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KAYMA ALTINDA KATILAŞAN SIVI UYGULANMIŞ BALİSTİK KUMAŞLARIN İPLİK ÇEKME VE DÜŞEN DARBE TESTİ PERFORMANSININ DEĞERLENDİRİLMESİ

Canan SARIÇAM*
Nazan OKUR

Istanbul Technical University, Department of Textile Engineering, Turkey

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YARN PULL-OUT AND DROP WEIGHT IMPACT PERFORMANCE OF SHEAR THICKENING FLUID IMPREGNATED BALLISTIC FABRICS

Canan SARIÇAM[1]*

Nazan OKUR[1]

[1] Istanbul Technical University, Department of Textile Engineering, Turkey

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ABSTRACT: Shear thickening fluids are known to enhance the performance of ballistic fabrics. However, the effect of shear thickening performance is influenced by various factors, primarily, the concentration of the shear thickening fluids applied onto the fabric. The preparation of highly concentrated shear thickening fluid is difficult in laboratory conditions. They cause a weight increase in the fabrics. Thus, this study aims to investigate the effect of impregnation of shear thickening fluid onto fabrics at lower concentrations. To this aim, shear thickening fluids were prepared at two concentrations (5% and 10%) and applied to three different types of para-aramid fabrics. Yarn pull-out test was established to check the effect of shear thickening fluid on frictional force between yarns of fabrics. Moreover, drop weight impact tests were applied to see the effect of shear thickening impregnation on the energy absorption behaviour of the single-ply ballistic fabrics. The findings were interpreted according to the concentration of shear thickening fluid solution as well as the fabric types.

Keywords: Shear thickening fluid, Ballistic fabric, Yarn pull-out, Drop weight impact test

KAYMA ALTINDA KATILAŞAN SIVI UYGULANMIŞ BALİSTİK KUMAŞLARIN İPLİK ÇEKME VE DÜŞEN DARBE TESTİ PERFORMANSININ DEĞERLENDİRİLMESİ

ÖZ: Kayma altında katılaşan sıvıların, balistik kumaşların performansını arttırdığı bilinmektedir. Ancak kumaş performansı üzerindeki etki, başta çözelti konsantrasyonu olmak üzere çeşitli faktörlerden etkilenmektedir. Yüksek konsantrasyonlarda kayma altında katılaşan sıvı çözeltilerinin laboratuvar koşullarında hazırlanması güçtür ve kumaşta büyük oranda ağırlık artışına yol açmaktadır. Bu sebeple bu çalışmada düşük konsantrasyonlarda hazırlanmış kayma altında katılaşan sıvıların kumaş performansı üzerinde etkisi incelenmiştir. Çalışma kapsamında iki farklı konsantrasyonda (%5 ve %10) hazırlanmış kayma altında katılaşan sıvı çözeltisi üç farklı türde para-aramid kumaşa uygulanmıştır. Kumaşlardaki iplik-iplik sürtünmesindeki artış performansı, iplik çekme testi kullanılarak analiz edilmiş, darbe direnci performans artışı ise kayma altında katılaşan sıvı uygulanmış tek kat balistik kumaş düşen darbe testine tabi tutulması sonucunda değerlendirilmiştir. Bulgular kayma altında katılaşan sıvı çözeltisinin konsantrasyonuna ve kumaş türüne göre yorumlanmıştır.

Anahtar Kelimeler: Kayma altında katılaşan sıvı, Balistik kumaş, İplik çekme testi, Düşen darbe testi

***Sorumlu Yazarlar/Corresponding Author:** saricamc@itu.edu.tr*
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1. INTRODUCTION

Various high-performance fibres like para-aramid based Kevlar®, Technora®, and Twaron® are used for soft armor applications. Depending on low density combined with high strength, toughness, and thermal stability, Kevlar became the widely used para-aramid fiber preferred for the fabrics used in ballistic applications [1]. However, para-aramid fabrics should be used in multiple layers to provide adequate ballistic protection. In this respect, the impregnation of non-Newtonian fluids onto woven fabrics has drawn attention as it increases energy absorption induced by impact phenomena [1].

