EXPERIMENTAL INVESTIGATION OF SHEAR THICKENING FLUID IMPREGNATED FLAX FABRIC AND FLAX/KEVLAR HYBRID FABRICS

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Experimental investigation of shear thickening fluid impregnated flax fabric and flax/Kevlar hybrid fabrics

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MASTER OF SCIENCE

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ABSTRACT

Shear thickening fluids have the potential to improve the effectiveness of fabric materials in body armor applications as they have shown to increase the puncture and ballistic resistance of Kevlar fabrics. However, the effect of using STFs with natural fabrics such as flax has never been studied. The rheology of STFs at varying concentrations of nanosilica dispersed in polyethylene glycol PEG was studied at different temperatures and it was found that the STFs behave as a non-Newtonian fluid in response to changes in shear rate. In this study the effectiveness on the puncture and ballistic resistance of impregnating flax fabric with STF of nanosilica in PEG were investigated. The effect of hybridization of flax and Kevlar was also investigated. The puncture and ballistic resistance of the samples treated with STFs was found to increase significantly and can be controlled by STF concentration.

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LIST OF ABBREVIATIONS

STF…………………………………………Shear Thickening Fluid

PEG…………………………………………Polyethylene glycol

SEM…………………………………………Scanning Electron Microscope

LIST OF SYMBOLS

P…………………………………………………..Density

F…………………………………………………..Force

v…………………………………………………..Velocity

m…………………………………………………..Mass

KE…………………………………………………Kinetic Energy

J……………………………………………………Joule

1. INTRODUCTION

Shear thickening fluids (STF's) or dilatant fluids are dense colloidal suspensions that exhibit abrupt increases in viscosity with increasing shear rate [1]. Shear thickening behavior was initially seen as undesirable, because in mixing processes the effect can cause greater stress on equipment and energy demands in order to achieve mixing [2]. More recently the unique behavior of this class of materials has lead to attempted development of smart materials and structures utilizing STF. Most reseacrh concerning STFs has been done in the field of protective applications such as body armors which has been taking place since around 2000. Besides protective applications STFs may be used as a damping material to absorb shock waves from earthquakes or severe winds [3]. STFs could also be incorporated into heavy machinery as a damping material. STFs are also suggested as a material for use in medical rehabilitation devices that restrict the movement of parts of the body such as the shoulder, knee, anlkes, or elbow and could help prevent further injury to patients and help their recovery [4]. Most recently multi-phase STF systems have been of interest. These systems can consist of multiple particle types like silica and polymethylmethacrylate (PMMA), multiple sizes of particles, multiple shapes of particles, or even systems which incorporate STFs with magnetorheological fluids (MRF) or electrorheological fluids (ERF).

As mentioned the majority of research into STF applications has been in the field of protective materials. STFs applications are most highly researched in this area because of the significant enhancement they can have on ballistic impact properties as well as enhancement in stab resistance of protective systems. The STF fluids are generally used as part of a composite system where they are impregnated into a fabric material. For body armors in most cases high performance fabrics such as Kevlar, Twaron, Dyneema, or Spectra are used. These fabric materials offer the advantage of flexibility and lightweight over higher performing materials such as protective ceramic plates [5]. Many researchers have investigated the effects of impregnating STF into Kevlar fabric. The impregnated fabrics have been impact tested under low velocity, high velocity, and quasi-static conditions [6,7,8,9] and has been shown to significantly increase the impact resistance.

Although effect of impregnation on Kevlar and some other synthetic fabrics with STF has been studied, there is no information regarding its effects when impregnating natural fabrics such as flax. In terms of its mechanical properties, flax is considered to be one of the strongest natural fibers [10]. As such flax is a promising candidate for study with impregnation of STF. In addition, the effects of hybridization of different fabric materials impregnated with STF have only undergone limited study. Hybridization of flax fabric and Kevlar fabric both impregnated with STF could lead to a material suitable for use in body armor applications while being partially bio-based and less costly.

1.1. Objectives

The goal of this work is to verify that STF's have a beneficial effect on flax fabric's puncture and ballistic impact resistance, as this has never before been studied. This is important because it could show that different types of fabric materials impregnated with STF's can be used to potentially create a new class of impact resistant materials. These materials could be fabricated from readily available plant based fibers and silica particles or even more readily available particles like corn starch. It is hypothesized that a completely bio-based and totally renewable puncture and impact resistant material can be made via utilization of bio based particle suspension impregnated into bio-based fabrics.

The objectives of this study are:

1. Develop method of manufacturing shear thickening fluid (STF) that shows clear shear thickening behavior through rheological testing using a rheometer.
2. Develop a method for impregnating STF into flax fabric and Kevlar fabrics.
3. Measure the impregnated fabrics and unimpregnated fabrics resistance to puncture and high speed impact to determine the effectiveness of the STF.
4. Measure puncture resistance of known STF suspension made with corn starch and water impregnated into fabric material.

2. BACKGROUND

2.1. Shear thickening fluid mechanisms

STFs are non-Newtonian fluids which show abrupt increases in viscosity with increasing shear rate applied. This thickening behavior is observed in dense colloidal suspensions made of solid particles and inert carrier liquids. The carrier liquids by themselves generally behave as Newtonian fluids, so the addition of solid particles (silica, PMMA, calcium carbonate etc.) is required to generate the effect. There are three theories that have been proposed to explain the shear thickening behavior of these suspensions.

2.1.1. Order-Disorder theory

In STF's the particles are assumed to be randomly suspended in the carrier liquid and dispersed in an equilibrium state. As the shear rate applied to the suspension is increased the suspension will generally show shear thinning initially. The particles will initially form layered structures leading to shear thinning, but at or beyond a critical shear rate, shear thickening is induced. The layered structures formed disassociate and form hydroclusters. The formation of hydroclusters leads to drastic increases in viscosity [11, 12]. Figure 1 shows a schematic of the proposed mechanism where initially the suspension is at rest and equilibrium. When a shear rate is applied and increased the particles start to form a somewhat layered or ordered structure. When a critical shear rate is attained the particles disassociated from the layers and form small agglomerates or groups of particles termed hydroclusters.

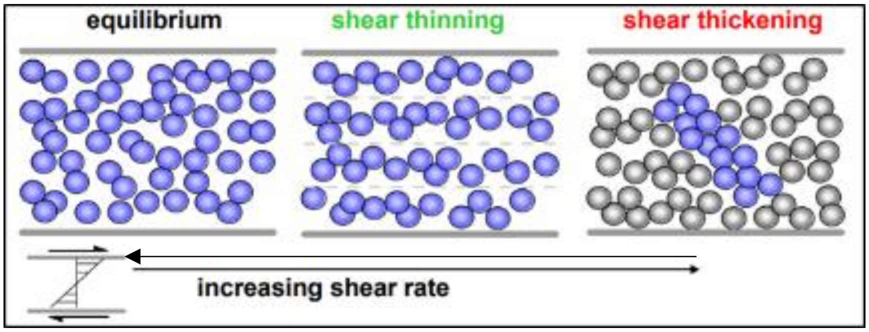

Figure 1: Schematic of proposed shear thickening mechanism- Hydro-cluster Theory [2].

Initial investigation into the STF mechanism was accomplished by Hoffman in his original study on the micromechanical structure of shear thickening fluids. His study became the basis for the order-disorder theory stating that: "below a critical shear rate, particles in suspension are in a layered order, but beyond a critical shear rate, hydrodynamic forces acting on the particles become stronger and the layered orientation is disrupted; as a result of this process, layered particles disorder and the transition from order to disorder causes a drastic increase in suspension viscosity" [13]. This layered orientation in a dense colloidal particle suspension exposed to high shear was verified in a later study also by Hoffman [14]. According to Hoffman's order disorder theory the transition from an ordered state to a disordered state is what is causing the abrupt changes in viscosity of the suspensions. The sudden change from ordered to disordered structure causes the fluid to jam. The shear thickening is also a reversible phenomenon. Once a shear force is no longer applied to the suspension it will return to its equilibrium state. This was verified by Luan who conducted rheological and small angle neutron scattering experiments for latex particles in glycols and reported the shear thickening is reversible and requires a critical shear rate to induce the shear thickening [15, 16].

2.1.2. Hydrocluster theory

The shear thickening mechanism is not fully dependent on an ordered orientation though because shear thickening can take place in hydroclusters that extend in different directions while hydrodynamic forces dominate the particles as demonstrated by Bossis et al [17]. This theory, called hydro-cluster theory, proposes that: "interactions between particles, either electrostatic or Brownian, make the suspension easily flow at low shear rates. However, at increasing shear rates, hydrodynamic forces begin to dominate suspension by suppressing the inter-particle repulsive forces and therefore, leading to the formation of stress-bearing particle clusters called hydro-clusters. These units cause a dramatic increase in viscosity by blocking the flowing and may be formed without particle orientation in the suspension" [17]. The lack of requirement of an ordered structure contradicts Hoffman's original order disorder theory. This hydro-cluster theory is supported by neutron scattering, rheological and rheo-optical tests, as well as various computer simulations [18-20].

2.1.3. Contact rheology theory

The most recent model proposed is called contact rheology model [21]. It states that: "the hydro-clustering prevails suspensions at low shear rates due to contactless rheology because particle pressure is too small to overcome the repulsion between particles… a purely hydrodynamic effect is only responsible for mild thickening at the thickening onset, but not the explanation of the strong shear thickening mechanism because stress transmission on a big scale is realized through contact interactions. Contact forces grow stronger for the thickening point where the colloidal particles contact each other at high shear rates. For the further increase in the shear rate, contact forces generate force networks that dominate thickening where the hydrodynamic interactions are claimed to be insufficient" [22]. The formation of these contact networks allows the fluid the ability to resist the applied shear forces, and results in viscosity change and the development of a yield stress in the fluid. According to this theory the major contribution to the viscosity increase is from inter-particle contacts which can be created by particle attraction. This model has been verified by simulation work done by Pednekar et al [23]. Figure 2 shows an example of contact networks formed within an STF suspension at a particle loading of 50%. Contacted particles are shown in red while noncontacted particles are shown in gray.

