Energy Absorption Behaviour of Kevlar Impregnated with Shear Thickening Fluid Under Low Velocity Impact

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ABSTRACT

Shear thickening fluid (STF) has been exploited in combination with high performance fabric such as Kevlar to produce new thin, flexible, lightweight, and inexpensive material that is equivalent or even better performance than existing body protection materials. This area of research has received a great deal of attention and number of publications related to STF studies has remarkably increasing in the past decade. However, up until now, there are still no clear and specific method or formulation to the production of smart materials from STF. Hence, the purpose of this study is to investigate the effect of different impregnation methods of Kevlar/STF fabric composites to the energy absorption behaviour of the composites under low velocity impact and to study the effect of STF-impregnated Kevlar to inter-yarn friction properties to support the mechanism of energy absorption. The composition of STF used in this study were 15 weight percentage (wt%) and 20 wt%. The first method (Method A) used to fabricate Kevlar/STF composites was adopted from previous studies, where dry STF was produced prior to the impregnation process. Ethanol was added to the STF to improve dispersibility of the mixture and after that the sample was dried in the oven to remove the ethanol. For the second method (Method B), Kevlar was directly impregnated with the mixture of ethanol, fumed silica particles and polyethylene glycol (PEG), before drying in the oven to produce the Kevlar/STF fabric composites. The performance of the composites fabricated using the first and second methods was analysed through drop weight impact test under low velocity and single yarn pull-out test. Kevlar impregnated with 20 wt% of STF showed significantly better performance than Kevlar impregnated with STF of 15 wt%. Between the first and second method, the latter shows better improvement by 19% in terms of the energy absorption.

Keywords: *Shear thickening fluid, energy absorption, impact test, fabric composite*

1.0 INTRODUCTION

Shear-thickening fluid (STF) is a non-*Newtonian* fluid that displays a sudden increase in viscosity with increasing shear rate or applied stress. It will behave like a solid when experiences an impact at high shear rate or strain rate that makes it become less penetrable [1-3].

Initially, engineering community defined STF as a problem in industrial processes which involve the combination of high shear rates such as coating and mixing due to jamming in small openings, and overloading mixers, thereby limiting process rate. However, the unique characteristic of this fluid has become attractive and has emerged in the past two decades in the development of smart materials for ballistic protection and energy absorption. STF have been exploited in combination with high performance fabrics to produce a new thin, flexible, lightweight, and inexpensive material that equivalent or even better ballistic, stab, and puncture protective materials than the existing body armour protective materials available [1,4].

Body armour for the military is designed to provide protection from the impact of high velocity projectiles such as bullets or bombshells fragments. Body armourhas been around for centuries. From as early as in the 500s (AD), soldiers have been outfitted in leather armour, and with the advancement of metal forging and increased availability of strong metals, plate armourhave been used for soldiers in around the 1500s. Next, the body armourwas improved to the lamellar typein around the 1700s in the form of thinner metal plate than plate armour. Later in the1900s, chain mail body armourwas developed with interlinked iron rings. Chain mail is perhaps the closest parallel to modern body armour, with its layers of tightly woven metal rings working to disperse the energy on an attack and catch weapons in its web. In the late 1960s, *DuPont* began developing their aramid fibre *Kevlar*, which is lightweight and incredibly strong, allowing the body armour to be made was light and thin enough to be worn [5].

The research behind these aramids is still helping to advance the body armour technology. There are number of exciting areas being currently researched, concerning the improvement of impact resistance performance of textile structures by impregnation of the fabrics with STF. This area of research has received a great deal of attention and the number of publications related to the STF studies has remarkably increased in the past decade as shown in Table 1. It has been found that the addition of STF increases the damage resistance to the fabric such as yarn pull-out and fabric windowing and hence improves the energy absorption of the STF-treated fabric. However, up until now there are still no clear and specific method or formula to the production of smart materials from STF. There is significant research in progress that is continually developing new STF to improve their properties.

Table 1: STF/fabric composites prepared using various types of nanoparticles and liquid medium in the literature

Colloidal particle (size, nm)	Liquid medium	Weight fraction	Fabric material	Focus of research	References
Colloidal silica (450)	Ethylene glycol (EG)	40 wt%	*Kevlar* KM-2 fabric	Investigate the ballistic properties of woven *Kevlar* fabrics impregnated with fluids that exhibit the shear thickening effect.	[6]
Colloidal silica (450)	Polyethylene glycol (PEG200)	20 and 52 wt%	*Kevlar* KM-2 fabric	Investigate the effect of STF addition on various yarn mobility mechanisms and the role of these mechanisms in the response of woven fabrics to ballistic impact.	[7]
Colloidal silica (~450)	PEG200	52 wt%	*Kevlar* and nylon fabrics	Investigate the stab resistance (different threat conditions) of conventional and STF-treated fabrics to determine the effect of fibre properties on overall STF-fabric response.	[8]
Fumed silica	EG	10, 15, 18, 20, 20.5 and 21.5 wt%	*Kevlar* KM-2 fabric	Investigate the mechanical properties and stab resistance of STF/fabric composites for application of body armour.	[9]
Silica	PEG 200	40, 50	*Kevlar*	Study the effect of two	[10]

(~278)		and 60 wt%	fabric	parameters, namely, the padding mangle pressure and silica concentration in STF on the impact performance of treated *Kevlar* fabrics.	
Spherical silica (100)	PEG 200	50, 60 and 70 wt%	*Kevlar* fabric	Study the role of STF in influencing the impact deformation of a *Kevlar* fabric and its energy absorption.	[11]

2.0 EXPERIMENTALSET-UP

2.1 Materials

The materials used in this project were *Aerosil OX50* fumed silica particles from Evonik Industries (Germany), polyethylene glycol of 400 g/mol (*PEG 400*) from Scientific Fisher, ethanol of 95% concentration, and *Kevlar29* fabric plain woven. More specifics on the fumed silica and *Kevlar* fabric that were used in this study are respectively displayed in Tables 2 and 3.