Acting as a non-Newtonian fluid, shear thickening fluid (STF) is a concentrated colloidal suspension and its viscosity increases drastically when the applied shear rate exceeds the critical value [2]. The performance of STF-impregnated Kevlar fabric to improve the impact resistance was explained with two factors, which are the increase in inter-yarn friction and the shear thickening mechanism respectively [2]. The influence of STF impregnation was measured by low and high-velocity ballistics tests, yarn pull-out test, and drop weight impact tests.

Comparing the force values in the yarn pull-out test, Alikarami et al. indicated that the STF-treated samples have three times higher force than that of a neat sample [3]. Similar results were obtained by Bai et al. and Saraloglu Güler [4, 5]. Other researchers investigated the effect of process conditions on yarn pull-out test results. Gurgen and Kushan indicated that the fabrics treated with multi-phase STF having carbide particles in it showed higher performance in both yarn pull-out and ballistics tests [6]. Saraloglu Güler implied that the pulling rate triggers the shear thickening behavior [5]. Li et al. studied the yarn pull - out test at different speeds and temperatures to evaluate the contribution of the shear thickening effect [7]. Zhao et al. found that STF-impregnated samples had higher tensile force values and the force increased significantly with the increase of the drawing rate [8]. Applying drop weight impact test on single-ply and multi-ply fabrics, Saraloğlu Güler found that the impact resistance of STF-treated Kevlar improved [5]. Investigating the efficiency of STF-impregnated plain-weave fabric made of Kevlar under high and low-velocity impact conditions, Tria et al. applied a drop weight impact test on single and multi-ply fabric and confirmed the positive influence of STF impregnation on the energy absorption [1]. Majumdar et al. applied both dynamic impact and low-velocity impact tests on STF-applied Kevlar fabrics, whose results were similar to each other. Apart from these, the impact of process materials on the drop weight impact test results was investigated [9]. In this respect, Majumdar et al. found out that the positive impact of STF is dependent on the padding condition and so the STF concentration [9]. Preparing STF with silica particles of 500 nm and 100 nm diameter, Bajya et al. found that the absolute energy absorption by STF-100 and STF-500 impregnated fabrics of 20 to 24 plies of fabric were around 19% and 42% higher than neat fabric according to the results of dynamic impact test [2]. Srivastava et al. drew attention to the impact of the impregnation process parameters and revealed that high padding pressure reduces the STF add-on % and so the energy absorption during the impact tests [10].

The literature review revealed that STF impregnation onto fabric increased the frictional force between yarns and in this way, it improved the energy absorption of the ballistic fabrics. Most of the researchers applied STF onto fabrics, whose concentration was above 20%. [2-6, 8-10]. But Zhao implied that preparing STF solution at these concentrations was difficult under laboratory conditions. Moreover, the impregnation of STF has also been known to increase the weight of the fabric, which increases in the weight of the protective clothing. Even though it depends on the dilution ratio, temperature, and process conditions, the impregnation of 25% STF onto fabric might increase the weight of the fabric by around 45% [11]. Therefore, it is important to know if the STF-impregnated fabrics also show high performance at lower concentrations of STF and so with lower add-on values. For this reason, in this study, the yarn pull-out tests and the drop weight impact tests were applied to the fabrics impregnated with STF at two concentrations of 5% and 10% respectively.