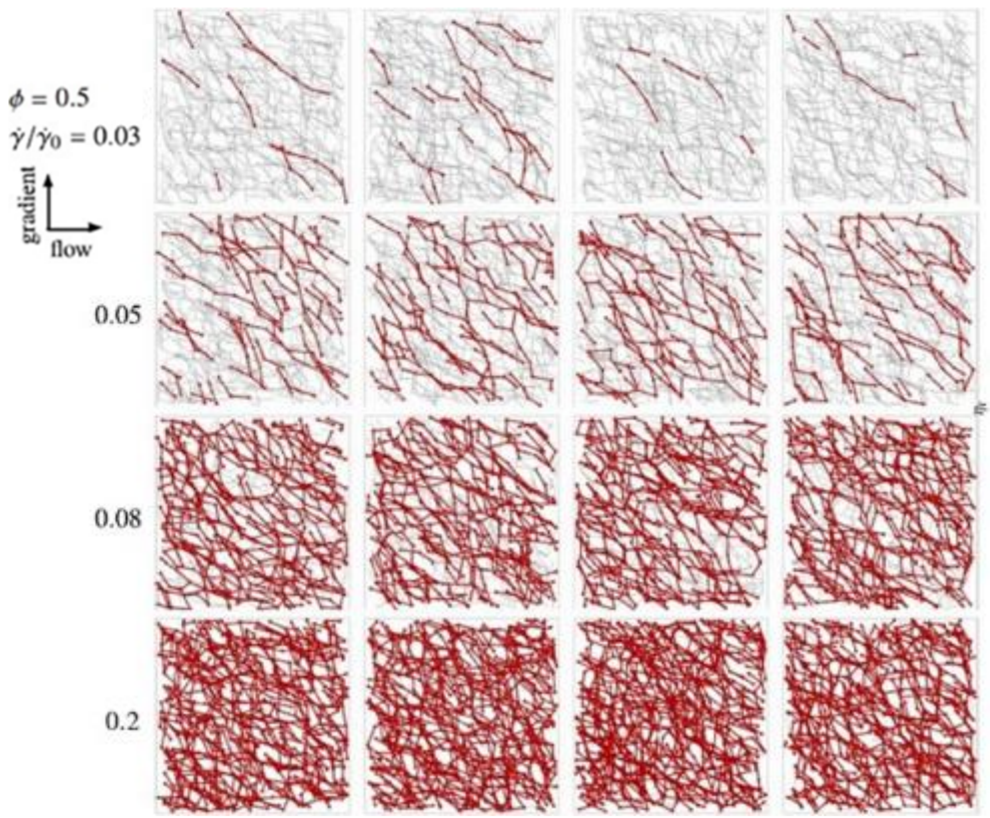

Figure 2: Contact networks shown in STF suspension at 50% particle loading [24].

Multiple theories have been proposed as to the mechanism of the shear thickening effect. With time and more experimental data, the theories have evolved from order-disorder theory to hydro-cluster theory, to the most current theory contact rheology model being proposed within the last decade. Although understanding of this mechanism has grown, more work still needs to be accomplished in order to fully understand it.

2.2. Rheological properties of shear thickening fluids

There are several factors which can affect the rheological properties of STFs. These include particle loadings, particle geometry, temperature, and particle size. In order for particle suspensions to show shear thickening behavior a minimum concentration of particles in suspension must be reached. The particle geometry can affect the rate at which shear thickening is induced and also to what degree. Temperature can affect the viscosity of the suspensions. Particle size can also influence the rheology of the suspensions.

2.2.1. Effect of particle loading

The most important factor that effects the rheology of the STF is the particle volume or weight fraction. It is generally accepted that as the particle loading is increased the shear thickening effect is enhanced. Also as particle loading is increased the critical shear rate required to induce shear thickening is also reduced. This is believed to be caused by increased hydrodynamic and contact forces experienced with higher particle concentrations, which leads to the lower required critical shear rate.

Most STFs display what is called discontinuous shear thickening. This means that the fluid does not show a linear trend with regards to viscosity as a function of shear rate. Initially the STF displays shear thinning behavior, before reaching a critical shear rate where abrupt increase in viscosity is observed. Shown in Figure 3 is a typical example of a rheological study of STF. Wetzel et al. investigated the rheology of PEG/nanosilica suspensions at varying volume fractions [7]. It can be seen that the suspensions which exhibit shear thickening, first show a region of shear thinning when the shear rate is low. As it increases some critical shear rate is reached and the suspensions show abrupt increases in viscosity. Also shown is that at higher particle volume fractions the critical shear rate required to induce the shear thickening is reduced.

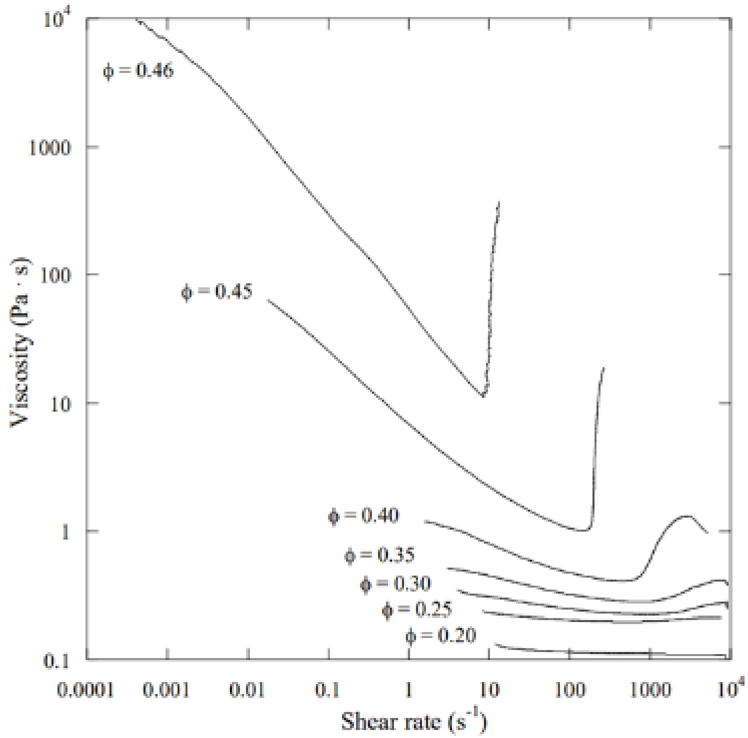

Figure 3: Viscosity as a function of shear rate for different particle volume fractions [7].

2.2.2. Effect of particle geometry

Particle geometry and aspect ratio can also have an influence on the rheological properties of an STF. In initial studies it was discovered that rod shaped particles are the most effective particle geometry at improving the shear thickening effect in the suspension [25, 26]. This suggests that particles with higher aspect ratios would be more suitable for use in STFs. It is suggested that the high aspect ratio particles are most effective because due to the higher chance of particle interlocking and rotation [27]. Figure 4 shows the viscosity as a function of shear rate for different particle geometries. It can be seen that particles with higher aspect ratios are more effective at inducing a shear thickening effect.

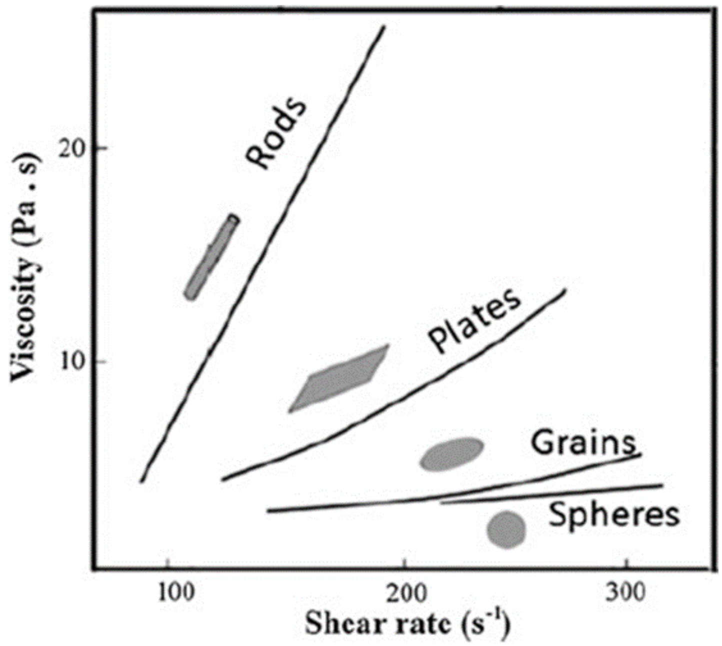

Figure 4: Effect of particle geometry on STFs viscosity [25].

2.2.3. Effect of temperature

Temperature also affects the rheological properties of an STF. Srivastava et al. [26] have studied the effect of temperature on the rheology of PEG/silica STFS. They found that at lower temperatures the shear thickening effect is more enhanced. Shown in Figure 5 is their results. It can be seen that at 0 ºC the shear thickening effect is most pronounced, with the shear thickening effect being least pronounced at 50 ºC.

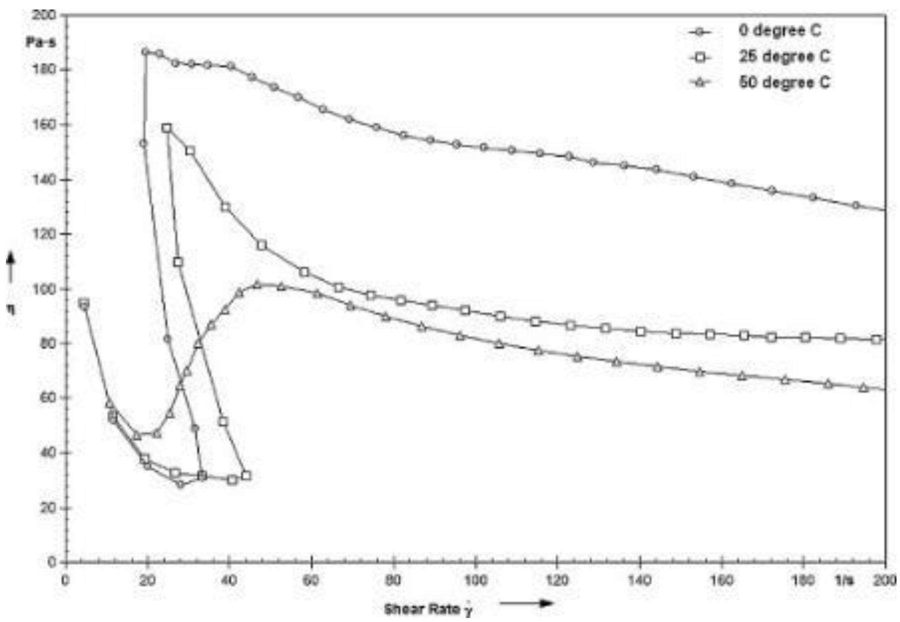

Figure 5: Effect of temperature on the rheology of PEG/silicaSTF suspensions [26].

2.2.4. Effect of particle size

Particle size and hardness also effect the performance of an STF. In general smaller particles enhance the shear thickening effect more than larger particles. Harder particles are desired for their higher mechanical properties and ability to withstand higher shear stresses although particle hardness has no direct effect on the STF performance. Figure 6 shows the effect of particle size on the critical shear rate required to induce shear thickening.

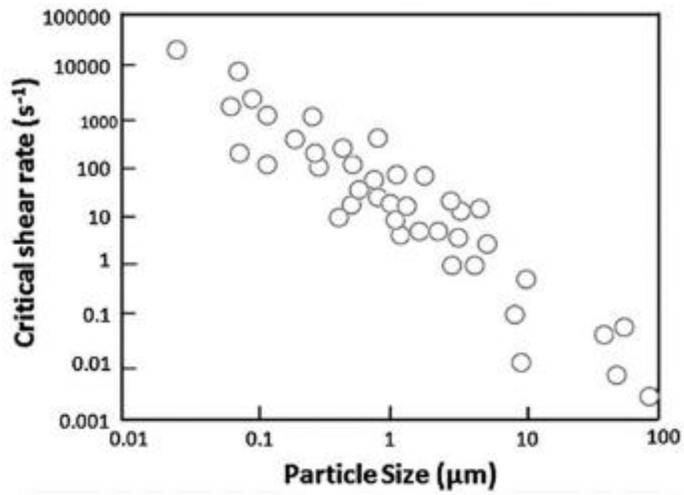

Figure 6: Effect of particle size on critical shear rate [26].

