Analysis of impact energy absorption of kevlar and polyester composite impregnated with corn starch shear thickening fluid

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Kevlar and polyester (PET) composite structures have been developed through layering by impregnation with optimized corn starch shear thickening fluid (CS−STF), prepared using corn starch (CS) and polyethylene glycol (PEG). Corn starch has been characterized for particle size and distribution through dynamic light scattering. The CS and PEG ratio (40:60, 46:54, 52:48 and 58:42) has been studied through fluidity and shear thickening measurements using in-house funnel collector and electro-mechanical shearing stirrer through ampere measurement studies respectively. Based on the established impact energy calibration curve and energy calculations, the impact energy absorption of CS−STF impregnated fibre composites have been studied. The order of layering of the STF in impregnated textile structures has been systematically studied for effective impact energy absorption. Shearing studies reveal that at and above shearing time of 3000 µs, shear thickening is found to be prominent for the optimum CS: PEG ratio of 52: 48. Similar trend is also observed in the impact energy absorption studies of textile structures impregnated with the CS−STF. One layer of kevlar woven fabric followed by one or more layers of PET nonwovens with CS−STF show good performance in impact energy absorption. Similar trend is also observed in 6, 5 and 4 kevlar layering. It is observed that the presence of more than one layer of kevlar on the top of the nonwovens in the composite does not contribute; rather it decreases the energy absorption. The treated structures show 100 % antimicrobial activity by AATCC 100 method and they do not develop smell, while the untreated samples develop microbes with intense smell.

Keywords: Corn starch, Dynamic light scattering, Impact energy, Kevlar, Nonwoven, Polyethylene glycol, Shear thickening fluids

1 Introduction

Shear thickening fluids (STFs) are promising to develop impact resistance structures as they have low viscosity under normal conditions and high viscosity on shearing[1]. Structures with these STFs are required where the material needs to have the flexibility particularly in case of bullet proof vest or foldable structures that can be carried from one place to another place like in defence application[2]. The rigid impact resistance structures lack the fold ability and accommodating into packaging containers. So the rigid structures cannot be transported easily whereas the foldable structures can be easily transported and could be reused. Moreover, once the rigid structures are attacked by the impact force, they fail and cannot be used further. However, STF structures can be reused

not only in high impact resistance application but also in low impact resistance applications[3]. Different types of STFs are available and some are used for commercial applications[4]. Various studies have been carried out for the development of STFs using nano technology along with suitable polymers. Mechanism of the action of shear thickening by various particles and polymers has been well exploited and explored[5].

One of the well-known natural materials for shear thickening effect is the corn starch (CS). It has been used as fun games and for some simple applications[6]. Corn starch is a low cost starch derived from corn. Considering shear thickening behaviour of the CS and its natural low cost source, it is promising to explore its STF behaviour for various impact resistant applications[7]. However its STF behaviour for impact resistant technical applications has not been well explored, probably because it is a natural material prone for microbial attack which might develop pungent odour.

High performance textile materials, like kevlar, ultra high molecular weight polyethylene

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(UHMWPE) and Vectron[8] (Aromatic polyester) have been used for impact resistant applications as layered structures and composites due to their high mechanical properties[9]. Further, if these fibres fail after a sudden impact attack, they need to be replaced with the new one[10]. Additionally, as these fibre fabrics are used in multilayer and composites, they turn out to be heavy and stiff[11]. Hence there is a need to make simple, flexible and techno economical structures.

In this research work, an attempt has been made explore the possibilities of using ordinary grade textile fibres by incorporating the shear thickening fluids in it[12]. For this purpose, the natural shear thickening material (corn starch, CS) has been used, addressing its limitations for suitable natural antimicrobial agents which are widely used for textile functional finishing purposes[13]. Additionally, attempts have also been made to develop various kinds of impact resistant structures with the combinations of high performance fabrics (kevlar) and nonwoven structures (polyester) with ordinary grade fibre. Hence, it is planned to prepare the STFs and to optimize the proportions of corn starch and solvent [polyethylene glycol, PEG] based up on the previous study. The optimized CS−STF is applied on the selected textile structures and then studied for the impact energy absorption for various samples that differ in structures and layering. Energy absorption study is carried out with help of classical physics involving equations of motions, concept of potential and kinetic energy. Such studies are correlated with the electrical energy required for shearing of CS−STF for various rates to establish the total energy absorption of the various CS−STF impregnated textile structures.

2 Materials and Methods

2.1 Materials

The kevlar fabrics with plain weave, 0.23 mm thickness, 22 ends/inch, 22 picks/inch, and 190 g / m^2 (GSM) were purchased from Nickunj Eximp Entp P Ltd, Mumbai. Thermally bonded polyester nonwovens with 240 GSM were purchased from Aadinaath felts, Karur. Polyethylene glycol (PEG) 200 Mw was purchased from Merk, Mumbai. Corn starch was purchased from Venus Starch, Salem, Tamilnadu. 4-chloro-3, 5-dimethyl phenol was purchased from Star Scientific, Erode, Tamilnadu.

2.2 Particle Analysis

The particle size analysis of corn starch (CS) was carried out by Nano plus dynamic light scattering spectrum in colloidal suspension using light scattering principle[14].