Table 2: Physical and chemical properties of *Aerosil OX50*

Average particle size	40 nm
Specific surface area (BET)	$50m^2/g$

Table 3: Mechanical properties of *Kevlar29*

Area density	$280g/m^2$
Yarn breaking strength	970 lbs/in
Thickness	0.38mm

2.2 Preparation of STF

STF was prepared by dispersion of 15 and 20wt% to improve the dispersibility of the silica particles in medium fluid PEG, the fumed silica particles were first dispersed in ethanol and then blended with PEG. Ethanol has no effect on the final STF, and PEG was chosen as a solvent due to its non-toxicity, low volatility, thermal stability and its ability to form hydrogen bond with the aramid fibres [2]. Mechanical stir machine (Figure 1a) was used to further improve the dispersibility and to prevent agglomeration. The mixing process was run for three hours until a homogenous and stable suspension was achieved. Figure 1b shows the homogenous solution of mixed silica, PEG, and ethanol. Ethanol was later removed through the evaporation process at $80^{o}C$ in the oven for 24 hours. Ethanol removal was done for the STF preparation in Method A. For Method B, ethanol was not removed from the STF.

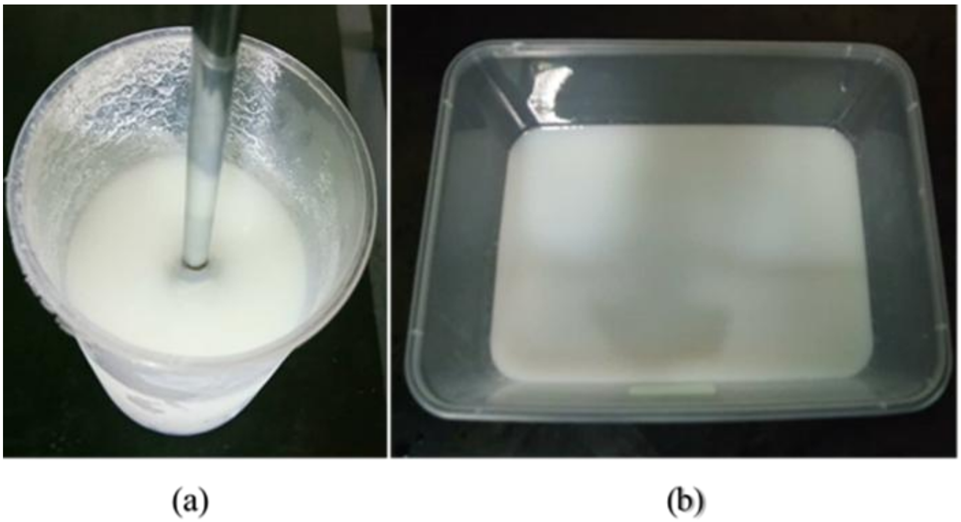


Figure 1: (a) Mechanical stir machine (b) Homogenous solution of mixed silica, PEG and ethanol

2.3 Preparation of the STF/*Kevlar* Composite Fabric

For the first method (i.e., Method A), to impregnate fabric with STF, STF must first be diluted beforehand due to the high viscosity of the STF after the removal of ethanol. STF was diluted with ethanol at 3:1 volume ratio of ethanol to STF to reduce the surface tension of the STF and to ensure proper penetration of STF into the fabric. The impregnation of the target was carried out by soaking the fabric specimen (15cm x 15 cm) for 10 mins in the STF containing a bath with the required particle concentration and then the fabric was padded to remove the excess fluid. The impregnated fabric was then dried in a hot air oven (Figure 2) at a temperature of 80^{0}C for 1 hour to remove ethanol from the fabric, thereby forming the composite STF/*Kevlar*.

Figure 2: Evaporation of ethanol form impregnated fabrics in the oven

As for the second method which is Method B after fumed silica, PEG and ethanol were mixed for 3 hours, the solution was directly used to soak the fabric. The fabric was soaked for 10 mins and padded to remove excess fluid before dried in the oven with the same parameters used in Method A. Figure 3 summarises the different sequences of the synthesis process for Methods A and B.