2.3. Fabrication methods of shear thickening fluid

STF's are produced by homogenously dispersing hard particles inside a newtonian carrier liquid. The behavior emerges one a certain particle loading is reached in the suspension which can depend on particle size and geometry. STF's can be produced from a variety of materials but the most well known STF suspension is corn starch dispersed in water, which can be produced simply by manually stirring the corn starch into the water. For research purposes different particles and carrier fluids have been explored as well as other methods of production. Nanosilica particles dispersed in low molecular weight polyethylene glycol (PEG) are typically used when producing STF for impregnating synthetic fabrics such as Kevlar.

2.3.1. High speed homogenization

High speed homogenization is one method used to disperse particles in a carrier liquid. It consists of a mechanical stirring apparatus capable of rotating at speeds of up to 15,000 rpm. The high stirring speed allows for excellent mixing and is capable of producing homogenous dispersions of nanoparticles in suspension. This method has been used to produce STF with nanosilica and PEG at mixing speeds ranging form 6000-8000 rpm [28-31]. Figure 7 shows a high speed homogenizing machine.

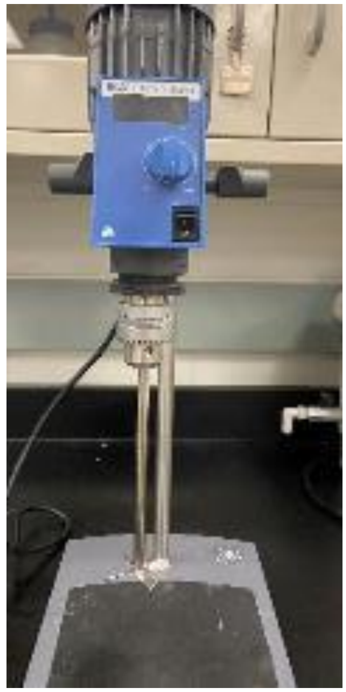

Figure 7: High speed homogenizer.

2.3.2. Ultrasonication

Ultrasonication is another popular method used for dispersing particles to create STF. Sonication is the process of apply sound energy to agitate particles. It is referred to as ultrasonication when the frequency is >20 kHz. The cycles of sound wave pressure lead to the formation of microscopic vacuum bubbles when used in solution. After a very brief existance the bubbles collapse in a process known as cavitaion, causing the release of powerful vibration waves creating high shear forces that aid greatly in mixing and degassing processes. Ultrasonication is very commonly used for nanoparticle dispersion and has been used to create nanosilica/PEG STF [32-35].

2.4. Effects of impegnating STF into fabric

Impregnating fabric materials with STF has been shown to significantly increase puncture and impact resistance of the material. This is attributed to an increase in the inter-yarn friction or yarn pullout force in the fabric material. An increase in the inter-yarn friction causes the yarns motion to be severly restricted when exposed to external forces consequently requiring more force to cause it to move.

2.4.1. Kevlar

Impregnation of STF has been most heavily studied in Kevlar fabrics. Though impregnation of nanosilica/PEG STF in Kevlar fabric A. Khodadadi et al. have measured and increase of 623% in the amount of energy absorbed from a ballistic impact an approximate increase in yarn pull out force of 125% in STF treated Kevlar compared to neat Kevlar [36]. Many studies have also reported similar increases measured with STF treated Kevlar [28, 30, 37-39].

Stab resistance of STF impregnated fabrics has also been heavily studied. R.G. Egres et al. showed that the impregnation of STF into Kevlar fabrics resulted in over a 500% increase in force required to puncture the STF Kevlar relative to neat Kevlar with a spike type puncture device [40]. Similar results have been obtained by other researchers confirming the STFs effect on stab resistance [41-43].

2.4.2. Hybrids

The hybidization of fabric materials impregnated with STF has received limited study but could possibly lead to a material with a unique combination of properties. Harish Rao et al. studied the stab charaterization of a Kevlar and Surlyn thermoplastic film hybrid material impregnated with STF. They measured signigicant increases in energy absorbed from dynamic stabbing impacts and also force required to puncture the material in quasi-static puncture tests [44]. Edison E. Haro et al. investigated ballistic impact response of a laminated hybrid composite consisting of an aluminum alloy, epoxy, and kevlar impregnated with STF. It was found that impregnation with STF improved the energy absorbed frob ballistic impact [45].

3. RESEARCH METHODOLOGY

This section will describe materials and equipment used, methods for sample production and testing of samples. It is separated into three distinct sub sections; materials and equipment, sample manufacturing, and material characterization. Materials and equipment section will elaborate in the materials used to create STF, the STF impregnated fabrics, and equipment used to do so. The sample production section will detail the processes used to create any samples for analysis. The charaterization section will describe any testing methods used to analyze material properties.

3.1. Materials and equipment

The following sections will decsribe materials and equipment used to produce STF and STF impregnated fabrics.

3.1.1. Sonicator

A MixSonix 3000 probe type sonicator manufactured by Misonix was used for ultrasonication based dispersion of nanoparticles into the carrier fluid. This device can deliver up to 600W of energy at 20kHz in controlled programmable bursts or in continuous operation. This allows for the development of an optimal process for sonication based dispersion. Figure 8 shows the sonicator in operation.

Figure 8 : Misonix 3000 sonicator.

3.1.2. Convection oven

A VWR convection oven was used to evaporate ethanol from impregnated fabrics. Oven circulates hot air at elevated temperatures up in a sealed enviornment. The oven is shown in Figure 9.

Figure 9: VWR convection oven.

3.1.3. Loadframe

An Instron 5567 electric load frame was used for conducting puncture testing. The machine was equiped with a 30kN loadcell which controls and records the force applied to samples. It also measures displacement in reaction to the applied force. With Bluehill 2.0 software the loadframe can be programmed to apply force at a specific rate or move a a specified rate of displacement and the frequency of data collection can be selected. The loadframe is shown below in figure 10.

Figure 10: Instron 5567 loadframe.

3.1.4. Spike

A hardend steel spike was used to perform punctue testing on the fabric materials. The spike was made of O1 tool steel and heat treated to a hardness on the Rockwell C scale of 35. The geometry of the spike was obtained from ASTM standard F1342 and is shown in Figure 11 below.

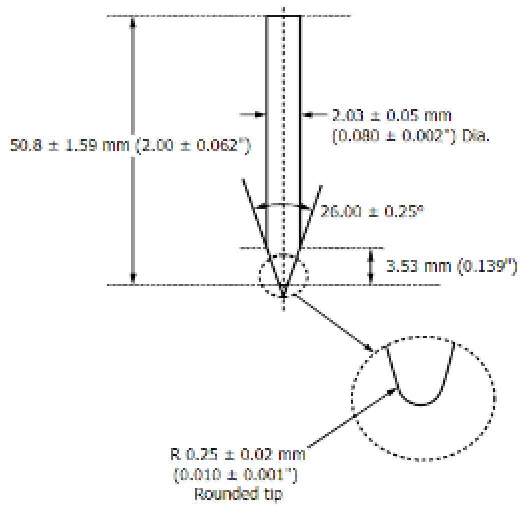

Figure 11: Geometry of steel spike.

3.1.5. Puncture specimen clamping device

A clamping device was used in order to secure puncture specimens. Two bolts were used to secure the top part of the clamp to the base and securly clamp the fabric samples before testing. An abrasive tape was adhered to the inside of the clamp in order to prevent the specimens from slipping during testing. The puncture testing setup is shown below in Figure 12.

Figure 12: Puncture testing setup.

3.1.6. High velocity ballistic impactor

A custom made high velocity ballistic impact testing machine was used for ballistic impact testing. It is a pnematically powered device capable of delivering projectiles with the same amount of kinetic enerjy as a .357 Sig FMJ flat nose bullet fired at a velocity of ~448m/s (1470 ft/s). This is equivalent to up to a level IIIA threat according to NIJ Standards. The pressure chamber can be charged to a desired level at which point a solenoid valve can be triggered, releasing the built up pressure and firing a shrapnel simulating projectile thorugh the barrel at the specimen to be impacted. Specimens are mounted very tightly via clamping system in an enclosed box at the end of the barrel. Two chornographs are mounted inside the box where the specimen is held. The first records the input velocity before impact, while the second records output velocity after the projectile penetrates the specimen. Figure 13 shows the high velocity ballistic impact apparatus.

Figure 13: Ballistic impact testing maching (left) capture chamber (right) pressure chamber.

The samples are clamped securly in between two steel plates with abrasive tape adhered to the inside clamp the specimen in order to prevent its movement during impact. The plates are then secured in place via a secondary clamping system. For flax fabric samples 4 layers of fabric were clamped in the device for ballistic impact testing. For hybrid samples 2 layers of fabric were clamped in the device for testing.

Projectiles used for the experiments were steel shrapnel simulating projectiles. The projectiles have a flat, blunt nose and are loaded into a sabot which fits snugly inside the barrel. The projectiles weighed approximately 17.0g. Figure 14 shows the type of projectiles used in the ballistic experiments.

Figure 14: Shrapnel simulating projectile.

3.1.7. Vacuum chamber

A vacuum chamber was used to extract any remaining air trapped withing STF samples. The vauum chamber applied a vacuum pressure of 25 inHg for 30min for each sample prior to rheological testing. Figure 15 below shows the vacuum chamber used.

Figure 15: Vacuum chamber.

3.1.8. Rheometer

An ARG2 rheometer, manufactured by TA Instruments, was used for rheological experiments. The machine can apply a desired shear force or shear rate to a material at a desired temperature and record the torque on the spindle with which it performs viscosity calculations. It is temperature controlled and water cooled via an external water pumping system running through the base peltier plate. A smart swap featue is used when equipping the spindle which automatically programs the machine for a gap distance of ~58 microns. The spindle used had a 40mm diameter with a 2^{o} cone angle. Figure 16 shows the rheometer.

Figure 16: ARG2 rheometer.

3.1.9. Nanosilica

Nanosilica or silicon dioxide nanoparticles, are an oxide of silicon with chemical formula SiO_2. Silica is a naturally occuring material commonly found in living organisms, quartz, and sand. It is very abundant and is used in structural components, electronics, components in food, and also in the pharmecutical industry. Nanosilica spheres of ~15-20nm diameter were suppied by Nanostructured & Amorphous Materials, Inc.

3.1.10. Polyethylene glycol (PEG)

PEG with a molecular weight of 200 was used for producing STF. The chemical formula of PEG is $C_{2n}H_{4n+2}O_{n+1}$. PEG was supplied by Sigma Aldrich. The chemical structure of the monomeric unit of PEG is shown below in Figure 17.

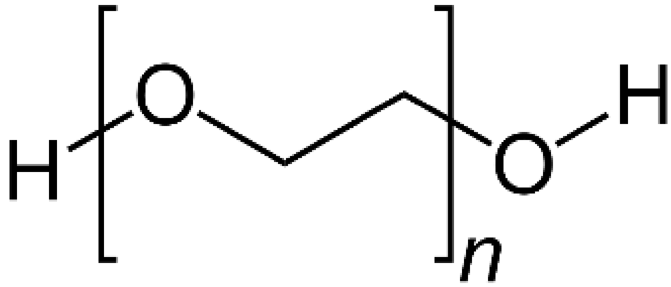

Figure 17: Chemical structure of PEG.