2.3 Preparation of CS−STF and Fluidity Test

The corn starch (CS) shear thickening fluid (STF), called CS−STF, was prepared with mixture of corn starch, polyethylene glycol (PEG) and the commercial antimicrobial agent 4-chloro-3, 5-dimethyl phenol. This CS−STF was thoroughly stirred by mechanical stirrer for homogeneous mixing.

The fluidity property and the flow of the shear thickening fluid are important to identify the flexibility and rigidity of the sandwich composite materials. The ratio of CS / PEG was taken as 40 / 60, 46 / 54, 52 / 48 and 58 / 42. The prepared CS−STFs of different composition were taken in a flask and then poured in to the other flask through a funnel; the quantity in gram collected in 10 s was measured.

2.4 CS−STF Shear Thickening Studies

Shear thickening effect of the corn starch was tested through change in ampere of electron flow to the mechanical stirrer which was used for the shearing of the STFs. For this purpose, a mechanical stirrer with the good blade deflection profile was selected for a good shearing action on the STFs. Shear thickening fluids were prepared using the CS / PEG ratios of 40:60, 46:54, 52:48 and 58:42. The flow of current to stir these different ratios of STFs was measured by the ammeter and was used to find the optimum ratio.

2.5 Bending Length Measurement

The flexibility of the composite structures was quantified through a bending length measuring instrument[15]. Test specimens were cut to 2.5 cm wide and 20 cm long and then placed on the platform of the instrument. The sample was moved with a gentle pressure and then projected like a cantilever, which bends at the some point due to its own weight and matches the datum mark provided in the instrument. At that point, the movement was stopped and the total length of movement was measured as the bending length. Such bending length measurements of the samples were carried out for post impregnate timings, after every 20 min till 120 min.

2.6 CS−STF Textile Layered Sandwich Composite Preparation

The textile sandwich composite materials were prepared by stacks of the kevlar and polyester nonwoven samples. The CS−STF impregnated kevlar and nonwoven (SKNW) were layered in different

orders to study the effect. The various samples used for this study along with their codes are presented in Table 1.

2.7 Impact Energy Absorption through Stab Resistance Testing

The inhouse drop tube test apparatus was made with the guidance of NIJ standard−0115.00, as shown in Fig.1. The testing apparatus primarily consists of a drop mass of 3.58 kg. In the drop mass, the knife or spike can be fixed. Further, the drop mass containing the knife slides over the two rods standing on a heavy bottom plate. The rods with a net height of 1.5 m are spaced by 0.4 m. The drop mass can freely slide down or up on these two rods. Further, the drop mass was made by the nylon (upper mass) which houses the bottom mass made by the steel. Two polyethylene foam discs were installed inside the upper mass for damping effect. The drop mass has the net dimensions of 51 mm diameter and 368 mm length. The sample (regarded as target) was placed over a specially prepared backing material (a multilayer foam as specified by NIJ standard 0115.0) This backing

Table 1 — Sample codes for STF filled nonwoven and kevlar composites with different layering orders

Sample code	No of layers	Layering order
SKNW$_1$	6	K$_1$, NW$_1$, NW$_2$, K$_2$, K$_3$,K$_4$
SKNW$_2$	6	K$_1$, K$_2$, K$_3$, NW$_1$, NW$_2$, K$_4$
SKNW$_3$	6	K$_1$, K$_2$, NW$_1$, NW$_2$, K$_3$,K$_4$
SKNW$_4$	6	K$_1$, NW$_1$, K$_2$, K$_3$, NW$_2$, K$_4$
SKNW$_5$	6	NW$_1$, NW$_2$, K$_1$, K$_2$, K$_3$, K$_4$
SKNW$_6$	5	NW$_1$, NW$_2$, K$_1$, K$_2$,K$_3$
SKNW$_7$	5	NW$_1$, K$_1$, NW$_2$, K$_2$,K$_3$
SKNW$_8$	4	NW$_1$, NW$_2$, K$_1$, K$_2$
SKNW$_9$	4	NW$_1$, K$_2$, NW$_2$, K$_3$

K – Kevlar and NW–Polyester Nonwoven
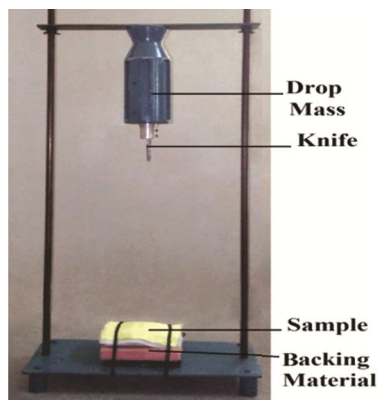
Fig. 1 — Stab resistance tester used for impact energy absorption studies

consists of four layers of 5.8 mm thick neoprene sponge, followed by one layer of 31 mm thick polyethylene foam, backed by two 6.4 mm thick layers of rubber. Synthetic polymer based poly art witness papers were placed between the target and foam backing and behind each layer of neoprene rubber.

The impact energy of the falling mass would depend on the height(taken as product of mass, height and gravitation force), from which the drop mass is allowed to fall. To establish the calibration curve of impact energy and the knife penetration depth in the backing material, various energy levels of (6 −24 J) falling mass were used. Different energy levels were obtained by changing the height of the falling mass. In the subsequent testing of the CS−STF impregnated and non-impregnated targets, the height of drop mass was fixed (0.684 m) corresponding to the energy level of 24 J. All the targets were kept in the bottom platform above the multilayer backing materials and the targets were strapped along the backing materials using cotton strap. After every test, the penetration depth was measured by the puncture mark in the witness paper.