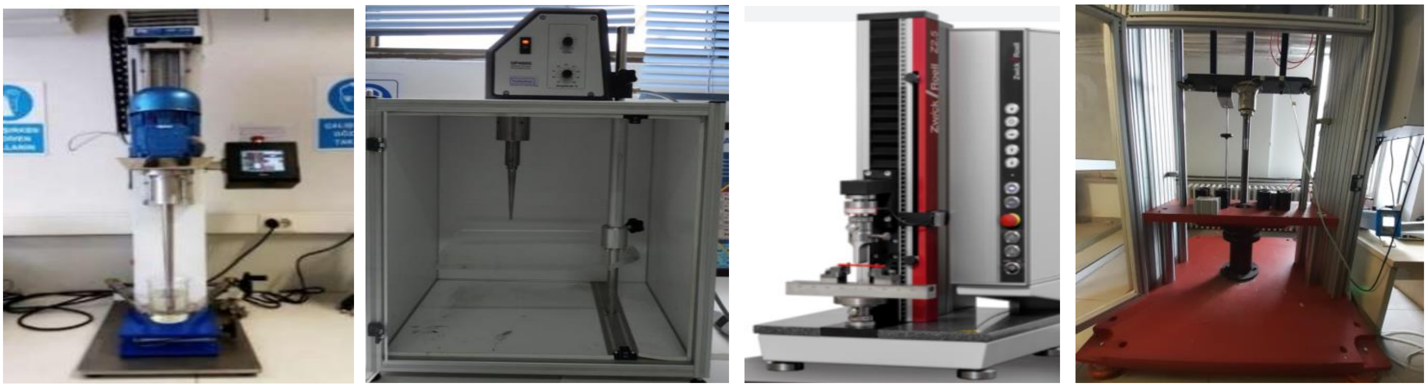
2. EXPERIMENTAL STUDY

Three types of fabrics were used for this study. The characteristics of fabrics were given in Table 1.

Fumed silica (Aerosil 200) having a specific surface area of 200 m^2/g and Polyethylene glycol (PEG) with a molecular weight of 400 g/mol) was used to prepare STF. Ethanol was used to decrease the concentration of shear thickening fluid solution to be applied onto the fabric. STF solutions were prepared at the concentration of 5% and 10% fumed silica in PEG solution. Solutions were prepared by using the mechanical mixer (VBR-6000, YOKEŞ® Mak. San. ve Tic. Ltd. Şti) at 1500 rpm for 45 minutes at room temperature. An ultrasound mixer (Hielscher UP400S) was used for one hour to improve the homogeneity of solutions (Figure 1). The solutions were kept at room temperature for 24 hours to remove air bubbles [7, 11, 12].

Table 1. Characteristics of fabrics

Fabric Type	Yarn Count (tex)		Warp and Weft Density (unit/cm)		Fabric Weight (g/m^2)	Thickness (mm)
	Warp	Weft	Warp Density	Weft Density		
Kevlar 200	92.66	93.51	9.5	9.5	200	1.24
Kevlar 410	322.19	319.59	6	6	410	1.58
Twaron	93.03	92.81	10.3	10.3	200	1.23



a. Mechanical Mixer **b.** Ultrasound Mixer **c.** Zwick Roell tensile tester **d.** Drop weight impact tester

Figure 1. Mixing and testing instruments

The solutions were diluted with ethanol at a 1:1 ratio and impregnated onto fabrics. The fabrics were immersed in the diluted solution for one hour. The excess fluid was padded manually with a roller and the impregnated fabrics were dried in the oven at 65°C for 30 minutes. Drying for some samples was continued until the weight of the samples stabilized.

Yarn pull-out test was applied on neat and impregnated fabrics. The yarn pull-out tests were applied in Zwick Roell tensile tester, as seen in Figure 1, at two-speed values (20 mm/minute and 100 mm/minute). Using a 100 N load cell, the maximum force load was recorded for each sample.

The energy absorption behaviour of STF-impregnated fabrics was tested by using a drop weight impact tester (Besmak BMT-DW) as seen in Figure 1. Samples were subjected to low-velocity impact loading at the kinetic energy of 200J.