3.1.11. Ethanol

Ethanol of 95% concentration was used for diluting the STF in order to reduce its viscosity for impregnation of fabrics. Ethanol was obtained from Sigma Aldrich.

3.1.12. Flax fabric

A 2x2 twill weave flax fabric of areal density 0.412 kg/m^2 was used for the experiments. Flax fabric was supplied by Composites Evolution, Chesterfield, UK. The flax fabric is shown below in Figure 18.

Figure 18: Flax fabric.

3.1.13. Kevlar fabric

A plain weave Kevlar fabric of areal density 0.459 kg/m^2 was used for the experiments. Figure 19 shows a sample of the fabric.

Figure 19: Kevlar fabric.

3.1.14. Corn starch water suspension

A corn starch water suspension is also commonly known to display shear thickening behavior. AGRO brand corn starch was mixed with tap water in order to create a STF.

3.2. Sample production

3.2.1. STF for rheological study

STF for rheology study was produced in 50g samples at concentrations of 30%, 35%, 40%, 45%, and 50% w/w of nanosilica in PEG. PEG was first introduced into a glass specimen jar. 1g increments of nanosilica were then introduced into the PEG and manually stirred before sonicating at 600W power and 20kHz frequency for 15 second intervals with a 30 second pause between each interval until suspension appeared homogenous. The glass container was kept in an ice bath in order to prevent the suspension from heating up excessively. As concentraions of nanosilica increased sonication time required for homogenous appearance increased. At 50% w/w concentration of nanosilica in PEG the sample was sonicated for 2.5 hours before appearing homogenous. Higher concentrations were not explored for rheological study due to the inablility to disperse higher concentrations with equipment and methods used. Once homogenous dispersions were obtained the samples were placed in a vacuum chamber with a vacuum pressure of 25 inHg for approximately 1 hour prior to rheological experiments in order to remove any remaining air trapped in the suspension. Figure 20 below shows samples of STF prepared via this method. There is a vary slight change in color with the samples becoming slightly darker as the concentration of nanosilica increases.

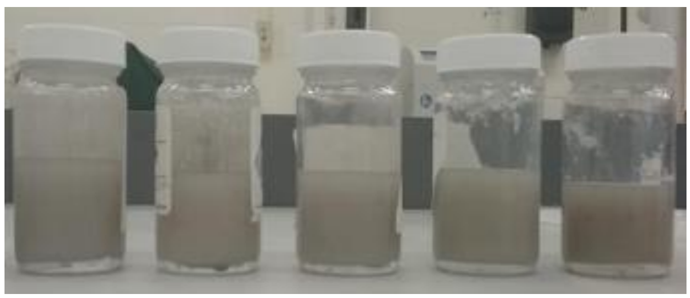

Figure 20: STF rheology samples (left to right: 30%, 35%, 40%, 45%, 50% w/w concentraion of nanosilica in PEG).

3.2.2. STF samples for impregnation

STF samples used for fabric impregnation were produced via a one pot method. As the viscosity of the STF suspensions is too great to impregnate the fabrics it must be diluted in order to impregnate the fabrics. In order to facilitate the impregnation STF samples were produced in single container at varying concentrations of nanosilica in PEG respectively 30%, 50%, 70% wt/wt diluted at a 1:3 volume ratio of STF to Ethanol. STF constituent materials were first added into a contianer then subsequently diluted with ethanol. The suspension was manually stirred to break up any large agglomerates and then sonicated at 600W, 20kHz for up to 10 min or until homogenous using pulses of sonication lasting 30 seconds with 30 second pauses.

3.2.1. Fabric preparation

Areal density of the fabrics was first measured by cutting 100mm x 100mm sections fabric and subsequently recording the mass of the fabric sample using the analytical balance. Areal density was calculated by dividing the mass *m* by the cross sectional area *A* shown in equation (3.1) below.

$$Areal\ Density = \frac{m\ (g)}{A\ (cm^2)} \tag{3.1}$$

20 sections of 6.4cm x 6.4cm squares of both flax and kevlar fabric were cut for use in puncture testing for each sample concentration. 20 sections of 21.6cm x 21.6cm of both flax and kevlar fabrics were cut for use in ballistic impact testing for each sample concentration. The weight of each layer of fabric was recorded prior to impregnation in order to measure the weight change post impregnation.

3.2.2. STF impregnation

Once STF samples of 30%, 50%, and 70% w/w concentration of nanosilica in PEG were diluted in ethanol at 1:3 volume ratio and homogenized they were poured into a container and each fabric layer of flax and kevlar was submersed in the desired suspension concentration for 120 seconds. Fabric layers were then removed from the suspension and placed in a convection oven at 80^{o}C for 30 minutes in order to evaporate the ethanol from the fabric. Once samples were dried the mass was recorded using the analytical balance and areal density was calculated.

3.2.3. Corn starch suspension impregnated fabrics

Corn starch suspension were created by mixing 30wt% corn starch with 70wt% water and 15wt% corn starch and 85wt% water by hand stirring. Flax fabrics were impregnated with the 30wt% cornstarch suspension by soaking for 2min. Kevlar fabrics were impregnated with 15wt%

cornstarch suspension by soaking for 2min. After soaking the fabrics were dried for 8 hours at 80^{o}C to evaporate the water off leaving only cornstarch impregnated fabrics.

3.3. Material charaterization

3.3.1. Rheological charaterization of STF

An ARG2 rheometer was used to evaluate the rheological properteis of the STF samples at 30%, 35%, 40%, 45%, and 50% w/w concentration of nanosilica in PEG. Rheological experiments were conducted under steady, shear stress controlled tests. The spindle used was a 40mm diameter 2^{o} cone with a gap distance of 58 microns. The rheometer was programmed to measured from shear stress of 0.1-2000 Pa collecting data at a frequency of 10 data points per decade. Tests were run at both 25^{o}C and 50^{o}C in order to anlyze the effect of temperature on the rheological properties.

3.3.2. Puncture testing

4 layers of flax fabric, 4 layers of kevlar fabric, and a hybrid of 2 layers of flax and 2 layers of kevlar fabrics (layers: Flax/Kevlar/Flax/Kevlar) were cut into 6.4cm x 6.4cm and were impregnated with varying levels of STF suspension, 0, 30%, 50%, 70% w/w concentration of nanosilica in PEG respectively. Flax and Kevlar fabric samples impregnated with cornstarch suspension were prepared with 4 layers of fabric material. The fabric layers were centered and clamped in the testing fixture. The steel spike was then moved to contact the specimen. The spike was then forced into the fabric at a rate oe 50mm/min until it punctured the fabric. The loadframe collected data on force and displacement at a frequency of 10Hz. The tests was run 5 times for each sample. Force displacment curves were constructed for all specimens tested.

3.3.3. Ballistic impact testing

4 layers of flax fabric, 4 layers of kevlar fabric, and a hybrid of 2 layers of flax and 2 layers of kevlar fabrics (layers: Flax/Kevlar/Flax/Kevlar) were cut into 21.6cm x 21.6cm squares and

were impregnated with varying levels of STF suspension, 0%, 30%, 50%, 70% w/w concentration of nanosilica in PEG respectively. The 4 fabric layers were centered and clamed tightly between the steel frame. The frame was then clamped tightly into the ballistic impact testing machine and the machine sealed shut. The mass of the shrapnel simulating projectile was recorded and the projectile was loaded into the barrel. The pressure chamber was charged to the desired pressure and after making sure the pressure was at equilibrium, the projectile was fired at the specimen. Each sample was tested with 3 specimens. The input and output velocites were recorded in order to calculate the energy absorbed during the impact using equation (3.2). With *m* being the mass of the projectile in grams, v_1 the velocity measured before impact in m/s, v_2 the velocity of the projectile after impact in m/s, and KE the energy absorbed from impact in J.

$$KE = \frac{1}{2}m(v_1^2 - v_2^2) \tag{3.2}$$

3.3.4. SEM

Scanning electron microscopy (SEM) was utilized to examine the surface of STF impregnated flax fabrics in order to evaluate the dispersion of the STF throughout the fabric. The specimens were sputter coated with a conductive layer of gold. Images were obtained with a JEOL JSM-6490LV scanning electron microscope with energy-sispersive X-ray information being collected at an accelerating voltage of 15 kV using a Thermo Scientific UltraDry Premium silicon drift detector with NORVAR light element window and Noran System Six imaging system.

4. RESULTS AND DISCUSSION

4.1. Rheological testing

The viscocity of the STF produced as described in section 3.2.1 was tested as described in section 3.3.1 in order to establish it is showing shear thickening behavior. Shown in Figure 21 is the effect of shear rate on the viscosity of the STF samples. It was observed that at 30% STF or 30% w/w concentration of nanosilica in PEG that there was minmal deviation from newtonian fluid behavior as the maximum change in viscosity was measured at 0.0475 Pa.s. However as the concentration of nanosilica increases the non-newtonian behavior is much more evident. The shear thickening significatly affects the viscosity change observed in the experiment as well as the shear rate required to induce shear thickening. It is seen that for higher concentrations the samples initially show shear thinning behavior before reaching a critical shear rate at which thickening or increase in viscosity is observed. These results are consitent with what has been seen in literature as described in the section 2. This For 35% STF, 40% STF, 45% STF, and 50% STF the maximum change in viscosity was measured to be 0.3269 Pa.s, 0.7831 Pa.s, 8.938 Pa.s, and 59.787 Pa.s respectively. The approximate shear rate required to induce a shear thickening effect was found to be 8.5 s^{-1}, 6.1s^{-1}, 2.0 s^{-1}, and 1.5 s^{-1} for 35%STF, 40%STF, 45%STF, and 50%STF, respectively.

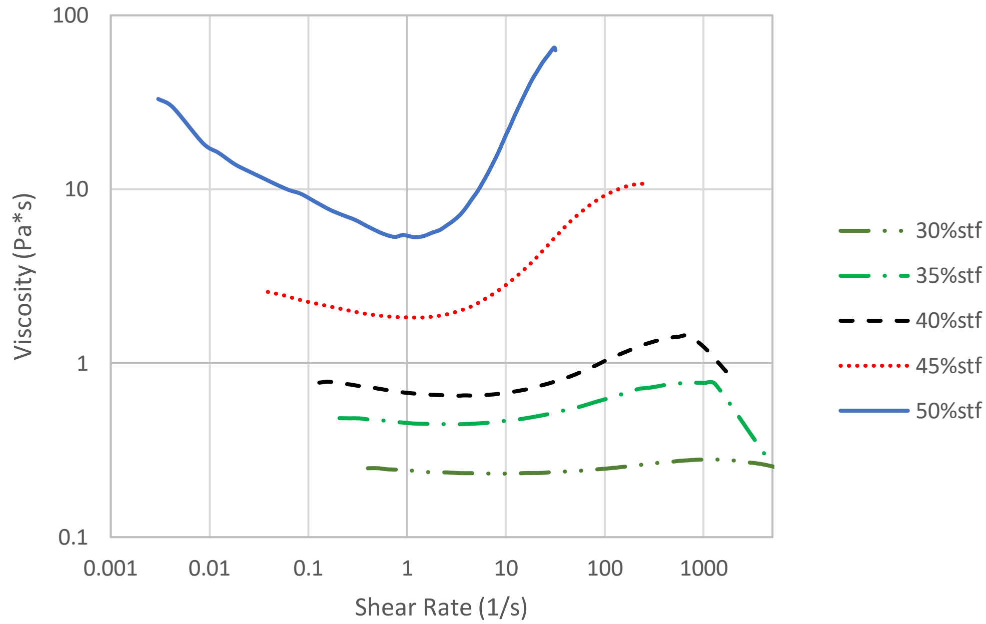

Figure 21: Shear rate effect on viscosity at 25°C.