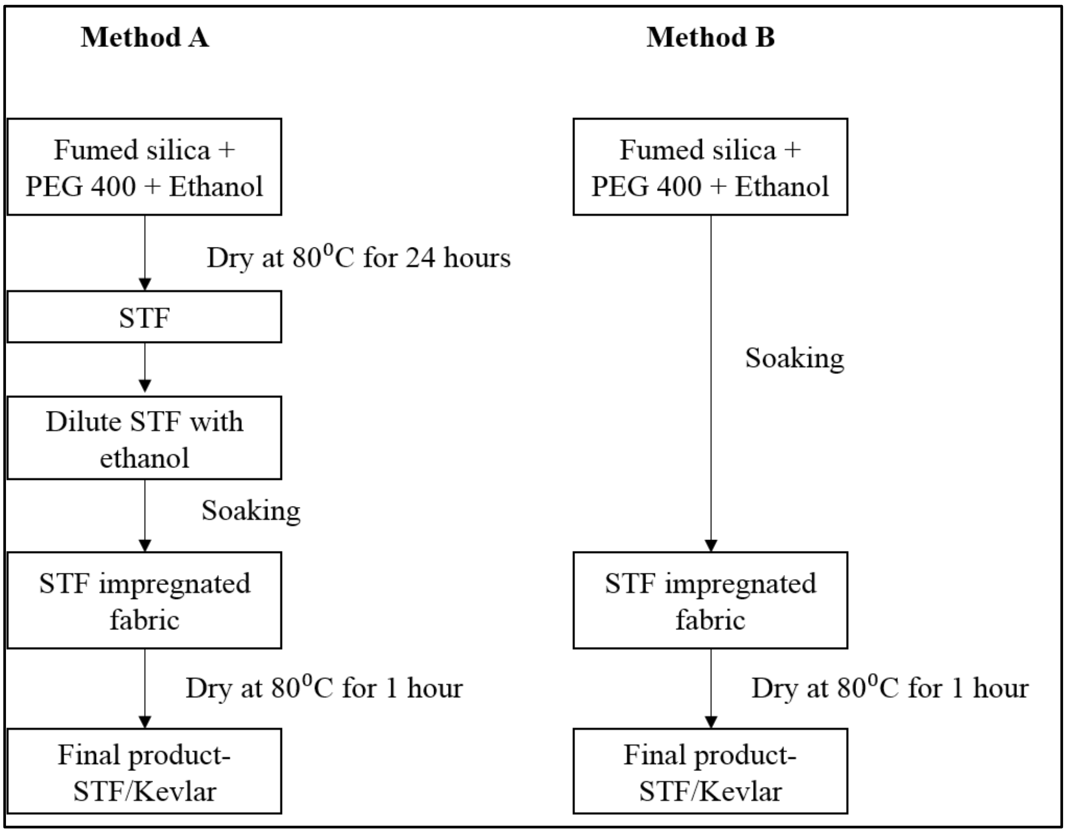


Figure 3: Two different synthesis sequences that were used in the study

The actual amount of STF present in the fabric composite, which is called the add-on percentage (*Add-on*%) was calculated by using the following expression.

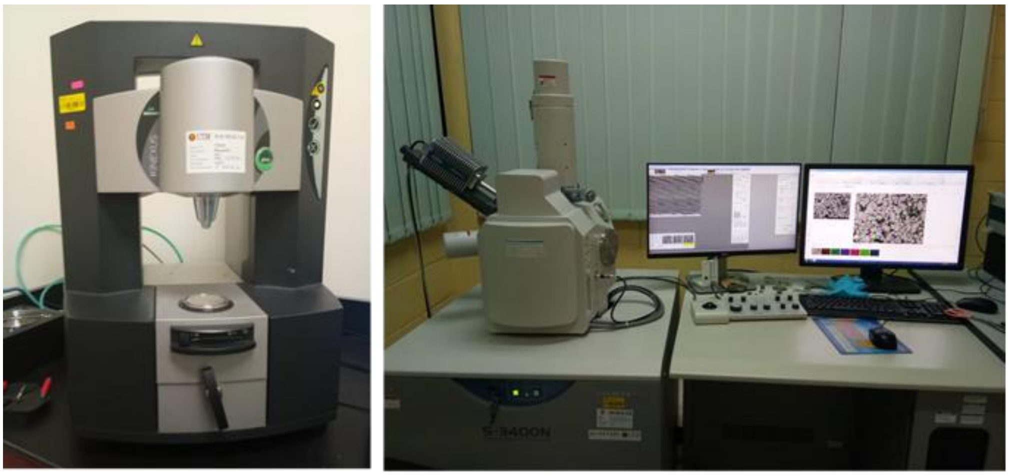
$$Add - on\ \% = \frac{m_f - m_i}{m_i} \text{x} 100 \tag{1}$$

Where $m_i$is the mass of neat fabric before STF impregnation and$m_f$is the mass of fabric composite after STF impregnation.Th above expression indicates the percentage of mass increased by the fabric after STF impregnation to the fabric.

2.4 Characterisation

The rheology analysis of STF was performed using *Kinexus Pro+* Rheometer (Figure 4a) to define how the STF viscosity changes. The test was carried out at a room temperature of 25^{0}C in a steady state flow mode with shear rate ramp increased from 0 to 500 s^{-1} using cone-plate geometry of size 40 mm diameter and 1 rad angle. The corresponding viscosity was then recorded.

S-3400N Scanning Electron Microscope (SEM) (Figure 4b) was used for high magnification observation of neat *Kevlar* fabric and STF/*Kevlar* composite fabric. Gold coating is needed prior to SEM imaging to enable and improve the imaging of samples. The coating was done using *BIO-RAD Polaron Division* SEM Coating System.