2.8 Antimicrobial Test

In this study, corn starch was used for preparing STFs. As corn starch is obtained from natural corn, it can undergo microbial degradation. Hence, to overcome this problem, in the shear thickening fluid the commercial antimicrobial agent 4-chloro-3, 5-dimethyl phenol was added. This antimicrobial agent was used at three different concentrations ranging from 5 gpL to 20 gpL. Hence, the STF treated kevlar; nonwoven and composite textiles along with control materials were tested for antimicrobial activity by colony count method according to AATCC 100[16].

3 Results and Discussion

This research work aims at developing impact resistant textile structure using corn starch (CS) as shear thickening fluids (STF) [17] along with the kevlar and polyester nonwoven samples as composite layered structures. The results of the various studies conducted are presented and discussed below.

3.1 Particle Size and Fluidity of CS & PEG STF

Prior to the fluidity study of CS−STF, the corn starch (CS) particle size was analyzed using dynamic light scattering (DLS) particle analyser, as the particle size and its distributions might have an effect on the

interaction of the particles upon swelling induced by the solvents. The average particle size, as obtained from the DLS results, is found to be 2925 nm (2.9 µm) and the maximum particle size with less frequency is found to be only 10 µm. The particle size distributions are quite narrow whose polydispersity index is obtained as 0.8. Hence, these particles could initiate a good interaction with the solvent medium and also amongst themselves due to very small particle size with narrow distribution, as the specific surface area of small particles are higher than the large particles[18].

In order to understand the viscosity of STF formed out of different properties of corn starch (CS) and the solvents, [polyethylene glycol (PEG) a hydrophilic solvent], fluidity test has been carried out[6]. This study is important to ensure enough penetrability of the STF inside the textile structures coupled with the good shear thickening effect. The fluidity study involves passing the STF through a standard funnel and measuring the quantity collected for a definite period of time. The quantity of STF collected for the selected CS / PEG ratios are shown in Table 2. It can be observed that for a higher solvent content (40:60), the quantity of STF collected is 11.5 g and with 54 % solvent in 46:54 CS /PEG ratio, it is only 2.6 g, which indicates the sudden shoot up of the viscosity, and hence fluidity decrease of 77.4 %, for a decrease in the solvent content of only 6 %. The corresponding solvent decrease for 52:48 and 58:42 ratios are found 12 % and 18 % whose fluidity decrease is 90.4 % and 100 % respectively. From these studies, it could be inferred that the STF is highly sensitive to the solvent content which interacts between the corn starch particles, facilitating their fluidity. Though the fluidity of the STF is required for the purpose of good penetration into the textile structures, too much fluidity would hinder the shearing effect, eventually affecting the thickening effect of the mixture. Hence, it is evident that the CS / PEG ratio of 58:42 could not be used for the purpose of impregnating textiles while the others could be. Hence, the effects of shearing and

thickening for these ratios need to be explored for the purpose of selecting the right proportion of CS / PEG for preparing optimum STF. Such study is carried out using a mechanical shearing blade whose results are discussed in the following section.

3.2 Shear Thickening Effect of CS STF

In the previous section, the corn starch shear thickening fluid (CS–STF) has been characterized for its fluidity, which has revealed that the presence of solvent below 48 % makes the mixture almost like dough without any free fluidity. However, the other mixtures which have 48 % and more solvent need to be studied for shear thickening effect in order to select the optimum solvent ratio. Hence, it is studied through inhouse mechanical stirrer with blade profile having good shearing ability with the fluid. Shear thickening fluids are prepared as per the CS / PEG ratios 40:60, 46:54, 52:48 and 58:42. In these experiments, the effect of shearing time upon change in ampere (electrical current flow to drive the mechanical stirrer) was studied and the results are presented in Fig. 2.

It is observed that the CS–STF with 40 % CS and 60 % PEG has almost same ampere for up to 3000 µs with slight increment up to that point and the increment is slightly steep beyond 3000 µs. Almost similar trend is observed for the second proportions i.e. 46 % CS and 54 % PEG, except that the steeping of curve starts even at 2000 µs, which becomes notable beyond 3000 µs. In the case of third ratio (52:48), the shear thickening effect can be noticed even from the beginning i.e. from 500 µs, whose effect is well noticed beyond 3000 µs and it continues

Table 2 — Fluidity measurement of CS STF made from corn starch and PEG mixtures

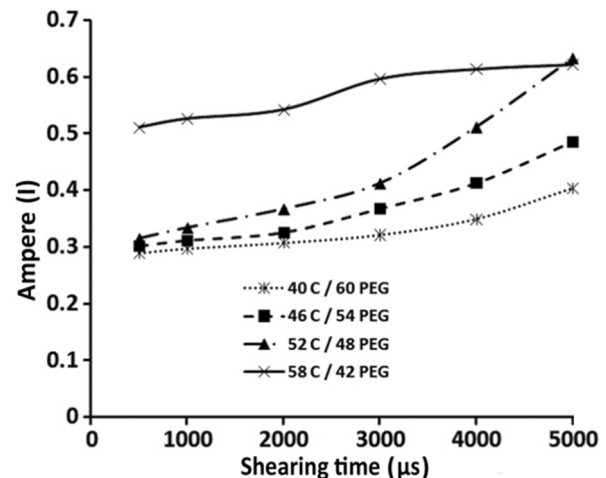| Corn starch : PEG (w/w)	Decrease in solvent content, %	Collected STF fluid, g	Decrease in fluidity, %
40 : 60	0	11.5	0
46 : 54	6	2.6	77.4
52 : 48	12	1.1	90.4
58 : 42	18	0.0	100.0