Figure 22 shows the viscosity measurements obtained as a funciton of shear stress. Viscosity is seen to react in a very similar manner to shear stress as it does to shear rate.

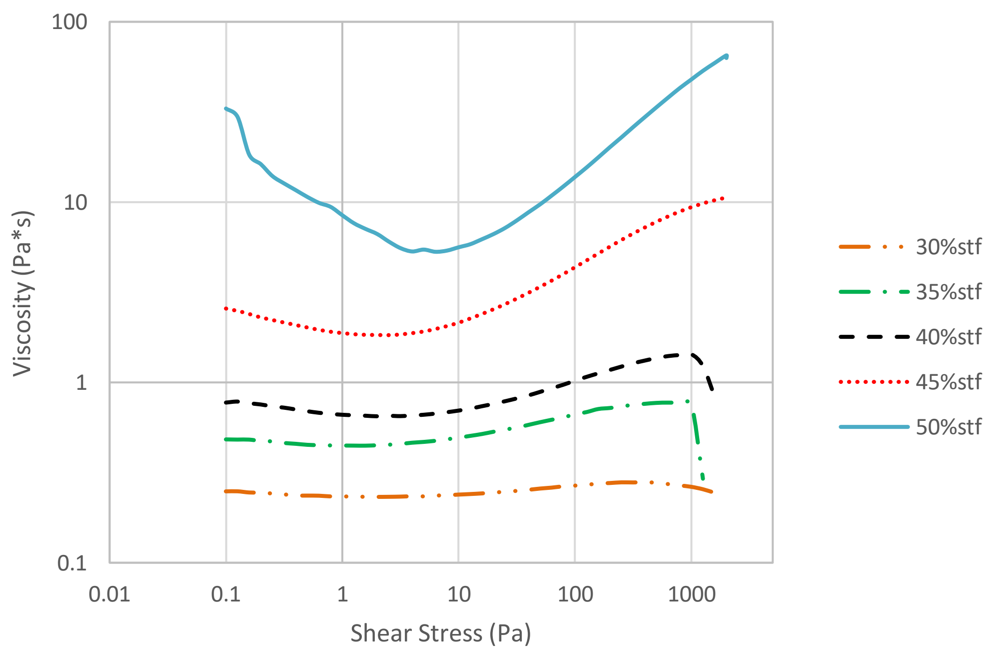

Figure 22: Shear stress effect on viscosity at 25 °C.

Figure 23 shows the effect of shear rate on the viscosity of the STF samples at an elevated temperature of 50°C. The trends for each sample are similar to what is observed at 25°C with some changes in critcal shear rate and the extent the STF will increase in viscosity under the tested conditions. The maximum changes in viscosity were found to be 0.0558 Pa.s, 0.1001 Pa.s, 0.2367 Pa.s, 1.9637 Pa.s, and 27.723 Pa.s in 30%STF, 35%STF, 40%STF, 45%STF, and 50%STF respectively. The approximate critical shear rates were found to be 8.9 s^{-1}, 8.2s^{-1}, 4.2s^{-1}, and 3.1 s^{-1}. These values correspond to a 4.7%, 34.4%, 110.0%, and 106.7% increase in the shear rate required to induce shear thickening in 35%STF, 40%STF, 45%STF, and 50%STF with an increase of 25°C. These results indicate that temperature can have a significant effect on the rheological properties of STFs.

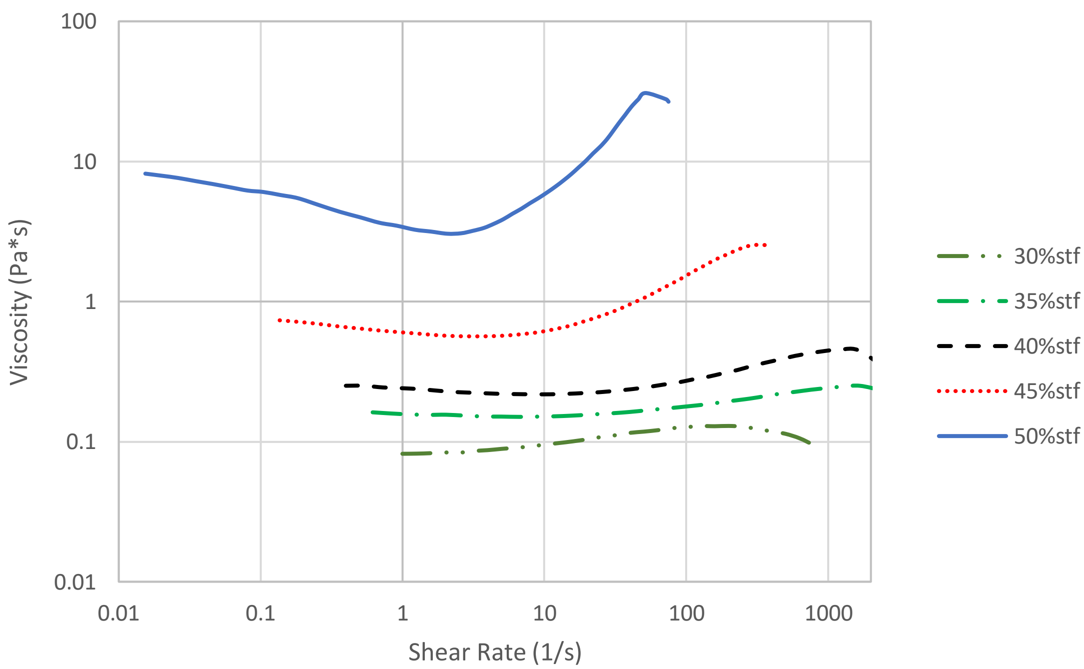

Figure 23: Effect of shear rate on viscosity at 50°C.

Figure 24 shows the measured viscosity as a funciton of shear stress. It is seen that viscosity also reacts very similar to shear stress as it does shear rate at an elevated temperature.

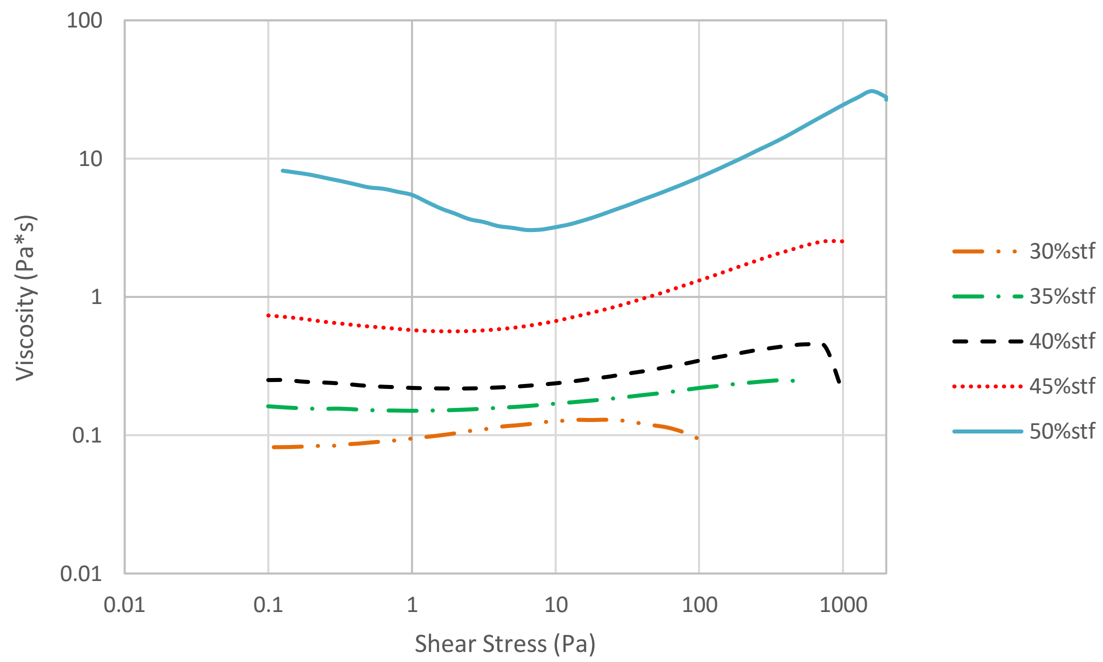

Figure 24: Effect of shear stress on Viscosity at 50°C.

4.2. Change in areal density

When considering the effectiveness of STF impregnated fabrics it is important to understand what is desirable in a soft body armor material. The material should be flexible so it does not severely restrict motion of the wearer. The material should also not be overly heavy as it will cause the wearer to fatigue faster. The material should also be able to stand up to the threat conditions it is exposed to. Keeping these requirements in mind, when adding STF to a fabric material it will increase the weight of the fabric. The increase in weight and the resulting increasing in areal density of the STF impregnated fabrics has been measured and is helpful in determining if the material has improved performance in terms of strength to weight ratio. Table 1 shows the measured areal density of the fabric materials and the percent increase when STF is impregnated into the fabrics. Figure 25 shows a graphical comparison of the areal densities and average of 5 specimens per sample. The highest increase in areal density resulted from impregnating the fabrics with STF at 70% wt/wt concentration of nanosilica in PEG. The smallest increase in areal density was seen for the 50% STF impregnated samples and the corn starch impregnated samples. It is hypothesized that at 30% STF concentration more PEG is soaked into the fabric materials relative to the nanosilica impregnated into the fabric, thus showing a larger increase in areal density than at 50% STF concentration.While at 70% STF cooncentration significantly more nanosilica can be impregnated into the fabrics.