(a) (b)

Figure 4: (a) *Kinexus Pro+* Rheometer (b) *S-3400N* Scanning Electron Microscope

2.5 Drop Weight Impact Test

The impact resistance performance of neat *Kevlar* and STF/*Kevlar* composite were tested on a drop weight impact testing instrument, *Instron CEAST 9350* as per *ASTM: D3763* standard procedure. A steel rounded tip rod with a diameter of 12.7 mm was used as the impactor. The single layer specimen of 15 cm x 15 cm was clamped between the two steel plates by eight screws. Only 10 cm diameter of central circular of the specimen was subjected to the impact. Neat *Kevlar*, *STF/Kevlar-15wt%-A/B*, *STF/Kevlar-20wt%-A/B* were tested at the given impact energy of 200 J and impact speed of 4.25 m/s. The force generated and energy against the displacement measurement were generated simultaneously by the instrument. However, for the analysis purposes, the raw data generated by the instrument during the impact testing was used to calculate the total energy absorption by the materials.

2.6 Yarn Pull-out Test

Yarn pull-out test was carried out to rationalise experimental findings related to the effect of *Kevlar* fabric impregnation on its energy absorption and the results were compared to those obtained for the corresponding neat *Kevlar*. The purpose of yarn pull-out test is to study the effect of STF addition on the friction between yarns. Figure 5 displays the experimental setup to perform single yarn pull-out test. The fabric sample shown in Figure 6 was clamped in between a mobile clamp and a fixed clamp, which is part of the pull-out test fixture. A single longitudinal yarn in the middle was gripped at one end and pulled at a constant speed of 50 mm/min and the force versus displacement curves were recorded.

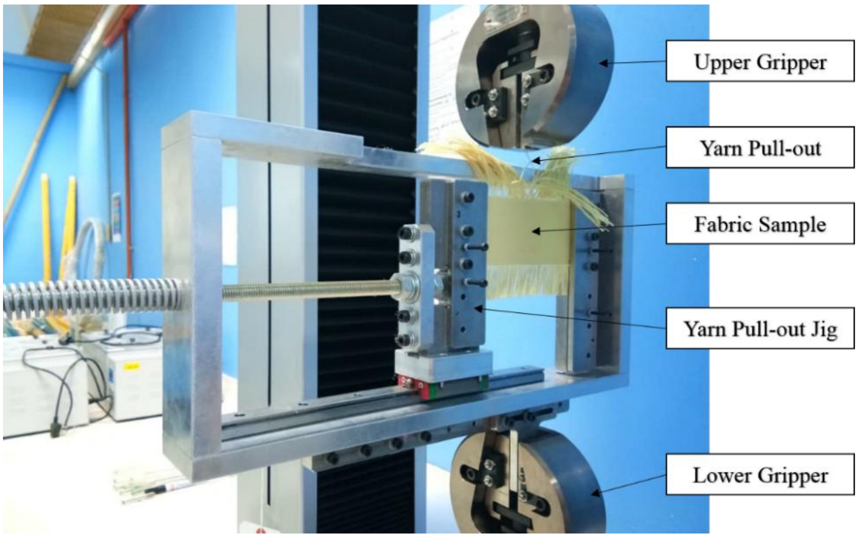


Figure 5: Experimental setup of yarn pull-out test

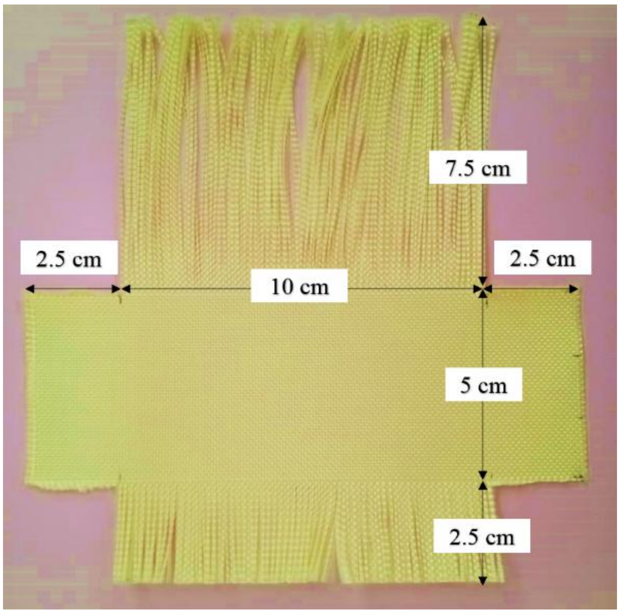


Figure 6: Fabric sample

3.0 RESULTS AND DISCUSSION

3.1 Rheological Results

Rheological analysis was conducted for STF containing the composition of 15 and 20wt% of fumed silica particles. The results of the rheology test can be seen in Figure 7 in which the viscosity is plotted against shear rate. Both curves demonstrate three different regions: a slight shear thinning behaviour at low shear rate, shear thickening behaviour at high shear rate, and finally steep shear thinning behaviour upon further increase of shear rate. It is observed that critical shear rate, γ_c (where shear thickening begins) of STF containing 20wt% (*STF-20wt%*) of particles is significantly lower compared to the STF containing 15wt% (*STF-15wt%*) of particles. The γ_c of STF decreases as the solid volume fraction of particles increases. The curves show that shear thickening behaviour commencing from 0.07 to 3.50 s^{-1} where the maximum value of viscosity for *STF-20wt%* is 154.10 PaS and from 0.08 to 8.4 s^{-1} for *STF-15wt%* where the maximum viscosity is 7.15 PaS. Similarly, previous studies done by Egres *et al*. (2004)confirmed that with the increase of solid volume fraction, the critical shear rate at which the shear thickening began will decrease [12].

