters at significance level, only those cases showing statistical significance beyond the 5% level were deemed significant ($0 \le p \le 0.05$).

3. RESULTS AND DISCUSSIONS

3.1 Mechanical Properties of Fabric Samples

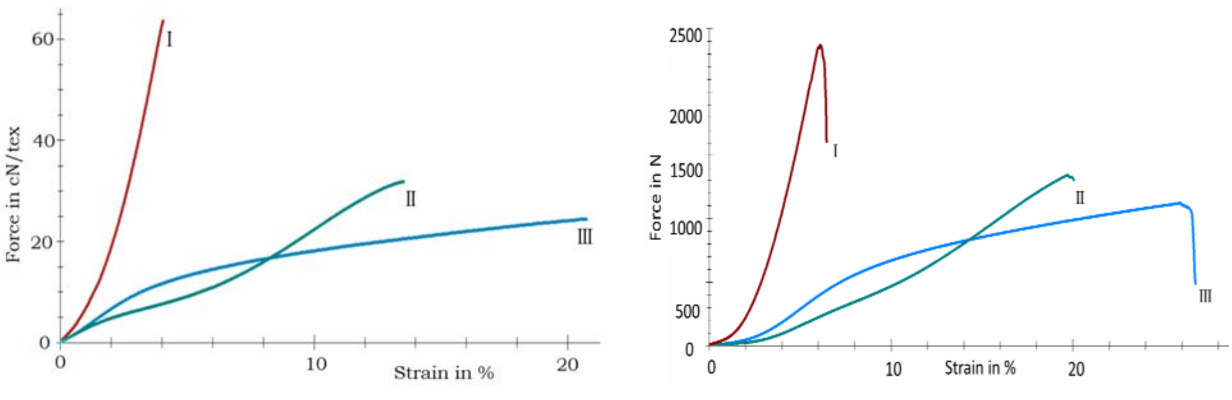
In Figure 4, the typical strain versus stress relationships for the experimental para-aramid, meta-aramid, FR PES yarns and fabrics 1, 4 and 7 show that there are differences in yarn failure mechanisms between yarns and fabrics tested. It can be seen that the tensile behaviour for both the yarns and woven fabrics follow similar trends. Para-aramid yarns and fabrics obviously have the characteristics of high strength, low elongation and high modulus (slope of a stress–strain curve) than meta-aramid and FR PES. This is attributed to the higher stiffness and superior fibre modulus of para-aramid fibres.

All measured properties of yarn and fabric samples are given in Table 2.

The mean values of the tensile strength and elongation of the weft yarns and fabrics (weftwise) are plotted in Figures 5 and 6, respectively. The statistical analysis proves that the yarn count and fibre type affect significantly ($p=0.00$) tensile strength and elongation properties of yarns and fabrics produced, except for the warpwise tensile strength of the fabrics ($p > 0.05$). As shown in Table 2, para-aramid yarns have the highest tensile strength values. This is due to the higher tenacity of the para-aramid fibres compared to meta-aramid and FR PES. The elongation increases, as the yarns become coarser. For all the three counts and fibre types para-aramid yarns and fabrics (weftwise) 1 to 3 have the least elongation, whereas the values of meta-aramid yarns and fabrics (weftwise) 4 to 6 are the highest.

Table 2. Properties of yarns and fabrics

Yarns, Fabrics	1	2	3	4	5	6	7	8	9
Weft yarn type	Para-aramid			Meta-aramid			FR PES		
Weft yarn count, Ne	10	20	30	10	20	30	10	20	30
Weft yarn tensile strength, cN/tex	61.81	60.20	50.86	24.42	19.69	19.94	30.64	30.88	26.20
Weft yarn elongation, %	4.06	3.61	3.05	20.66	15.68	15.43	13.51	12.49	10.83
Fabric tensile strength, N (weftwise)	2368	1062	574	1106	443	309	1318.	689	369
Fabric elongation, % (weftwise)	6.25	5.53	5.26	26.12	21.56	20.87	19.99	19.09	17.48
Fabric tensile strength, N (warpwise)	1885	1814	1785	1777	1698	1809	1779	1905	1931
Fabric elongation, % (warpwise)	15.09	8.38	6.67	12.62	7.06	5.65	10.74	6.07	5.02
Fabric weight, (g/m^2)	183.16	127.01	111.50	187.38	124.65	112.24	178.83	133.88	117.84
Thickness (mm)	0.53	0.46	0.44	0.52	0.43	0.40	0.54	0.42	0.39
Carbonized area (cm^2)	4.50	5.14	5.29	6.85	6.90	6.88	70.55	29.43	12.77
Fabric tensile strength, N (warpwise)	1885	1814	1785	1777	1698	1809	1779	1905	1931
Fabric elongation, % (warpwise)	15.09	8.38	6.67	12.62	7.06	5.65	10.74	6.07	5.02
Warp yarn type	30/2 Ne spun para-aramid yarn								
Warp yarn tensile strength, cN/tex	46.6								
Warp yarn elongation, %	2.64 %								



(a) (b)