Table 1: Areal Density of STF Fabric Samples

Sample	Areal Density kg/m^2	Percent Increase in Areal Density Relative to Neat Fabrics
Neat Flax	0.412	-
Neat Kevlar	0.459	-
30% STF Flax	0.823	99.8%
50% STF Flax	0.776	88.3%
70% STF Flax	0.86	108.7%
30% STF Hybrid	0.725	66.5%
50% STF Hybrid	0.6875	57.9%
70% STF Hybrid	0.771	77.0%
15 % Corn Starch Kevlar	0.655	42.7%
30% Corn Starch Flax	0.692	40.4%

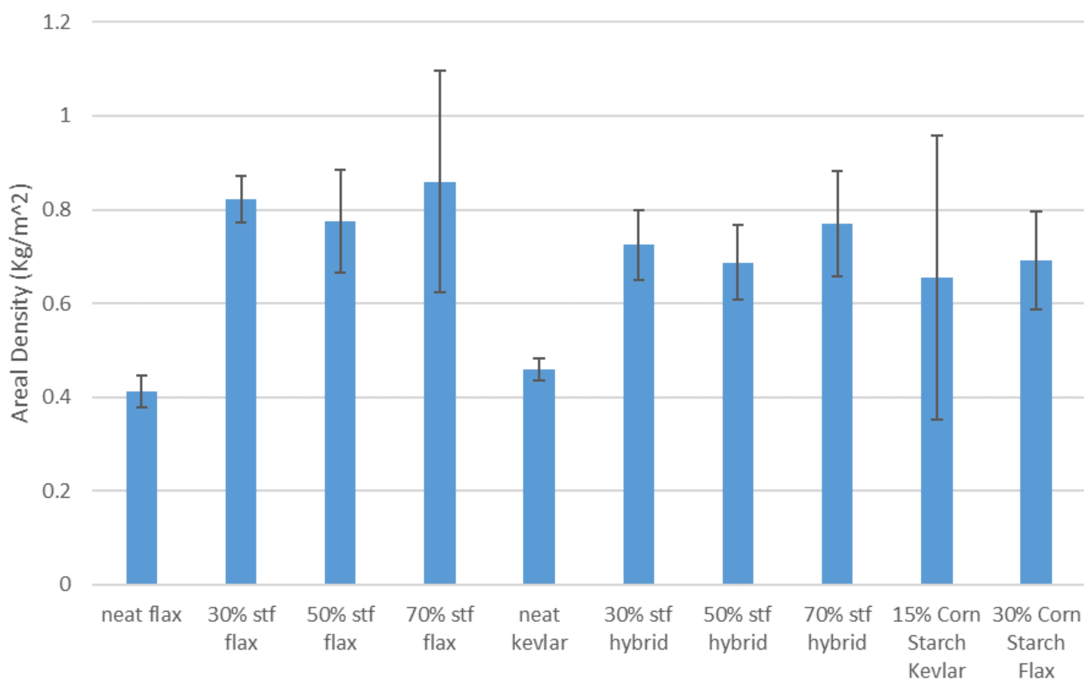

Figure 25: Comparison of areal densities of STF fabric materials.

4.3. Puncture testing

Puncture testing was performed to evaluate the materials resistance to stabbing on 5 specimens per sample. Samples were manufactured as described in section 3.2.3 and 3.2.4 tested as described in section 3.3.2. The resultant force displacement curves from the puncture testing of flax and STF treated flax is shown below in Figure 26. The data is summarized in Table 2. It can be seen that the impregnation of STF into the flax fabric significantly increases the force to puncture the materials or its puncture resistance. As the concentration of the STF suspension increases from 30% wt/wt nanosilica in PEG to 70% concentration the impregnated fabrics puncture resistance is increased as well. For 30% STF flax, 50% STF flax, and 70% STF flax a 144.1%, 182.4%, and 254.6% increase respectively in force required to puncture the material was measured compared to neat flax. This is similar to reports in literature for Kevlar fabrics impregnated with STF. A study by Kalman et.al showed a 224.4% increase in peak force to puncture Kevlar fabric when impregnated with a 31.5wt% SiO_2/PEG based STF [9]. These values indicate that impregnation of STF into flax fabric is extremely effective in increasing the materials puncture resistance, making flax fabrics impreganated with STF an effective material for use against stabbing threats. The amount of displacement the material can undergo before puncture is also increased with STF impregnation. For neat flax fabric the average fabric displacement at maximum force applied before puncture was measured at 10.15 mm. For 30% STF flax, 50% STF flax, and 70% STF flax this value was measured at 12.18 mm, 13.37 mm, and 13.34 mm respectively. These values correlate to a 20.0%, 31.7%, and a 31.4% increase measured in the fabric displacement at maximum force compared to neat flax. These results show that the material is still flexible after impregnation with STF. This has also been observed by Kalman et.al and when a 31.5wt% STF suspension was used in Kevlar fabric the displacement at peak force was increased 25.76% [9].

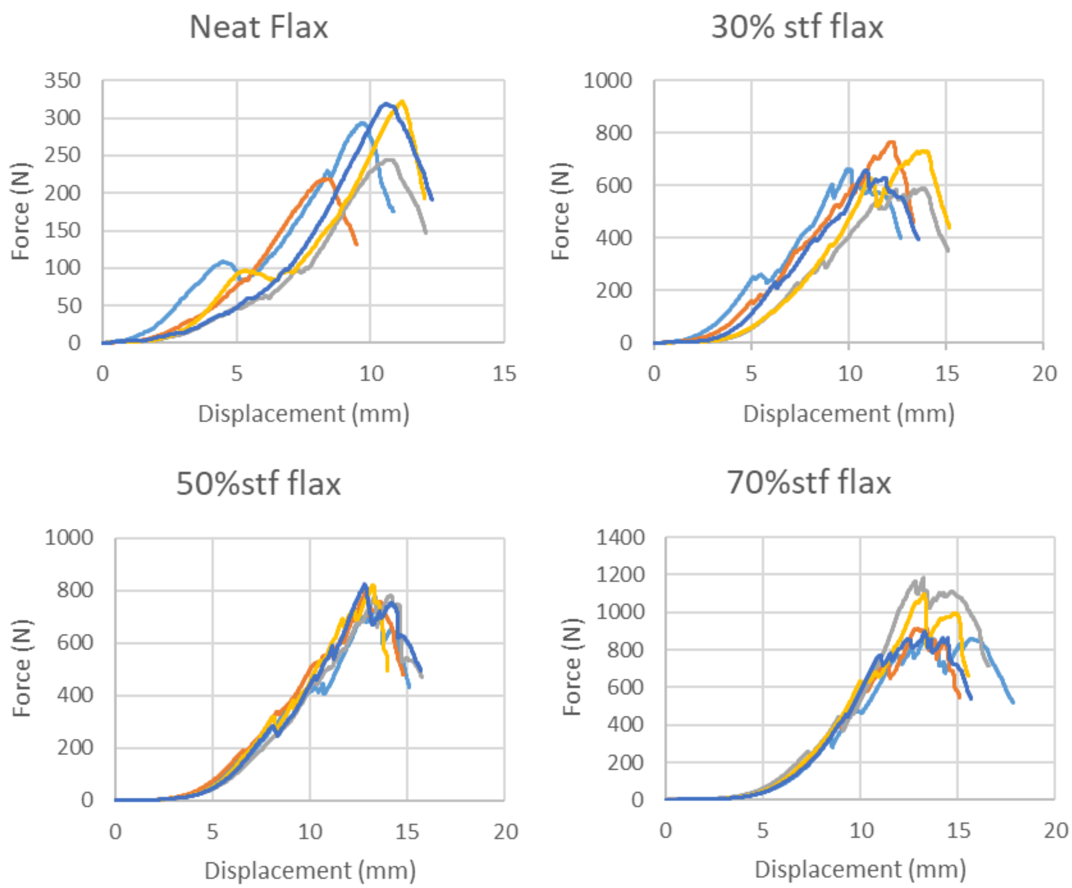

Figure 26: Force diplacement curves of flax and flax-STF impregnated specimens.

Table 2: Summarized Results of Flax and STF Impregnated Flax Fabric Puncture Testing.

	Average Maximum Force (N)	Standard Deviation	Average Displacement at Maximum Force (mm)	Standard Deviation
Neat flax	279.30	45.90	10.15	1.10
30% STF flax	681.80	69.78	12.18	1.67
50% STF flax	788.85	43.30	13.37	0.55
70% STF flax	990.51	142.67	13.34	0.09

Figure 27 shows the force displacement curves for Kevlar and flax/Kevlar hybrid fabrics and STF impregnated hybrid fabrics. Table 3 summarizes the data. Again the impregnation of STF into the fabrics significantly increases the force to puncture the fabric materials. As the concentration of the STF used to impregnate the fabrics increased the force to puncture increased as well. For the neat Kevlar sample the average maximum force required to puncture the samples was measured at 404.5N. The average maximum force required to puncture the neat hybrid sample was measured at 232.37 N, which oddly is lower than the average maximum force of 279.30 N required to puncuture neat flax fabric. When the hybrid material was impregnated with STF, large increases in puncture resistances were obtained. For the 30% STF hybrid sample an average maximum force required to puncture the meaterial was measured at 1641.62 N. This corresponds to a 606.5% increase in the force required to puncture the material compared to the neat hybrid, a 305.8% increase over neat Kevlar, and a 140.8% increase over the 30% STF flax sample. For the 50% STF hybrid sample an average maximum force required to puncture the material was measured at 1929.93N. This corresponds to a 730.5% increase over the neat hybrid, a 491.0% increase compared to neat Kevlar, and a 144.7% increase compared to 50% STF flax. For the 70% STF hybrid sample the average maximum force required to puncture the sample was measured at 2210.36N. This corresponds to an increase of 851.2% over the neat hybrid sample, a 446.4% increase over neat Kevlar, and a 123.2% increase compared to the 70% STF flax sample.

An increase in fabric displacement at the average maximum force to puncture was also observed in the hybrid samples. The average displacemant at the maximum force required for puncture was found to be 9.71 mm and 11.60 mm for the neat hybrid and Kevlar samples, respectively. The average displacemant found at the maximum force required for puncture was found to be 15.51 mm, 14.48 mm, and 13.13 mm for the 30% STF hybrid, 50% STF hybrid, and 70% STF hybrid samples, respectively. These values correspond to an increase in displacement at puncture strength compared to the neat hybrid of 59.7%, 49.1% and 35.2% for the 30% STF hybrid, 50% STF hybrid, and 70% STF hybrid samples, respectively. When compared to the neat Kevlar fabric the increase was found to be 33.7%, 24.8%, and 13.2% for the 30% STF hybrid, 50% STF hybrid, and 70% STF hybrid samples, respectively. These results show that through the impregnation of STF the fabric materials can undergo a greater displacement before being punctured, showing the materials still remain flexible enough for use in soft body armor applications.

These results show the effectiveness of hybridization of the fabrics when impregnated with STF, as the hybrid samples showed much larger increases in puncture resistance compared to the unhybridized flax samlpes relative to the neat fabric samples. The effectiveness of impregnating STF on the puncture resistance was improved with hybridization of the fabric materials as the hybrid samples show much higher force to puncture than the STF impregnated flax samples. Hybridized fabric materials impregnated with STF show much promise for use in puncture resistant applications. It is hypothesized that hybridizing STF impregnated Kevlar fabric with STF impregnated flax fabric significantly improves puncture resistance due Kevlar being a fabric material with better mechanical properties than flax and STF enhancing the Kevlar fabric more significantly than the flax fabric.