There are two different mechanisms that may be attributed to this shear thickening behaviour. The first mechanism was proposed by Hoffman(1974)where he suggested an order-disorder transition in which the flow structure changes from ordered layers to a disordered structure, which also results in drag forces between particles [13]. A second mechanism is hydroclustering, where particles tend to rearrange itself into clusters under shear. The chains then overlap to form a network which is hard to break apart [14].

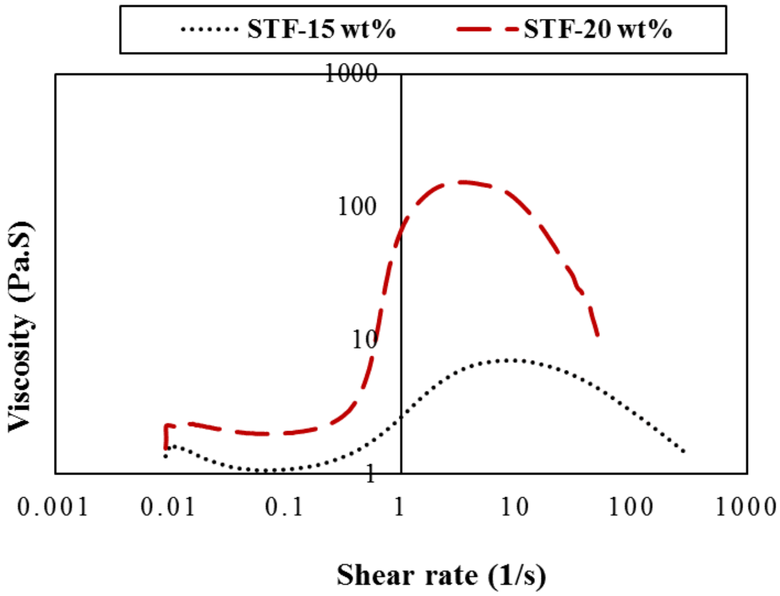


Figure 7: Viscosity against shear rate for STF with different particle weight fraction

3.2 STF Add-on % of Fabric Composites

Table 4 shows the values of STF *Add-on %* on *Kevlar* fabrics at different silica wt% for each method. It was observed that, under the same silica wt%, Method B has higher *Add-on %* of STF compared to Method A. Figure 8 displays the SEM micrograph of neat *Kevlar*, STF impregnation on *Kevlar* fabric for *Kev/STF-20wt%-A* and *Kev/STF-20wt%-B*. Figure 8a represents the SEM image of neat *Kevlar* without STF. Figure 8b shows the dispersion of STF over the surface of *Kevlar* for method A and the image of the fibres can clearly be observed under the magnification of 37 times. However, for Method B (Figure 8d), under the same magnification size, it is observed that the STF has completely covered the surface of the *Kevlar* and the fibres can hardly be seen. Figures8c and8e display the higher magnified image of *Kev/STF-20wt%-A* and *Kev/STF-20wt%-B,* respectively. From Figure 8b, it can be seen that STF is incorporated between the fibres.

It can thus be deduced that the silica was well dissolved in the STF through Method A because it went twice through the diluting of the STF with ethanol and heating process to remove ethanol. Meanwhile, the STF produced in Method B is thicker compared to Method A because it only went through a single process of diluting and heating. This explains the higher *Add-on %* of STF for Method B compared to Method A because the STF produced in Method B is denser than that produced in Method A.Based on Table 4, it can also be observed that under the same methods but different silica wt%, the STF with higher silica wt% has higher *Add-on%* of STF compared to the STF with lower silica wt%. This is because, the higher content of silica will result in correspondingly higher viscosity of the STF, hence more STF is deemed impregnated into the fabrics.