3. RESULTS

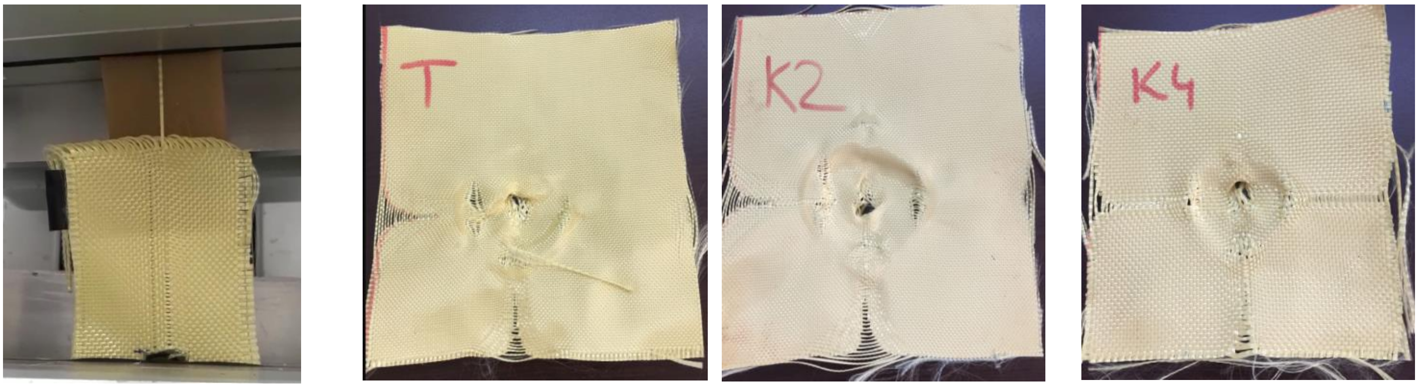
STFs prepared at two concentrations and diluted with ethanol at ratio of 1:1 were applied onto yarn pull-out and drop impact samples. The weight increase after the impregnation of STF onto fabric was given in Table 2. Table 2 revealed that the average add-on values were around 12.5% and 15.5% at STF concentrations of 5% and 10% respectively.

The yarn pull out test was applied in the tensile tester at two speeds of 20mm/min and 100mm/min as depicted in Figure 2a.

The maximum tensile force obtained in the yarn pull out tests was recorded in Table 3.

Table 2. The impregnation of STF onto fabrics and weight increase (Average and standard deviation values)

Sample Code	STF concentration (%)	Initial weight (g) (Std. Dev.)	Change in weight		
			Weight after impregnation (g) (Std. Dev.)	Weight after drying (g) (Std. Dev.)	Add-on (%) (Std. Dev.)
T-Weft	Neat fabric	1.104(0.009)			
T-Warp	Neat fabric	1.146(0.016)			
T-5-Weft	5	1.183(0.000)	2.401(0.012)	1.313(0.020)	11.000(1.556)
T-5-Warp	5	1.158(0.019)	2.287(0.014)	1.290(0.031)	11.350(0.778)
T-10-Weft	10	1.147(0.004)	2.323(0.035)	1.319(0.031)	15.050(2.192)
T-10-Warp	10	1.153(0.057)	2.313(0.008)	1.342(0.061)	16.400(0.424)
K2-Weft	Neat fabric	1.054(0.004)			
K2-Warp	Neat fabric	1.175(0.036)			
K2-5-Weft	5	1.186(0.004)	2.350(0.071)	1.337(0.006)	12.700(0.141)
K2-5-Warp	5	1.137(0.016)	2.301(0.115)	1.301(0.015)	14.450(0.354)
K2-10-Weft	10	1.152(0.026)	2.224(0.112)	1.351(0.0259	17.250(0.495)
K2-10-Warp	10	1.152(0.023)	2.277(0.128)	1.372(0.012)	19.000(1.414)
K4-Weft	Neat fabric	2.681(0.308)			
K4-Warp	Neat fabric	1.989(0.308)			
K4-5-Weft	5	2.800(0.085)	5.397(0.468)	3.206(0.164)	14.600(9.334)
K4-5-Warp	5	2.894(0.019)	5.895(0.167)	3.157(0.093)	9.100(2.546)
K4-10-Weft	10	2.780(0.015)	5.540(0.052)	3.285(0.155)	18.150(4.879)
K4-10-Warp	10	2.800(0.138)	5.528(0.302)	3.110(0.030)	11.250(6.576)