Fig. 2 — Shear thickening effect of CS-STF of varying proportions through current flow measurement

to increase with the shear rate proportionally with a maximum ampere of 0.632 A at 5000 µs. In case of 58:42, the initial current flow itself is found very high (0.511 A) at 500 µs and it remains same with little increase in shear time (2000 µs). From 2000 µs to 3000 µs, the increase almost remains constant and shows little further increase even up to 5000 µs with a maximum ampere of 0.621 A at 5000 µs. In this case, the increase in ampere is because of the high viscosity of the fluid, but not probably because of the increase in shear. However, an important point should be noted from these results (Fig. 2) that for the ratio of CS / PEG 52 : 48, the maximum ampere of 0.632 A is observed for shearing time 5000 µs, which is even greater than the ampere (0.621 A at 5000 µs) for the higher viscose paste of CS / PEG 58:42. It implies that at these particular proportions (52:48) the shear thickening fluid has lower viscosity as a paste, compared to the next level (58:42) and when it is sheared, it reaches viscosity of greater than the higher concentration paste (58:42).

It is clear from this study that among various combinations of CS & PEG mixtures, 52:48 ratio stands out to be the best in terms of shear thickening effect. When higher concentration of corn starch is taken, the mixture becomes too viscous that it is difficult to handle and impregnate onto textile structure. On the other hand, in lower concentrations of corn starch, the fluidity of the liquid becomes too high that it does not develop any notable thickening effect with shear and so would not effectuate good impact resistance in STF impregnated textile structures. Additionally such low concentrations of CS / PEG mixture cannot make them adhere to the textile substrates and might drip off textile substrates. Hence, it can be safely inferred that 52:48 (CS/PEG) is an effective ratio for preparing the STFs.

3.3 Effect of Post Impregnation Time on Flexibility of CS STF Impregnated Textiles

For the preparation of STF from corn starch, any hydrophilic solvents could be used. In order to explore the possibilities of using water, being the cheap and powerful hydrophilic compound, this study was carried out. However, one of the concerns when using different types of solvent for preparing STF is their ability to vaporize, which might affect the flexibility of the impregnated textile structures. Hence, first STF is prepared using the optimum (52: 48) CS & solvent (PEG or water separately) ratio and then it is applied both on nonwoven and on kevlar

fabric. The flexibility of the structures so developed using these combinations is measured through one of the test method which is available for evaluating the flexibility of the textiles structures (bending length measurements), as described earlier. The results of such measurement of bending length for the STF impregnated nonwovens and kevlar textiles are presented in Fig. 3. It can be observed that for the nonwoven impregnated with STF prepared with CS 52 / W 48, the bending length increases from 2.4 cm to 3 cm slowly and gradually up to 40 min, after which the trend is increasing drastically. At 60 min and 80 min, a very high increase in bending length of 6.7 cm is observed finally reaching a value of 7.7 cm at 120 min. In the case of nonwoven impregnated with CS 52 / PEG 48, it can be observed that it has a bending length of 3.2 cm which remains steady from beginning with a slight decrease in value to 3 cm at the end of 120 min. Similar trends are observed for the STF impregnated kevlar fabric also, but with difference in values of bending lengths.

CS 52 / PEG 48 and CS 52 / W 48

Kevlar impregnated with CS 52 / W 48, has bending length of 3.4 cm in the beginning and gradually increases to 5.2 cm at the end of 120 min, while the kevlar impregnated with CS 52 / PEG 48, has bending length of 4 cm and remains steady from beginning with a slight decrease in value to 3.8 cm at the end of 120 min (Fig. 3). Such trends can be explained due to the vaporization of solvents. It is known that the water can evaporate even at room temperature due to difference in the vapor pressure between the substrates and the atmosphere. Therefore, the STF prepared with water would lose the water molecules due to the vaporization effect during the post impregnation time. As a result, the textile structures become stiff making it difficult to bend on its self weight. This requires a long length of the fabrics to initiate bending to reach the end mark as
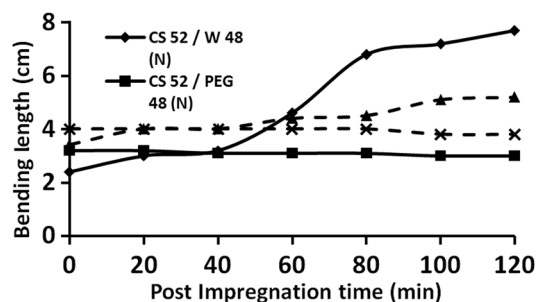

Fig. 3 — Effect of time on bending length of nonwovens and kevlar impregnated with CS52/PEG 48 and CS52/W48

described earlier. However, in the case of PEG, by virtue of polymeric nature of the compound, it would not vaporize and so remain in the corn starch STF. Hence, the bending length of both the nonwoven and kevlar structures impregnated with the CS 52 / PEG 48 STF remains the same without such stiffening effect. Such stiffening effects, in the case of water, would not only make the textile structures unfoldable but also would minimize the fundamental shearing action, which is the cause of thickening effect. The difference in bending length between nonwoven and kevlar structures could be because of the nature of the structures and the STF add-on. Both the nonwoven and kevlar impregnated with CS 52 / W 48 STF has the dried up flakes of corn starches on their surfaces, due to evaporation of water, while the nonwoven and kevlar impregnated with CS 52 / PEG 48 STF had no such flakes and the samples remain flexible. This study clearly indicates that the use of PEG as a solvent for the preparation of STF impregnated textile structures would yield efficient and durable impact resistant structures.