Table 4: *Add-on* % of STF on *Kevlar* fabrics

Silica wt%	Method	*Add-on* %
15	A	17.82
15	B	56.46
20	A	33.52
20	B	63.56

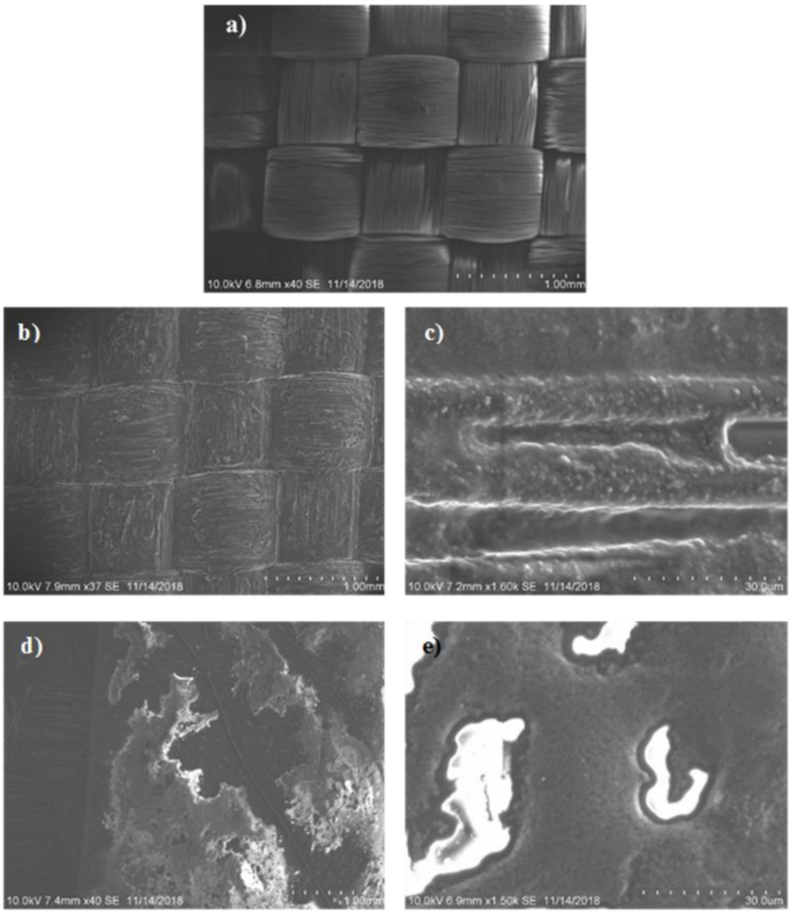


Figure 8: SEM images for (a) neat *Kevlar* (b-c) *Kev/STF-20wt%-A* and (d-e) *Kev/STF-20wt%-B*

3.3 Drop Weight Impact Test Results

Figure 9 shows the force against displacement relationship that was generated during the penetration process by the drop weight impact instrument. The total energy absorption by each material was then calculated through mathematical integration using trapezoidal rule which approximates the area under load-displacement curve to calculate the total energy absorption of the material. The total energy absorption of each material is represented in Figure 10.

Generally, it was observed that the *Kevlar* fabrics that were treated with STF have significant increase in energy absorption compared to the neat *Kevlar*. Meanwhile, *Kev/STF-20wt%-B* has the highest energy absorption (114.47 J) compared to neat *Kevlar* (64.51 J), which represents a 77.45% increment. For *Kev/STF-20wt%-A*, the percentage increment compared to the neat *Kevlar* is 49.12% which is lower than *Kev/STF-20wt%-B*. This undoubtedly shows the significance of STF presence in energy absorption under low-velocity impact at 4.25 m/s. In addition, the fabric composites that were synthesised using Method B display better energy absorption outcome compared to Method A, an improvement of about 19%. The same trend goes for *Kev/STF-15wt%* where the fabric composites that were produced by Method B has moderately higher energy absorption of 87.29 J compared to Method A at 82.02 J.

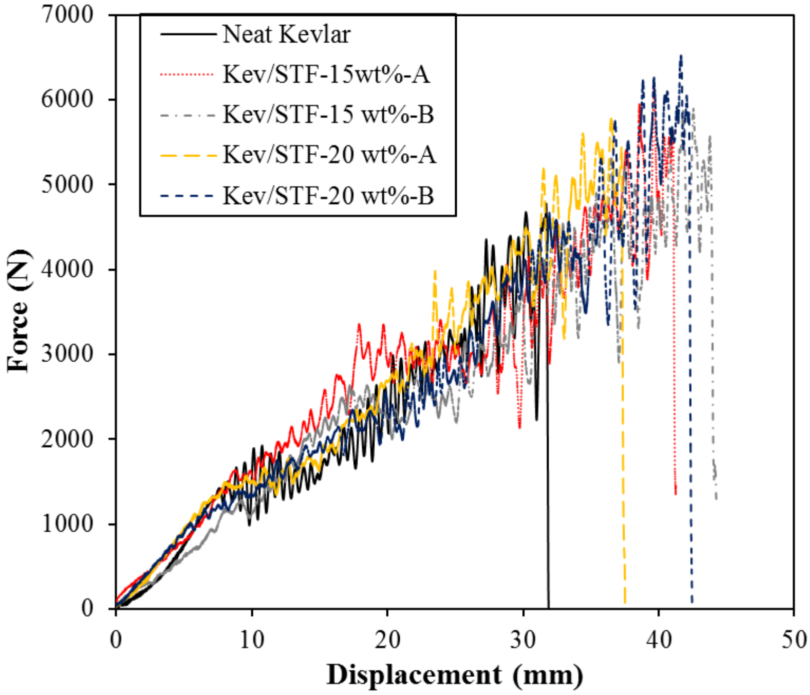


Figure 9: Force-displacement relationships curves under the impact of a rounded tip rod at an initial velocity of 4.25 m/s with the impact energy of 200 J