(a) Yarn pull out test (b) Twaron (c) Kevlar 200 (d) Kevlar 410

Figure 2. Yarn pull-out and drop weight impact test samples

Table 3. Yarn pull out test results in two different speed values (Average and (standard deviation values))

Sample Code	Yarn pull-out speed (mm/ min)	Maximum tensile force (cN)	Sample Code	Yarn pull-out speed (mm/ min)	Maximum tensile force (cN)
T-Weft	20	305.67 (183.817)	T-Weft	100	136.82 (46.004)
T-Warp	20	318.50 (37.567)	T-Warp	100	141.14 (24.153)
T-5-Weft	20	305.51 (48.848)	T-5-Weft	100	314.59 (32.485)
T-5-Warp	20	618.30 (89.204)	T-5-Warp	100	615.84 (168.540)
T-10-Weft	20	345.50 (47.649)	T-10-Weft	100	352.65 (55.560)
T-10-Warp	20	749.89 (133.178)	T-10-Warp	100	743.27 (197.659)
K2-Weft	20	169.62 (10.239)	K2-Weft	100	180.43 (17.999)
K2-Warp	20	136.69 (10.068)	K2-Warp	100	135.82 (15.472)
K2-5-Weft	20	378.97 (110.275)	K2-5-Weft	100	300.67 (36.390)
K2-5-Warp	20	219.53 (21.299)	K2-5-Warp	100	260.96 (38.537)
K2-10-Weft	20	327.43 (28.457)	K2-10-Weft	100	381.88 (66.953)
K2-10-Warp	20	223.20 (35.294)	K2-10-Warp	100	243.00 (18.720)
K4-Weft	20	248.19 (0.000)	K4-Weft	100	218.50 (25.422)
K4-Warp	20	391.10 (10.492)	K4-Warp	100	277.87 (27.298)
K4-5-Weft	20	314.97 (54.380)	K4-5-Weft	100	283.14 (36.379)
K4-5-Warp	20	532.13 (96.571)	K4-5-Warp	100	539.11 (51.736)
K4-10-Weft	20	352.65 (37.266)	K4-10-Weft	100	344.35 (70.638)
K4-10-Warp	20	588.56 (82.436)	K4-10-Warp	100	565.24 (14.333)

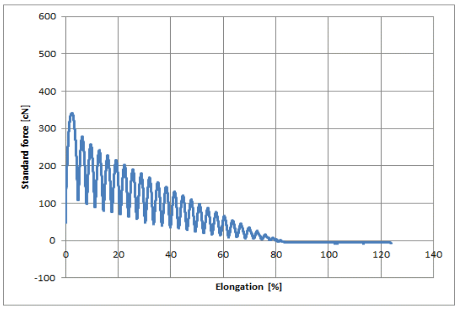
In neat fabrics, the highest tensile force value in warp direction was obtained in Kevlar 410 fabric. It was followed by Twaron and Kevlar 200, respectively. This was probably due to the coarser yarn in the Kevlar 410 fabric, as earlier studies have indicated that pull-out force increased as fabric yarn count increased [13-15]. In Kevlar 200 and Twaron, which have similar fabric structural properties, the higher warp density in the Twaron may have resulted in higher pull-out force due to higher friction [16, 17]. High densities increase the number of cross over points in the fabrics enabling the maximum tensile force required for yarn pull-out to increase.