Figure 4. Stress-strain curves of (a) yarns and (b) fabrics (weftwise), (I) para-aramid, (II) FR PES and (III) meta-aramid

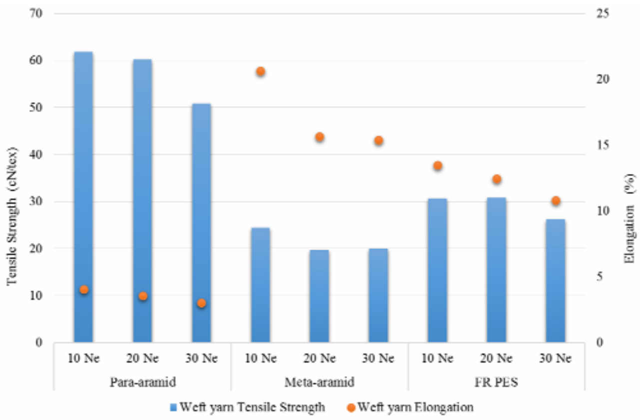


Figure 5. The tensile strength and elongation values of weft yarns used in the study

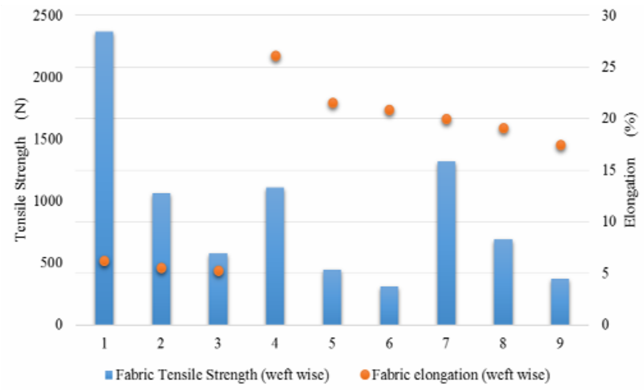


Figure 6. The tensile strength and elongation values of fabric samples (weftwise)

The warp yarns had the same yarn count. However it is observed from Table 2 that the warpwise elongation of the fabrics showed an increasing trend, as the weft yarn count became coarser. This could be attributed to that coarser weft yarns create more crimps and consequently the elongation is higher for those fabrics. This is probably due to the fact that coarser weft yarn is more rigid and as a result warp yarns bend more than occurred for finer weft yarns within the same weft density. There was no significant difference ($p > 0.05$) in tensile strength of the fabrics in warp direction as shown in Table 3.

3.2 Flame Retardancy Properties of Fabric Samples

Flame spread is the ignition of the specimen by an initiating fire and propagation of flame along the surface. It is an important evaluation criteria, if a garment does catch fire. A garment made from a flame resistant fabric gives the wearer more time to take off the garment or extinguish the fire. This extra time provides a margin of safety which can have a major impact on the degree and extent of burn injuries. In this study, three samples from each fabric were evaluated to meet the limited flame spread test requirement of code letter A1 in EN ISO 11612:2008. Fabrics 7 and 8 burned up to the top. Fabric 9 ignited but instantly self-extinguished when the flame is removed. Fabrics 1 to 6 did not ignite or spread the flame. Cracks and holes did not occur only for the fabrics 1, 2 and 3. These fabrics also had the lowest carbonized areas than other fabrics, so only fabrics 1 to 3 made of 100% para-aramid fibres met the code letter A1. Fabrics 4 to 6 with meta-aramid weft yarns showed small shrinkage when the flame is exposed and due to the holes occurred on the surface, these fabrics didn't meet the requirements stated in the standard "EN ISO 11612:2008 for code letter A1". None of the fabrics melted or dripped. The captured images of the fabrics after the flame spread test are shown in Figure 7.

By processing these images with an image analysis software, carbonized areas were calculated for the samples and arithmetic mean value of carbonized areas for each fabric is given in Table 2. Fabric weight and thickness versus carbonized areas are given in Figure 8. The carbonized areas of fabric 1 to 6 are inversely related to the weight of the fabric per square meter. However, fabrics 7 to 9 did not melt or drip, but ignited and heavier fabrics 7 and 8 burned for much longer as they contained more material (FR PES) to feed the fire. The carbonized areas of fabrics 1 to 6 increased as the weight and thickness of these fabrics decreased. Nevertheless, fabrics 7 to 9 woven with FR PES weft yarns showed an inverse proportion.

Table 3. The variance analysis table of the fabrics

		Sum of Squares	df	Mean Square	F	Sig.
Fabric Tensile Strength (weftwise)	Between Groups	16938885,011	8	2117360,626	3033,237	,000
	Within Groups	25129,913	36	698,053		
	Total	16964014,923	44			
Fabric elongation (weftwise)	Between Groups	2521,628	8	315,203	935,288	,000
	Within Groups	12,132	36	,337		
	Total	2533,760	44			
Fabric Tensile Strength (warpwise)	Between Groups	218437,404	8	27304,675	1,456	,208
	Within Groups	675122,057	36	18753,390		
	Total	893559,461	44			
Fabric elongation (warpwise)	Between Groups	484,995	8	60,624	579,155	,000
	Within Groups	3,768	36	,105		
	Total	488,763	44			