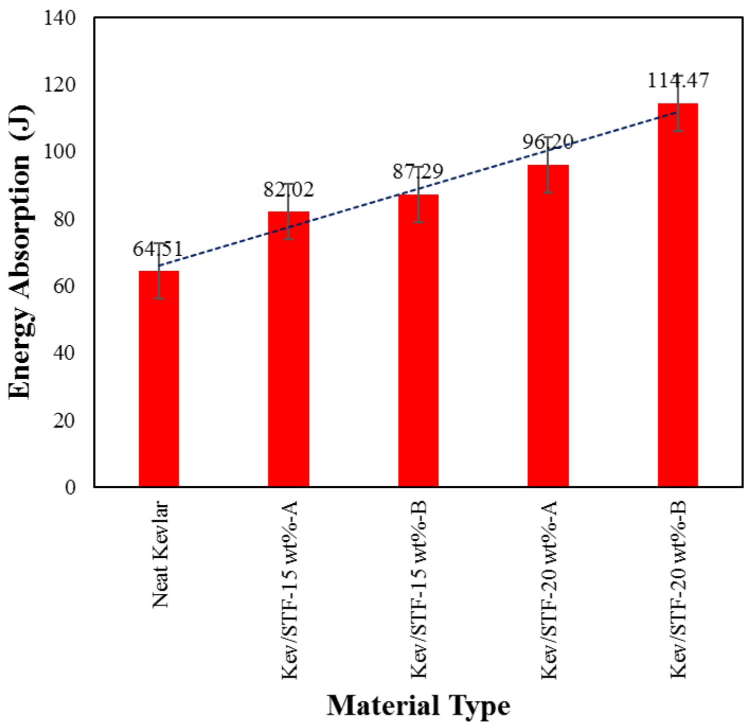


Figure 10: The energy absorption by each material

3.4 Yarn Pull-out Test Results

Yarn pull-out test was conducted to observe the inter-yarn friction in fabric composites in order to rationalise the experimental findings related to the impact energy absorption of fabric composites. The results of single yarn pull-out test for *Kevlar* impregnated with STF were compared with those obtained for the neat *Kevlar* fabric. Figure 11 illustrates the result of single yarn pull-out test for neat *Kevlar* at testing speed of 50 mm/min. The pull-out force can be divided into two types which are static force and dynamic force. Static force is referred to the value of force that is needed to overcome the static yarn friction where the yarn starts to move after being pulled. When the free end of the yarn begins to slide into the fabric weave, the static force changes to dynamic force and gradually decreases.

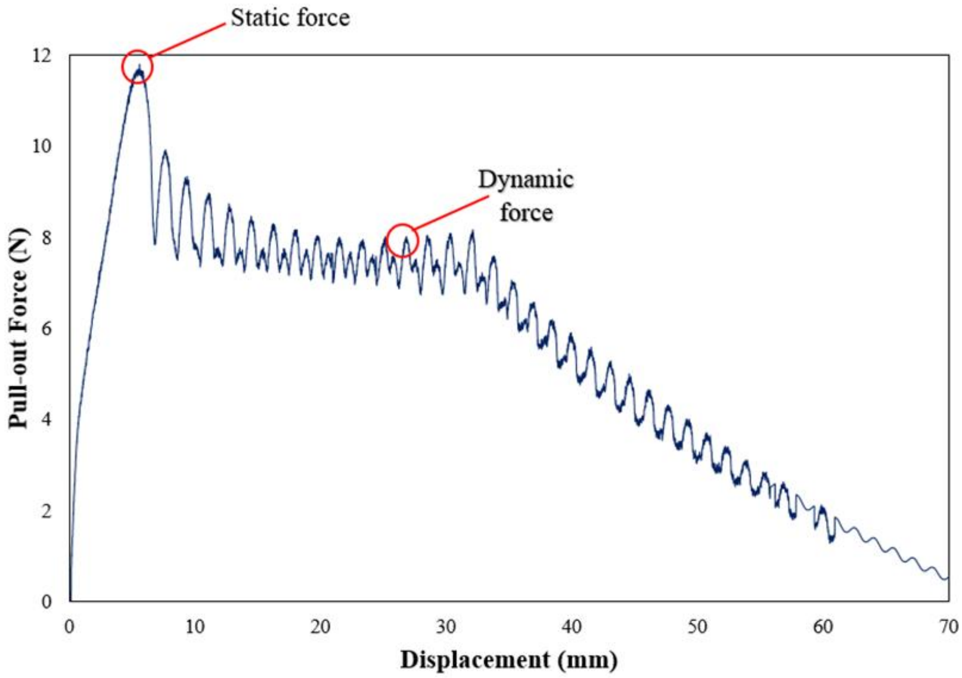


Figure 11: Single yarn pull-out test result for neat *Kevlar* at testing speed of 50 mm/min

In the meantime, Figure 12 displays the results of load-displacement relationship of the different fabric composites in comparison to the neat *Kevlar*. Typically, for a load-displacement curve of yarn pull-out test, the result expectedly shows a gradual decreasing trend of the pull-out force when it surpasses the static friction until the yarn gets ejected from the weave [3,15]. On the contrary, for this experiment, it was observed that the results did not obey the typical trend. The results show that the dynamic force for the fabric composites increases towards the middle of the weave region until it reaches the maximum force and eventually dropped significantly.