3.4 Impact Testing of CS–STF composites

3.4.1 Effect of Impact Energy on Penetration Depth in Backing Material

The developed CS−STF textile structures are subjected to impact resistance performance test using the inhouse tester. In this study, the depth of knife penetration in the backing material is studied for various energy levels (6−24 J) of the falling mass. The energy of the falling mass is varied based on the height from which they are released, and the energy is obtained in terms of potential energy (product of mass, gravitational force and height)[19]. As the knife penetrates through the backing material, by measuring the depth of its penetration, the energy absorbing capacity of the backing material can be calculated for various energy levels (Fig. 4). It can be observed that
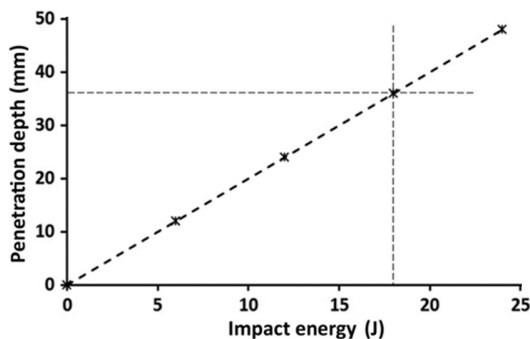

Fig. 4 — Penetration depth of knife in backing material for various impact energies

the penetration depth of the knife in the backing material increases with the increasing the impact energy and the trend is found to be linear. This result could be used for interpretation of energy absorbed by the target through measuring the penetration depth of the knife in the backing material after passing through the target material.

3.4.2 Impact Energy Absorption of CS−STF Impregnated Textiles

Kevlar and polyester nonwoven composite structures using CS−STF with ratio of CS / PEG 52:48 have been developed and subjected to impact energy absorption test (Tables 3 and 4). The table present the sample codes and the energy absorption study results. NK refers to 4 layers of plain kevlar fabrics; SK refers to 4 layers of kevlar fabrics with STF; SN refers to 4 layers of nonwoven with STF; and SKNW refers to 4 layers of nonwoven with STF and kevlar on top. Explanation about the sample codes and the layering order is presented in Table 1. The relationships associated with each of the parameters in the Tables 3 and 4 are outlined below.

$$\text{Add-on \%} = [(m_{TS} - m_T)/m_T] \times 100 \qquad \ldots (1)$$

where m_{TS} is the mass of textile with CS–STF; and m_T, the mass of textile.

Thickness (T) and penetration depth (d) are directly obtained results, as described in experimental section. Energy absorbed by backing material (E_b) is obtained from the calibration curve (Fig.4) based on the depth of penetration in the backing materials. For example, if the depth of the knife penetration in the backing material is 36 mm, correspondingly the energy associated would be 18 J, as it could be extrapolated (Fig. 4). Thus, the energy absorbed by the target is obtained by subtraction of E_b from the total energy 24 J.

Table 3 — Analysis of CS–STF impregnated textiles structures for impact resistance performance

Sample code	ao, %	t mm	d mm	E_b J	E_t J	V_b m/s	$-a$ m/s^2	t_t μs
NK	-	0.9	36	18.0	6.0	3.17	1858	263
SK	596	6.0	27	13.5	10.5	2.75	417	1881
SN	1550	16.2	18	9.0	15.0	2.24	455	5486
SKNW	944	13.5	6	3.0	21.0	1.29	469	5447

ao–STF add-on (%), t–target thickness (mm), d - penetration depth (mm), E_b –energy absorbed by backing material (E_b), E_t-energy absorbed by target (24 E_b), V_b – velocity at backing surface [sqr (E_b / 1.79)], $-a$–retardation [(V_t^2–V_b^2)/2t, and t_t - time (μs) to travel the target [(V_t-V_b)/a]×10^6.

Table 4 — Effect of layering order and number of layers on impact resistance performance of CS STF textiles

Sample code	ao, %	t mm	d mm	E_b J	E_t J	V_b, m/s	$-a$, m/s^2	t_t µs
6 Layers								
SKNW$_1$	757	12.1	18	9	15	2.24	364	4098
SKNW$_2$	760	12.9	24	12	12	2.59	289	4126
SKNW$_3$	614	11.1	24	12	12	2.59	286	3550
SKNW$_4$	649	11.4	18	9	15	2.24	367	3861
SKNW$_5$	532	10.2	18	9	15	2.24	355	3454
5 Layers								
SKNW$_6$	591	10.9	24	12	12	2.59	291	3486
SKNW$_7$	658	11.5	12	9	15	1.62	468	4358
4 Layers								
SKNW$_8$	686	11.7	24	12	12	2.59	286	3742
SKNW$_9$	588	10.8	18	9	15	2.24	361	3658

The velocity of the falling mass (V_b) at backing material surface is obtained by relating change in kinetic energy to the work done by the mass, as shown below:

$$\Delta KE_{BM} = WD_{BM} \qquad \qquad \dots (2)$$

where ΔKE_{BM} is the change in kinetic energy of the mass in while penetrating the backing material; and WD_{BM}, the work done by the falling mass, after crossing the target, on the backing material

$$\Delta KE_{BM} = 0.5mv_i^2 - 0.5mv_f^2 \qquad \qquad \dots (3)$$

Where m is the mass of drop mass (3.58 kg) ; v_i, the velocity of falling mass at the surface of backing material; and v_f, the velocity of falling mass after completely penetrating the backing material which is zero.