STF impregnation increased the pull-out force of all fabrics, since the impregnation of (STF) significantly increases the resistance to withdraw a yarn. The comparative results of the fabrics are similar in the neat form and STF-impregnated form actually. This indicates that the fabrics' structural parameters (yarn count, density) still continue to dominate the pull-out force.

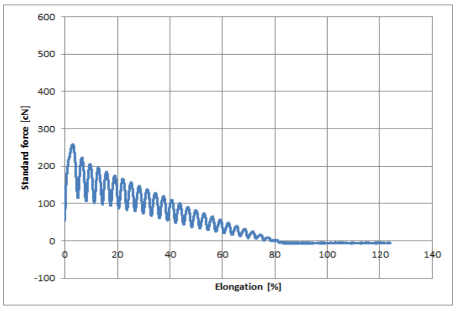
On the other hand, the yarn pull out test results revealed that, the maximum force is higher in the warp direction for Twaron and Kevlar 410 fabrics in both neat and STF impregnated form. However, the maximum for force is higher in weft direction for Kevlar 200 fabric. For the balanced plain weave woven fabrics (with the same weft and warp density and yarn count), it has been found in the literature that the warp pull-out force is higher than the weft or vice versa [18-20,16]. In the present study, Figure 3 shows the yarn pull-out force–elongation curves for each corresponding cross-over points between the warp and weft yarns in the fabric during the pulling of the yarn. For the sake of simplicity, a representative curve was shown for each type of fabric in each direction. After reaching to the maximum pull out force, yarn continues to pulled out through all cross-over points in the fabric, and the curve has one maximum and one minimum value for each of cross-over point. The amplitude (difference between the maximum and minimum force value) is affected by varying waviness [20]. In Twaron and Kevlar 410, the amplitude is greater in the warp direction than in the weft direction, but the opposite is true for Kevlar 200 fabric. This may indicate that the waviness of the weft-directed Kevlar 200 fabric is higher than that of the warp-directed fabric, which may be attributed to the different yarn tensions applied during weaving process.

The results of yarn pull-out test for one sample of Kevlar 200 was shown in Figure 4. It was observed that peak force increased with the amount of STF impregnated. No specific difference was observed for the speeds of 20 mm/min and 100 mm/min.

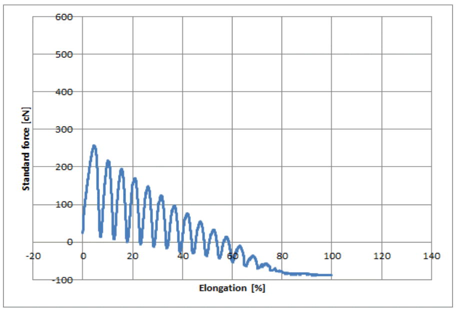
Drop weight impact tests were applied on the neat and impregnated fabrics. The drop weight impact was applied on the single ply of fabrics and all the test samples were damaged as seen in Figures 2b, 2c and 2d. The results of the drop weight impact tester were given in Table 4. Kevlar 200 was found to absorb higher amount of energy in both neat form and STF-impregnated form (at the concentration of 10%). Twaron fabric was found to absorb more energy when impregnated with STF at a concentration of 5%. Kevlar 410 fabric was found to show the minimum performance in terms of energy absorption probably because of lower warp and weft densities as the striker moving with high velocity might well pass through the fabric.