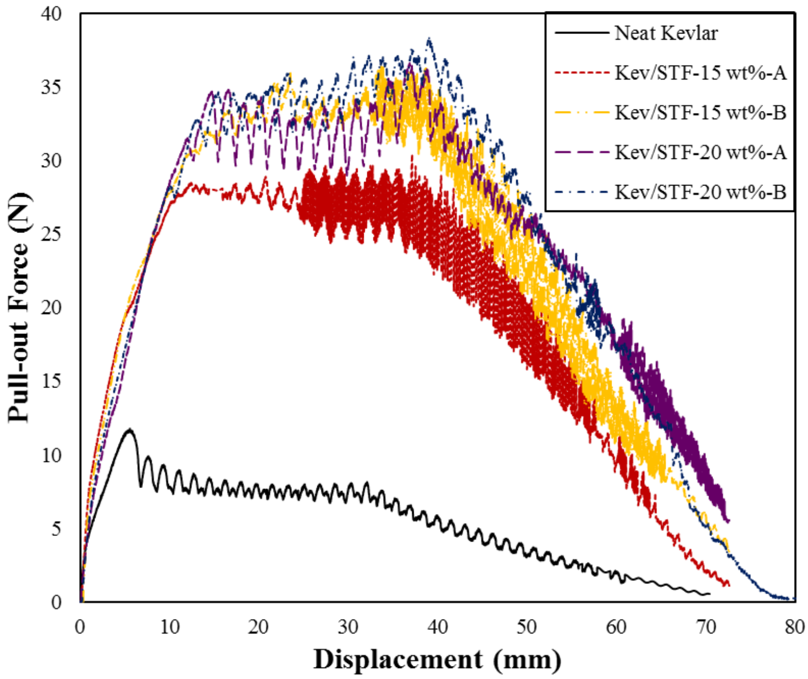


Figure 12: Force vs displacement curves of neat *Kevlar* and different fabric composites at the speed of 50 mm/min

Figure13 illustrates in detail the value of maximum static force and maximum dynamic force of neat *Kevlar* and different fabric composites. Generally, the results demonstrated that fabric composites exhibit higher static and dynamic force compared to neat *Kevlar*. In terms of particle fraction, the fabric composite with higher silica content at 20 wt% displays higher pull-out force compared to the lower silica content. Between the two methods of composites synthetisation, Method B is proven to be slightly better than Method A.

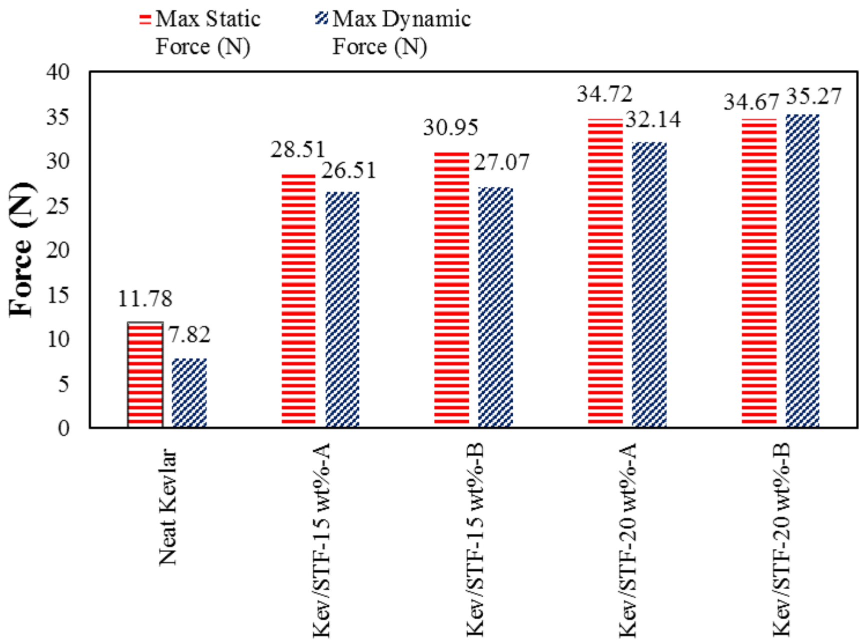


Figure 13: Maximum static and dynamic forces of neat *Kevlar*and different fabric composites

For instance, *Kev/STF-20wt%-B* has higher dynamic force at 35.27N compared to *Kev/STF-20wt%-A* which is at 32.14N, even though the static force is similar. This test inferred that the addition of STF could greatly restrict the yarn movement, thereby showing a significant increase in the pull-out force compared to neat *Kevlar*. The STF additives increase the roughness of yarn surface and hence, the friction between the yarns increased, resulting in better coupling and load distribution under impact. Additionally, fabric composites that contain higher STF concentration and synthetised using Method B demonstrated better performance.

4.0 CONCLUSION

In this experimental study, the *Kevlar*/STF composites were developed to examine the energy absorption behaviour of the composites. Different STF composition which were 15wt% and 20wt% of silica content were used to fabricate the fabric composites through two synthetisation methods; namely, Methods A and B. The former used the typical method that was used in most of the previous studies to fabricate the *Kevlar*/STF composites, while the latter was the new method proposed in this research. The main difference between both methods is that in Method B, the STF only went through a single heating process to remove the ethanol content, while in Method A, the STF went through twice the heating process. Rheology test was conducted on the different STF composition to define the shear thickening behaviour of the STF. Meanwhile, the performance of the fabric composites was analysed via low velocity drop weight impact test and single yarn pull-out test.In conclusion, the *Kevlar*/STF fabric composites that were synthesised through Method B displayed significantly better performance in terms of energy absorption and inter-yarn friction compared to Method A. The percentage increase of energy absorption of the composites fabricated through Method B is 19% compared to Method A. In addition, Method B is likely more economical in relation to the cost and fabrication time. Further investigation should be carried out on multiple layers of the*Kevlar*/STF fabric composites using Method B because it would represent the actual application of the fabric composites itself. Besides, it would be interesting to redo everything that was previously done while controlling closely the padding pressure applied to the fabric during the impregnation process.

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