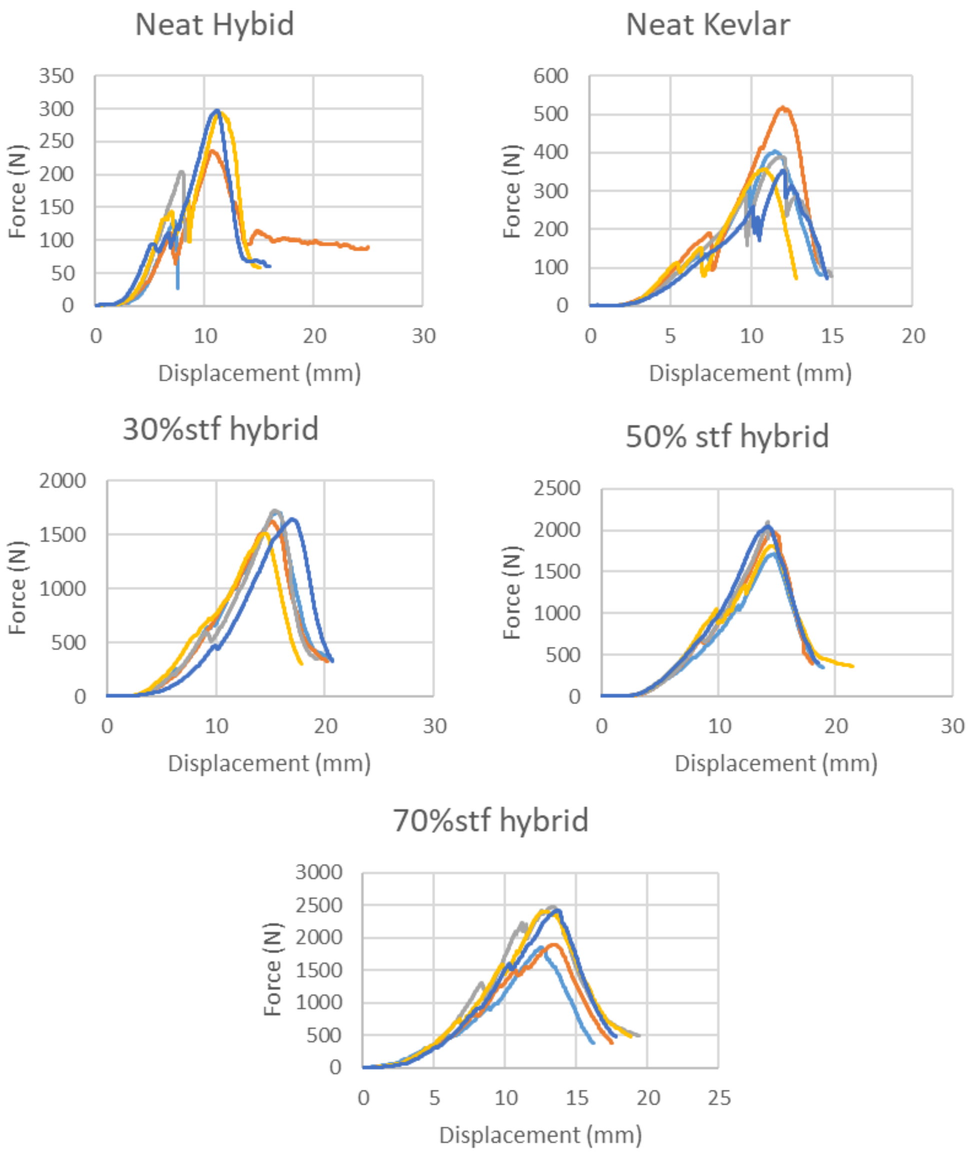

Figure 27 : Force displacement curves for Kevlar and flax/Kevlar hybrid STF impregnated samples.

Table 3: Summarized Results of Kevlar and Hybrid STF Sample Puncture Resistance Results

	Average Maximum Force (N)	Standard Deviation	Average Displacement at Maximum Force (mm)	Standard Deviation
Neat Kevlar	404.50	67.50	11.60	0.52
Neat hybrid	232.37	69.52	9.71	1.99
30% STF hybrid	1641.62	85.01	15.51	0.89
50% STF hybrid	1929.93	161.41	14.48	0.25
70% STF hybrid	2210.36	307.82	13.13	0.52

Figure 28 shows the force displacement curves for 15% corn starch Kevlar and 30% cornstarch flax fabrics. Table 4 summarizes the data. The concentrations of the suspensions used were the maximum at which the fabric would absorb the suspension. It was observed that flax fabrics were able to be impregnated with higher concentrations of cornstarch suspension. From Table 4 it can be seen that the 30% cornstarch flax sample was able to withstand more force before being punctured as well as being able to fail at a significantly higher displacement, indicating it has higher flexability or tenacity of the fabric.

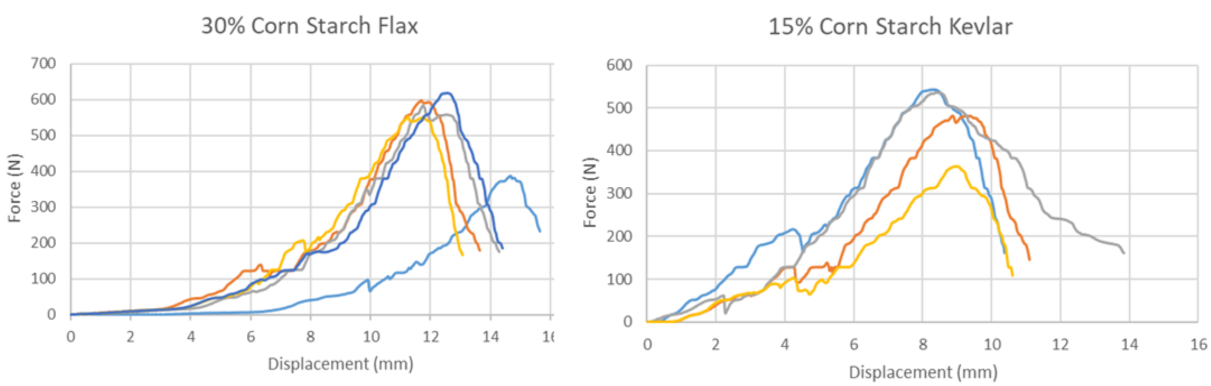

Figure 28: Corn starch impregnated fabric force displacement curves.

Table 4: Corn Starch Impregnated Fabric Puncture Data

	Average Maximum Force (N)	Standard Deviation	Average Displacement at Maximum Force (mm)	Standard Deviation
15% Corn Starch Kevlar	481.2	83.09	8.63	0.35
30% Corn Starch Kevlar	547.78	92.85	12.39	1.36

When evaluating puncture resistance of the materials tested the specific properties should be reported on as well. Although large increases in puncture resistance were measured, the increased weight of the STF impregnated samples should be taken into account as well. The specific puncture strength of the materials can be calculated by dividing the force required to puncture the material by the materials areal density. This specific puncture strength is a more accurate representation of the effectiveness of the STF impregnation. The equation used to calculate specific puncture strength is shown below in equation (3.3), with F being the average maximum force required to puncture the material in newtons and ρ being the areal density of the material in kg/m^2.

$$Specfic\ Punture\ Strength = \frac{F}{\rho} \tag{3.3}$$

Figure 29 shows a comparison of the specific puncture strength of the materials. Table 5 details the results. Significant increases in specific puncture strength are seen with the impregnation of STF into the fabric materials. As the concentration of the STF used to impregnate the fabrics increased the specific puncture strength increased as well. The specific puncture strength of the neat flax fabric sample was measured to be 677.92 N/kg/m^^{2}. The specific puncture strength of the 30% STF flax, 50% STF flax, and 70% STF flax samples were measured at 828.43 N/kg/m^^{2}, 1016.56 N/kg/m^^{2}, and 1151.75 N/kg/m^^{2}, respectively. These values corredspond to an increase in specific punture strength compared to neat flax of 22.2%, 50.0%, and 69.9% for

30% STF flax, 50% STF flax, and 70% STF flax, respectively. The increase in specific puncture strength is significatly less than the base increase in puncture strength.

The specific puncture strength of the neat hybrid sample was measured at 533.58 N/kg/m^^{2}. The specific puncture strengths of the 30% STF hybrid, 50% STF hybrid and 70% STF hybrid samples was measured to be 2264.31 N/kg/m^^{2}, 2807.17 N/kg/m^^{2}, and 2866.88 N/kg/m^^{2}, respectively. Compared to the neat hybrid this corresponds to an increase in specific puncture strength of 324.4%, 426.1%, and 437.3% for the 30% STF hybrid, 50% STF hybrid, and 70% STF hybrid samples, respectively. The specfic puncture strength to the Kevlar sample was measured to be 881.26 N/kg/m^^{2}. When compared to the neat Kevlar fabric the percentage increase in specific puncture strength for the 30% STF hybrid, 50% STF hybrid, and 70% STF hybrid was found to be 156.9%, 218.5%, and 225.3%, respectively. Again the increase in specific puncture strength was found to be much less than the increase in puncture strength for the hybrid samples. When compared to the neat Kevlar fabric the 15% cornstarch Kevlar sample showed a 16.6% reduction in the specific puncture strength, indicating it was not effective at enhanicing the materials puncture resistance on a per weight basis. Comparing the 30% cornstarch flax sample to the neat flax sample a 16.8% increase in specific puncture strength was measured. This value indicates that cornstarch can increase the puncture resistance of flax fabrics on a per weight basis.

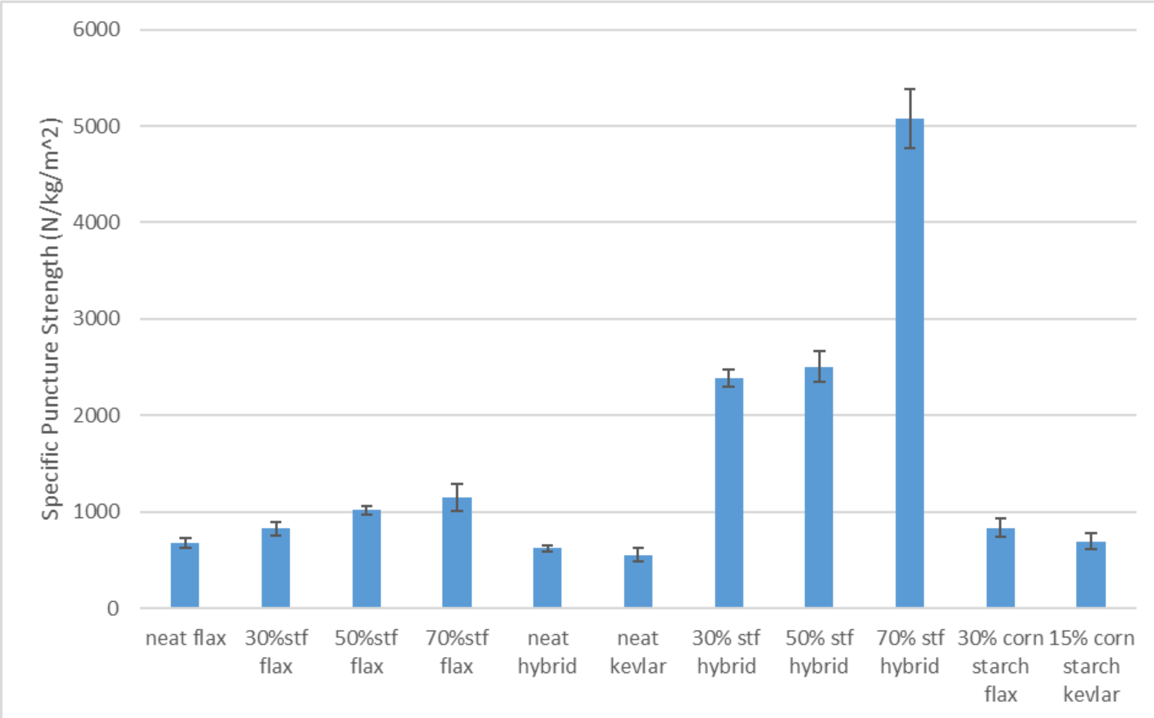

Figure 29: Comparison of specific puncture strengths.