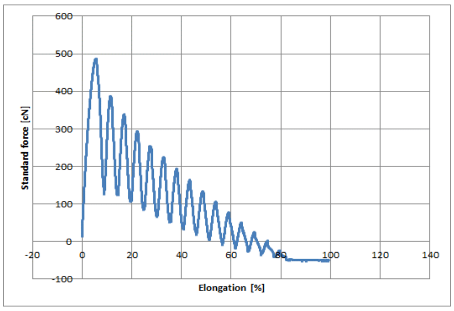
(a) K2-5-Weft (20 mm/min)



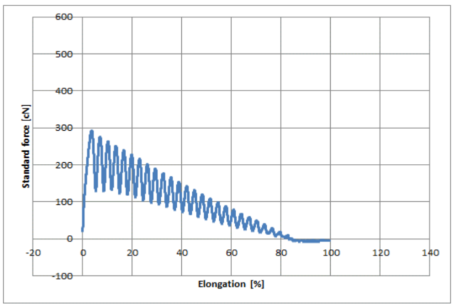
(b) K2-5-Warp (20 mm/min)



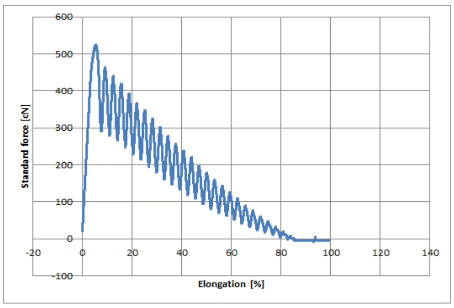
(c) K4-5-Weft (20 mm/min)



(d) K4-5-Warp (20 mm/min)

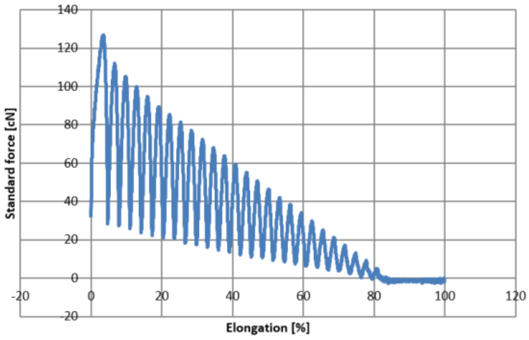


(e) T-5-Weft (20 mm/min)

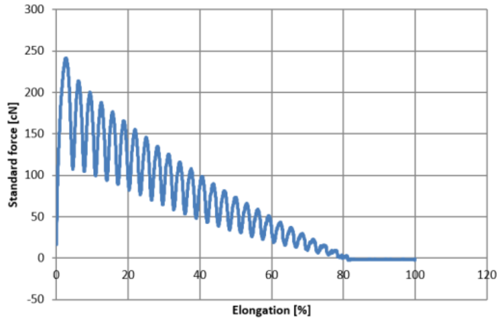


(f) T-5-Weft (20 mm/min)

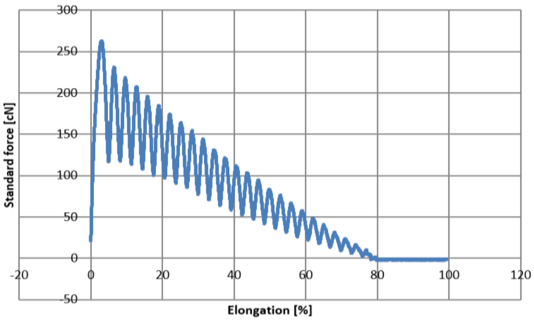
Figure 3. Force-elongation curve examples for each fabric.



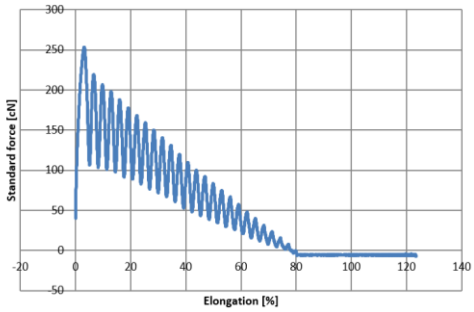
(a) K2- Warp (neat fabric, 20 mm/min)



(b) K2-5-Warp (20 mm/min)



(c) K2-10-Warp (20 mm/min)