From Eqs (2) and (3), we have

$$0.5mv_i^2 - 0.5mv_f^2 = WD_{BM} \qquad \qquad \dots (4)$$

As $0.5mv_f^2$ is zero, Eq. (4) becomes

$$0.5mv_i^2 = WD_{BM} \qquad \qquad \dots (5)$$

$$0.5 \times 3.58 \times v_i^2 = WD_{BM}$$
$$v_i = [sqr (WD_{BM} / 1.79)] \qquad \qquad \dots (6)$$

As v_i is the velocity at the backing material surface, it is rewritten as V_b and WD_{BM} corresponds to the E_b, Hence, the Eq (6) becomes

$$V_b = [sqr (E_b / 1.79)] \qquad \qquad \dots (7)$$

The retardation (-a) of the falling mass as it passes through the target, can be obtained Using the following equation:

$$(V_t^2 - V_b^2)/ 2t = a \qquad \qquad \dots (8)$$

where V_t is the velocity of the falling mass, at surface of the target; V_b, the velocity of falling mass at the surface of the backing material; t, the thickness of target material in meter; and a, the retardation in m/s^2.

Velocity of the falling mass at the surface of the target (V_t) is obtained using the equations of motion ($v^2 = u^2 + 2as$). As the initial velocity of the drop mass is zero, 'u' becomes zero and the final velocity at the point of surface of the target is related, as shown in following equation:

$$V_t^2 = 2gS \qquad \qquad \dots (9)$$

where g is the gravitational force (9.81 m/s^2) ; and S, the height of falling mass (0.684 m).

Substituting the values of 'g' and 'S' in Eq. (8), V_t is calculated to be 3.66 m/s. Further, the time taken by the falling mass to travel through the target is calculated using the following equation:

Time (µs) to travel target = $[(V_t-V_b)/a] \times 10^6$ … (10)

Table 3 shows that with only 4 layers of neat kevlar (NK) the energy absorption is found to be only 6 J, while for the kevlar sample SK in the presence of STF (CS 52 / PEG 48) with an add-on value of 596 % , the energy absorption level increases to 10.5 J. Such increase in the impact energy absorption could be obviously attributed to the presence of corn starch STF as an additional energy absorbing medium in the 4 layers of kevlar fabrics. In the next set of results for sample SN, [4 layers of nonwovens (N) with STF], the energy absorption is found to be 15 J, while for the sample SKNW (presence of kevlar on the top of 4 nonwoven layers), the energy absorption level

increases to 21 J. From this study, it could be clearly noticed that the kevlar is acting as a medium of spreading the energy of the falling mass within more areas and volume of STF, and hence contributes for high energy absorption. The impact energy absorption of 4 layered CS-STF impregnated PET nonwovens with the presence of a single kevlar fabric showS the maximum energy absorption of 21 J. Such structures can be recommended for various impact energy absorption applications, for example shoe for trekking. Impact penetration depth of 4 layers kevlar impregnated silica particles STF is found 23mm[19] and CS – STF impregnated depth of 4 layers Kevlar is found 27 mm (Table 3).

Schematic view of CS−STF impregnated textiles and the crystallization effect of STF upon shearing; resulting in the thickening effect is shown in Fig. 5. Additionally, the effect of time of travel of the mass through the STF in the target could also be noticed among the samples NK, SK, SN and SKNW, which are found to be 263 µs, 1881 µs, 5486 µs and 5447 µs respectively. These timings could be related with the straining time of the STF, as discussed earlier (Fig. 2) that with low straining time (1000 µs) the thickening effect is found to be very low and a moderate thickening effect is observed up to 2000 µs, beyond which a notable increase is observed, particularly beyond 3000 µs. Hence, in samples SN and SKNW, the energy absorption is found to be much higher, due to more straining timings than the samples NK and SK where the time of straining is found to be below 2000 µs.

3.5 Effect of Layer Order of Kevlar and Nonwovens in CS−STF Composite

Based on the previous trials, the effect of number and the order of layering of STF impregnated kevlar and nonwoven has been studied for energy absorption and the results are presented in Table 4. For the study, various samples with different number of layers and combinations are prepared and hence each sample is given a unique sample code (Table 1). In brief, 'S' stands for CS-STF, 'K' stands for kevlar and 'NW' stands for PET nonwoven.