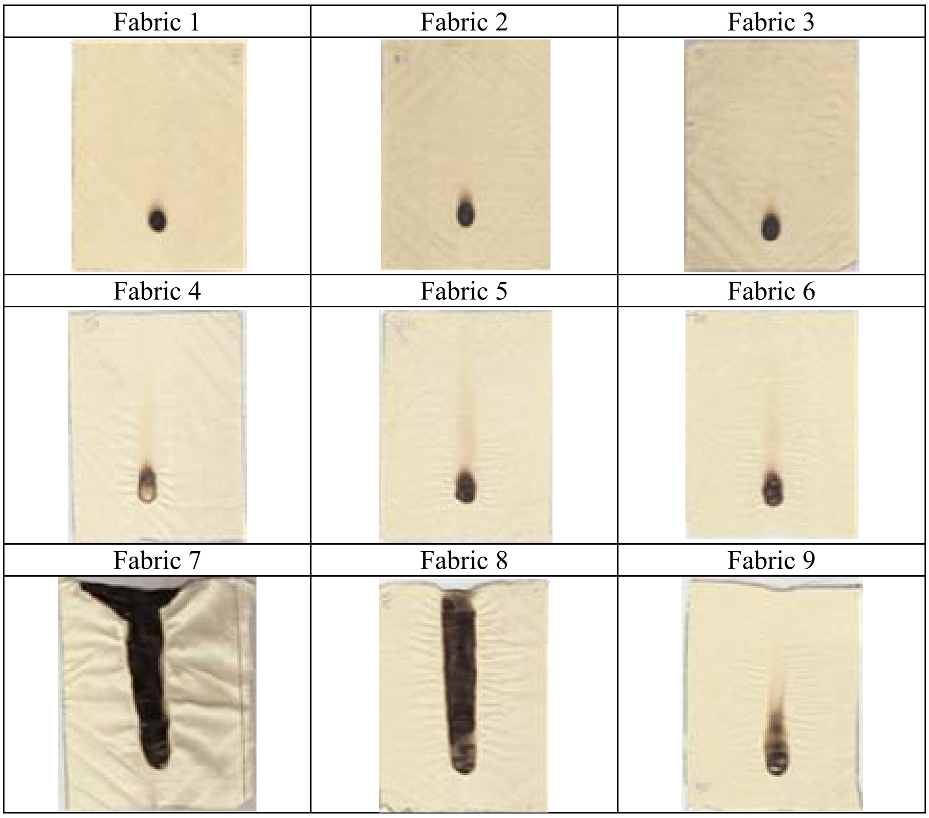


Figure 7. Images of the EN ISO 15025 test samples

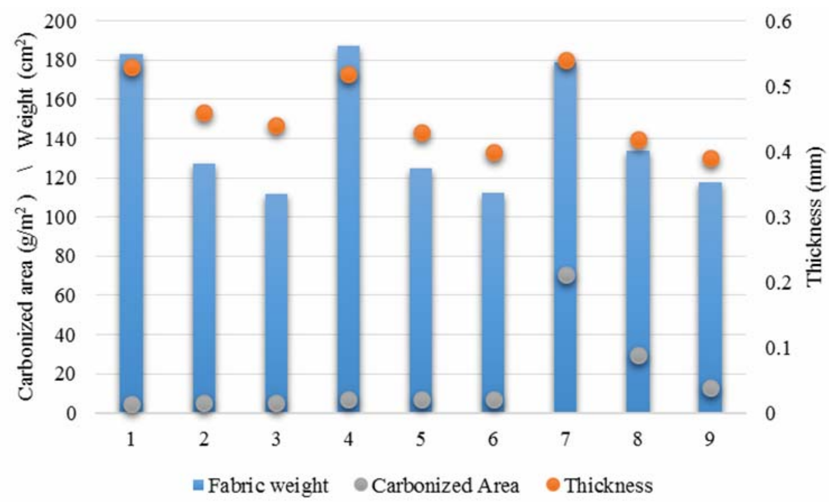


Figure 8. Carbonized areas versus thickness and fabric weight

4. CONCLUSIONS

This research investigated mechanical and flammability properties of the fabric samples woven with ring spun aramid and FR PES yarns. Tensile properties of yarns and fabrics, vertical flammability test, image analysis for carbonized areas on the flame spread test samples have been carried out to characterize the samples. The properties of yarns and woven blend fabrics observed within the scope of this study can be summarized as follows.

Spun para-aramid yarns and fabrics possess significantly higher tensile strength but lower elongation. As a result of the flame spread test, it was clearly seen that FR polyester fibres exhibit relatively poor performance in case they are used with para-aramid fibres in fabric construction. The carbonized areas of the fabrics blended with FR PES yarns increased, as the weft yarn count became coarser. It was observed that para-aramid fibres were thermally more stable than meta-aramid and FR PES fibres as the 100% para-aramid fabrics produced smaller carbonized areas and no holes or cracks. Consequently for the production of protective garments, considering weaving of FR PES yarns with aramid yarns to obtain cost-effectiveness, may not meet the standards associated to protective clothing.

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