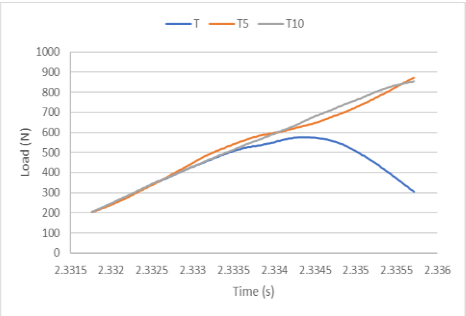
(d) K2-10-Warp (100 mm/min)

Figure 4. Force elongation curve example for one sample

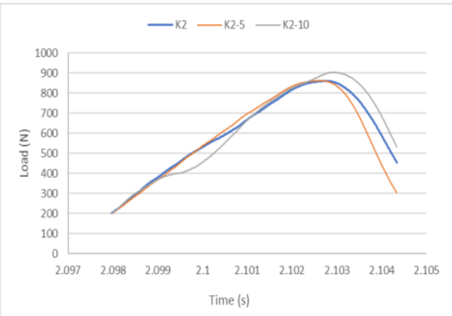
Table 4. Drop weight impact test results of the neat and STF impregnated fabrics.

	Max Load [KN]	Absorbed Energy [J]	Max Displacement [mm]
T	0.577 (0.208)	2.939 (3.032)	12.314 (4.132)
T-5	0.992 (0.069)	9.002 (1.147)	20.578 (1.400)
T-10	0.854 (0.173)	6.708 (2.500)	17.779(3.432)
K2	0.859 (0.002)	8.133 (0.224)	20.937 (0.630)
K2-5	0.863 (0.021)	7.686 (0.398)	19.677 (0.874)
K2-10	0.905 (0.023)	8.481 (0.174)	21.425 (0.244)
K4	0.846 (0.223)	5.260 (0.771)	15.244 (6.417)
K4-5	0.400 (0.132)	3.719 (0.323)	28.077 (6.360)
K4-10	0.663 (0.183)	4.365 (0.632)	15.357 (0.056)

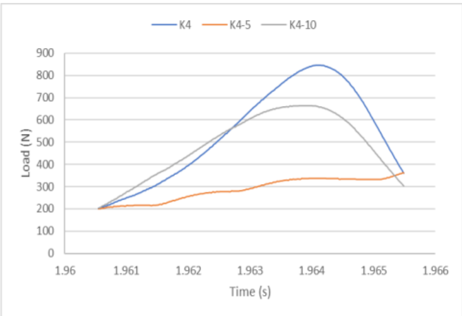
Apart from the comparison of absorbed energy, the load versus time sketches for each fabric type were shown in Figure 5.



a. Twaron fabric



b. Kevlar 200 fabric



c.Kevlar 410 fabric

Figure 5. Load-time curves for different fabric types

The findings revealed that whereas STF impregnation was seen to increase impact resistance of Twaron but it did not change that for Kevlar 200 fabric. Even the impact resistance was seen to decrease when impregnated with STF for Kevlar 410 fabric. Thus, further evidence is needed to claim that STF impregnation improved the performance. STF impregnation at these concentrations did not suggest an improvement in the performance of ballistic fabrics in this study. The reason, why good performance achieved in yarn pull-out test was not reflected on the impact behaviour, might be attributed to the fact that the impact mechanism is not interpreted with only yarn-to-yarn friction.

4. CONCLUSION

This study attempted to show that STF impregnation can improve the performance of ballistic fabrics even at low concentrations. The performance was measured with yarn pull-out and drop weight impact test.

The findings revealed that STF-impregnated fabrics had a higher yarn-to-yarn surface friction than the neat fabrics even at low concentrations and low add-on values. But, the level of energy absorption as well as the impact resistance did not differ for the neat and impregnated fabrics even though some improvements have been realized for some specimens. Based on these results, it is suggested to apply STF at higher concentrations for ballistic purposes.

ACKNOWLEDGMENT

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