Accordingly, it can be seen from Table 4 that for the sample $SKNW_1$ (K_1, NW_1, NW_2, K_2, K_3, K_4) the energy absorption is found to be 15 J, while for the sample $SKNW_2$ (K_1, K_2, K_3, NW_1, NW_2, K_4) the energy absorption is found to be only 12 J. It should be noticed from these two results that in spite of the 3 layers of kevlar present on the top of the two nonwoven samples, the energy absorption of the sample $SKNW_2$ is less than that of the sample $SKNW_1$ by 3 joules. This may be due to the presence of more than one layer of kevlar, which might reduce the total straining force that would act on the STF present in the nonwoven structures below the three layers of kevlar fabrics. However, in the sample $SKNW_1$, the presence of only one layer of kevlar acts as only a medium of spreading the force on the immediate layer of nonwoven containing STF but not reducing the falling mass force itself. This reasoning is reinforced by the results of the next two textile STF composite layers, i.e. $SKNW_3$ (K_1, K_2, NW_1, NW_2, K_3, K_4) and $SKNW_4$ (K_1, NW_1, K_2, K_3, NW_2, K_4) whose impact
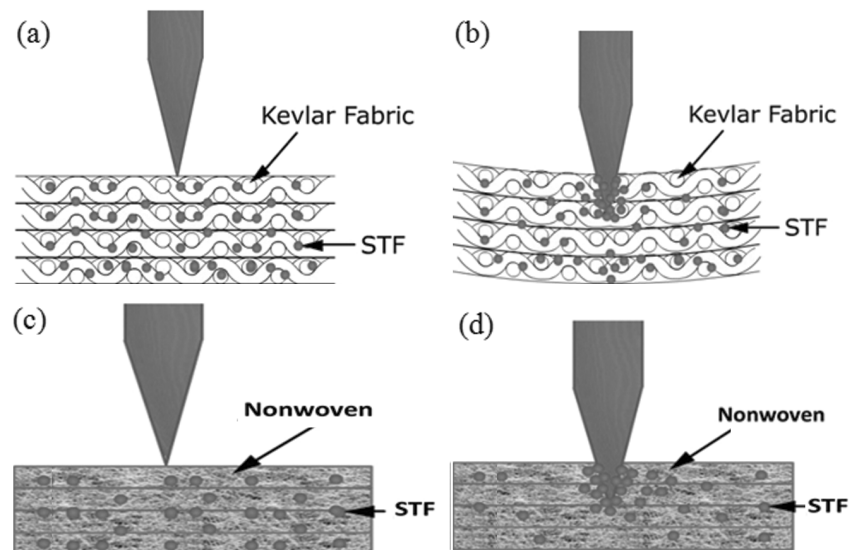

Fig. 5 — Schematic views of (a) STF kevlar fabric layers before knife penetration, (b) STF crystallization in kevlar fabrics during knife penetration, (c) STF nonwoven before knife penetration and (d) STF crystallization in nonwoven during knife penetration

energy absorptions are observed to be 12 J and 15 J respectively. It can be noted that the sample $SKNW_3$ has less energy absorption than the $SKNW_4$ probably due to the presence of two layers of kevlar on sample $SKNW_3$. The sample $SKNW_4$ has good energy absorption because of the impact force spreading effect by mainly K_1 on NW_1 and also by K_2 and K_3 on NW_2. In another experiment, the effect of placing the two nonwoven STFs on top and the rest of the kevlar fabrics below as in $SKNW_5$ (NW_1, NW_2, K_1, K_2, K_3, K_4) is studied and the energy absorbing capacity of the layer is found to be 15 J. The high energy absorption of the layer $SKNW_5$ may be due to the fact that the first nonwoven (NW_1) might primarily act as an energy spreading layer with slight absorption and the second nonwoven (NW_2) might contribute for the energy absorption due to the strain thickening effect of the STF present in it which is further supported by the presence of four kevlar fabrics present below the two nonwoven fabrics.

Based on the above 6 layer structure trials, as the effect of number of kevlar appears to play a less significant role, separate experiments with only 5 layer and 4 layer structures have been conducted and the results are presented in Table 4. It is observed that in the 5 layer structure experiments also similar trend is observed, i.e. $SKNW_6$ (NW_1, NW_2, K_1, K_2, K_3) and $SKNW_7$ (NW_1, K_1, NW_2, K_2, K_3) show energy absorption of 12 J and 15 J, respectively. The presence of kevlar (K_1) over nonwoven (NW_2) has contributed for higher energy absorption in sample $SKNW_7$ than in sample $SKNW_6$. In the subsequent 4 layer structure experiments also, similar trend is noticed that the energy absorption values of layers $SKNW_8$ (NW_1, NW_2, K_1, K_2) and $SKNW_9$ (NW_1, K_1, NW_2, K_2) are found to be 12 J and 15 J respectively, wherein the presence of kevlar (K_1) over nonwoven (NW_2) has contributed for higher energy absorption in sample $SKNW_9$ than in sample $SKNW_8$.

It is inferred from the above study that the presence of one layer of kevlar fabric on one or more layers of nonwovens with STF in the structure shows good performance in the impact energy absorption. Such trend is also observed in 6, 5 and 4 layered structures. Presence of more than one layer of kevlar on the top of the nonwovens in the composite does not contribute; rather it decreases the energy absorption due to the reduction in impact force and hence inhibiting the shear thickening effect of the STF. However, placing the kevlar and nonwovens alternatively would also contribute for good impact energy absorption. Hence, it could be inferred that the spreading of the impact force over the STF impregnated structures contribute greatly in the energy absorption of falling mass. As the objective values of these experimental trials are presented as averages values after repeating many times, the findings can be considered as practically significant.

3.6 Antimicrobial Study

In common, the use of corn starch along with water has a tendency to develop microbes and intense smell generation and even worms formation can be observed over a period of time. Hence, a suitable commercial antimicrobial agent 4-chloro-3, 5-dimethylphenol was used for imparting antimicrobial activity to the CS-STF textile composites structures. For the purpose, 3 different concentrations of the antimicrobial agents are used (5−20 gpL). The treated textiles along with the control samples are tested for the antimicrobial activity against standard microbes through AATCC 100 colony count test method.

The results reveal that all the control samples i.e. STF kevlar sample (SK), STF nonwoven (SNW) and STF kevlar, nonwoven (SKNW) have 0 % activity without the antimicrobial agents which indicate that the substrates would develop a strong microbial attack. These samples, on the next day, were practically observed to develop intense stinking smell as evaluated subjectively by various people. However, for the antimicrobial agent treated samples even with 5 gpL the antimicrobial activity is found to be 90 % almost for all the samples and when the concentration is further increased to 10 gpL and 20 gpL the antimicrobial activity is found 100 % for all the samples. Hence, these results indicate that the application of the CS−STF to the textile structures along with the antimicrobial agents would support these structures to perform over a long period of time.

4 Conclusion

4.1 Corn starch particles have average size of 2.9 μm with polydispersity index of 0.8. Shear thickening effect of the CS STFs is found to be high over the shearing time of 3000 μs for the optimum CS & PEG ratio of 52: 48. High degree of stiffening of textiles is observed when water is used as solvent, while with PEG the flexibility of the structure remains the same. The energy absorption of textile structure increases significantly with the presence of STF.

4.2 With only 4 layers of neat kevlar (NK), the energy absorption is found to be only 6 J, while with the presence of STF (CS 52 / PEG 48), the energy absorption level increases to 10.5 J. The energy absorption of nonwoven with STF is found to be 15 J, while with the presence of kevlar on the top of the 4 nonwoven layers, the energy absorption level increases to 21 J.

4.3 Shear thickening effect and hence the energy absorption is found to be high when the straining time of the falling mass is greater than 2000 µs and particularly beyond 3000 µs. One layer of kevlar fabric followed by one or more layers of nonwovens with CS STF shows good performance in the impact energy absorption. Such trend is observed in 6, 5 and 4 layering also.

4.4 Presence of more than one layer of kevlar on the top of the nonwovens in the composite do not contribute; rather it decreases the energy absorption due to the impact force reduction and hence inhibiting the strain thickening effect of the STF.

4.5 Placing the kevlar and nonwovens alternatively also contribute for good impact energy absorption. The STF textiles structures without antimicrobial agents develop intense smell with 0 % antimicrobial activity, while those treated with 4-chloro-3, 5-dimethylphenol, show 90 % activity at 5 gpL concentrations and 100 % activity at higher concentrations.

References

1 Wagner, Norman J & Brady J F, *Phys Today*, 62 (2009) 27.
2 Egres R G (Jr), Decker M J, Halbach CJ, Lee YS, Kirkwood J E, Kirkwood K M & Wetzel E D, *Proceedings, the 24th Army Science Conference, Orlando, Florida (CD-ROM, ADM001736)* (Defense Technical Information Center, US Army) 29 November – 2 December 2004.
3 Wetzel ED, Lee YS & Egres RG, *Proceedings, 14th International Conference on Composite Materials (IICM)* (San Diego, CA, USA) 2003, 18.
4 Yıldız S, *Synthesis and Rheological Behavior of Shear Thickening Fluids (STFs) for Liquid Armor Applications*, M.Tech, thesis, İzmir Institute of Technology, İzmir, 2013.
5 Kurahatti RV, Surendranathan AO, Kori SA, Singh N, Kumar AR & Srivastava S, *Defense Sci J*, (2010) 60.
6 Crawford Nathan C, Lauren B Popp, Kathryn E Johns, Lindsey M Caire, Brittany N Peterson & Matthew W L, *J Colloid Interf Sci* , 396 (2013) 83.
7 White EE, Chellamuthu M & Rothstein JP, *Rheol Acta*, 49 (2010) 119.
8 El Messiry, Magdi & Eman Eltahan, *J Ind Text*, 45 (2016) 1062.
9 Grujicic M, Arakere G, He T, Bell WC, Cheeseman BA, Yen CF & Scott B, *Meter Sci Eng*, 498 (2008) 231.
10 *High-Performance Fibres*, edited by JWS Hearle (Elsevier), 2001.
11 Matthews FL & Rawlings RD, *Composite Materials: Engineering and Science*, (Elsevier), 1999.
12 Lee, Young S, Eric D. Wetzel, Norman J & Wagner, *J Meter Sci*, 38 (2003) 2825.
13 Fall A, Bertrand F, Ovarlez G, & Bonn D, *J Rheol*, 56 (2012) 575.
14 Jane JL, Shen L, Wang L & Maningat CC, *Cereal Chem*, 69 (1992) 280.
15 Booth E, *Principles of Textile Testing*, 3rd edn (Butterworths, London), 1983.
16 Gulrajani Deepti Gupta ML, Periyasamy S & Muthu SG, *J Appl Polym Sci* ,108 (2008) 614.
17 Ding J, Tracey PJ, Li W, Peng G, Whitten PG & Wallace GG, *Text Light Ind Sci Technol* ,2 (2013) 161.
18 Barnes H A, *J Rheol*, 33 (1989) 329.
19 Joselin R & W Jacob Wilson, *Defence Sci J*, 64 (2014) 236.