Table 5: Summarized Results of Specific Puncture Strength

	Specific Puncture Strength (N/kg/m^2)
neat flax	677.92
30% STF flax	828.43
50% STF flax	1016.56
70% STF flax	1151.75
neat kevlar	881.26
neat hybrid	533.58
30% STF hybrid	2264.31
50% STF hybrid	2807.17
70% STF hybrid	2866.88
15% corn starch Kevlar	734.66
30% corn starch flax	791.60

Figure 30 shows the average energy absorption of the samples during puncture testing. It was shown that as the concentration of the STF suspension increased the energy absorption of the impregnated samples also increased. Flax samples impregnated with STF were able to absorb significantly more energy than neat Kevlar specimens. Table 6 shows the numerical values for energy absorption and the standard deviation.

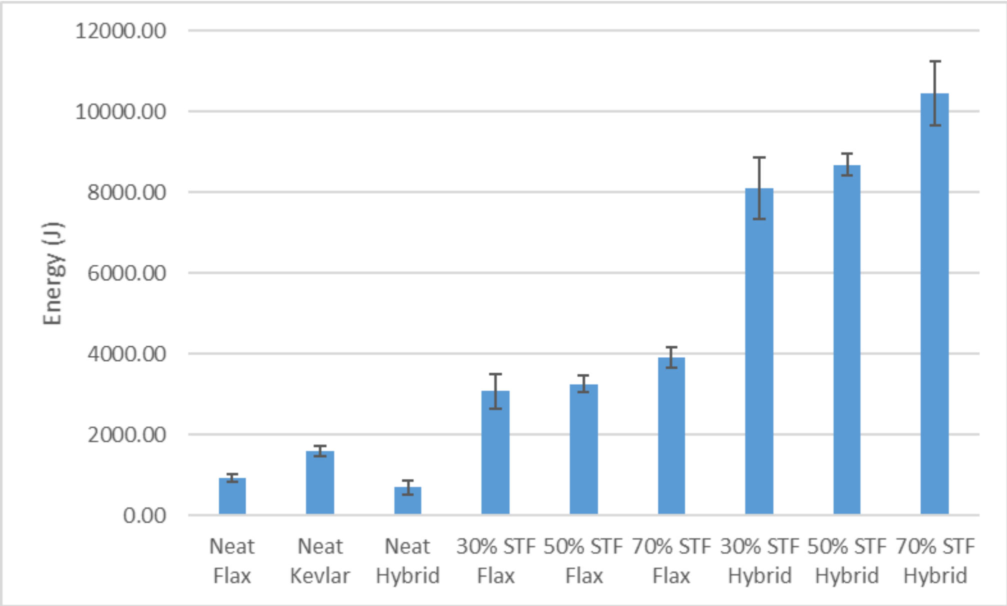

Figure 30: Comparison of average energy absorbed during puncture testing.

Table 6: Summarized Results of Puncture Energy Absorption

	Average Energy Absorption	Standard Deviation
Neat Flax	917.44	197.30
Neat Kevlar	1598.89	272.95
Neat Hybrid	701.41	342.20
30% STF Flax	3076.34	867.62
50% STF Flax	3260.77	389.55
70% STF Flax	3915.85	522.95
30% STF Hybrid	8110.83	1544.26
50% STF Hybrid	8693.47	527.82
70% STF Hybrid	10465.93	1579.67

4.4. Ballistic impact testing

High velocity ballistic impact testing was perfomed as described in section 3.3.3 on 3 specimens per sample. Steel projectiles were fired at the specimens and the maximum velocity at which the specimens were not punctured was recorded. Energy absorption values were calculated by taking v_2 in equation 3.2 to be 0. Table 7 summarizes the ballistic impact testing energy absorption results for neat flax and STF flax impregnated samples. 4 layers of neat flax was able to stop a projectile delivered with 107.406 J of kinetic energy. 30% STF flax, 50% STF flax, and 70% STF flax samples were able to stop projectiles delivered with 121.2 J, 184.680 J, and 240.969 J of kinetic energy, respetively. These values correspond to an increase in ballitic impact energy absorption of 12.8%, 71.9%, and 124.3% for 30% STF flax, 50% STF flax, and 70% STF flax samples, respectively. Figure 31 shows a graphical comparison of the results. These results prove that impregnating flax fabric with STF can significatly improve their ballistic impact resistance.

Table 7: Summarized Results of Ballistic Impact Energy Absorption for Flax Samples

	neat flax	30% STF flax	50% STF flax	70% STF flax
energy absorbed (J)	107.406	121.2	184.680	240.959

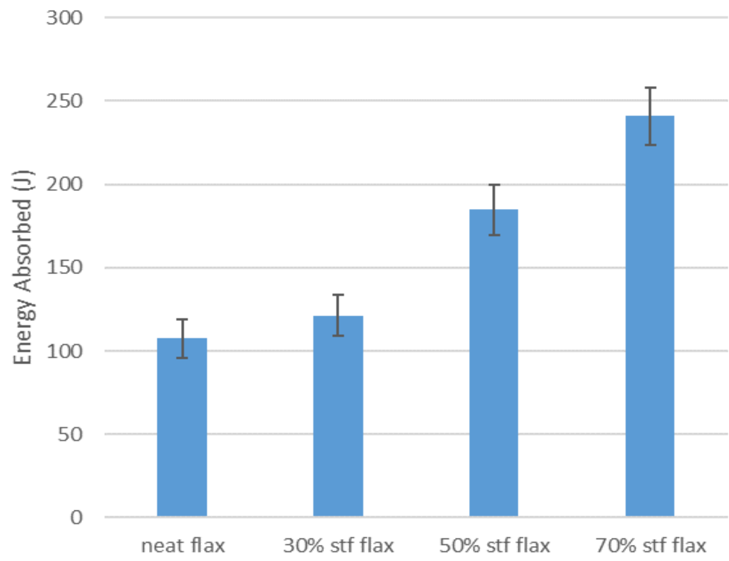

Figure 31 : Comparison of ballistic impact energy absorption for flax fabric samples.

Ballistic impact testing perfomed on hybrid samples was accomplished as described in section 3.3.3. 2 layers of fabric, one flax and one kevlar, were used for the ballistic impact testing. Table 8 summarizes the results of the hybrid samples ballistic impact energy absorption. The neat hybrid sample was able to stop a projectile that was delivered with 482.77 J of kinetic energy. The 30% STF hybrid, 50% STF hybrid, and 70% STF hybrid samples were able to stop projectiles delivered with 602.78J, 961.04 J, and 1402.48 J of kinetic energy, respectively. This corresponds to an increase in ballitic impact energy absorption of 24.9%, 99.1%, and 190.5% for 30% STF hybrid, 50% STF hybrid, and 70% STF hybrid samples, respectively. Figure 32 shows a graphical comparison of the results. These results show that hybridization of flax with Kelvar signigicantly improves the ballistic impact resistance of the material.

Table 8: Summarized Results of Ballistic Impact Energy Absorption for Hybrid Samples

	neat hybrid	30% STF hybrid	50% STF hybrid	70% STF hybrid
Energy absorbed (J)	482.77	602.78	961.04	1402.48

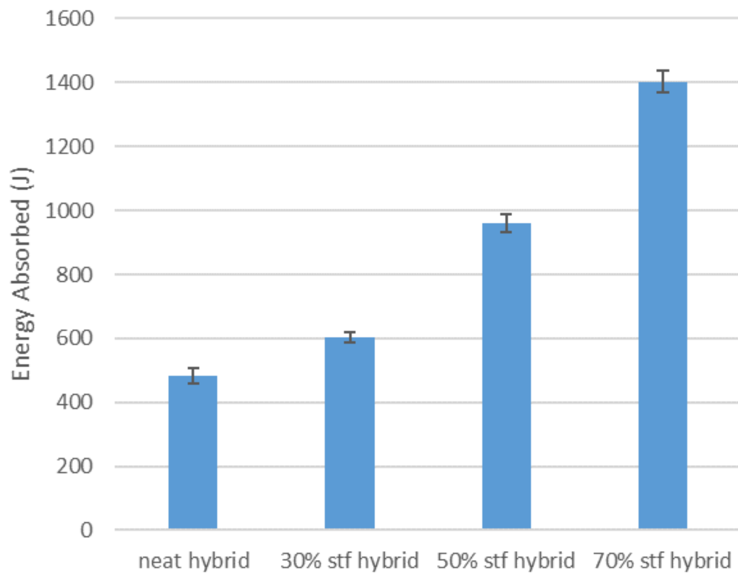

Figure 32:Comparison of ballistic impact energy absorption for hybrid samples

As impregnating fabrics with STF increases the weight of the material the ballitic impact testing should also evaluate the how the increased weight effects the performance of the materials. The specific energy absorption was calculated for all samples and divided by the number of layers ballistic impact testing was performed on. Table 9 summarizes the results of specific ballistic impact energy absorption per layer. It was found that neat flax had a specific ballistic impact energy absorption per layer of 260.69 J/kg/m^2. 30% STF flax, 50% STF flax, and 70% STF flax samples were measured to have a specific impact energy absorption per layer of 147.27 J/kg/m^2, 237.99 J/kg/m^2, and 280.18 J/kg/m^2, respectively. These results show that although STF treated flax can absorb more energy it does so at the expense of increased weight. Only the 70% STF flax sample was shown to be more effective at absorbing energy from ballistic impact than the neat flax sample on a per weight basis and only by 7.5%. This means that impregnation of STF into flax fabrics does not have significant improvement in the specific ballistic impact energy absorption of the material.

The neat hybrid sample was measured to have a specific impact energy absorption per layer of 1108.53 J/kg/m^2. The 30% STF hybrid, 50% STF hybrid, and 70% STF hybrid were found to have specific impact energy absorption per layer values of 831.42 J/kg/m^2, 1397.87 J/kg/m^2, and 1819.04 J/kg/m^2. The 30% STF hybrid is not as effective in terms of impact energy absorption per unit weight, however the 50% STF hybrid and 70% STF hybrid showed significant improvement. The 50% STF hybrid and 70% STF hybrid showed increases in specific ballistic impact energy absorption per layer of 26.1% and 64.1% respectively. These results show that the hybridization of flax with Kevlar fabrics impregnated with STF can improve the materials ballistic impact resistance if the concentration of STF used is high enough. The results also show the hybrid STF impregnated materials promise for use in soft body armor applications. Figure 33 shows a comparison all samples specific impact energy absorption per layer.

Table 9: Summarized Results of Specific Ballistic Impact Energy Absorption

	Specific impact energy absorption per layer (J/kg/m^2)
neat flax	65.17
30% STF flax	36.82
50% STF flax	59.50
70% STF flax	70.05
neat hybrid	554.27
30% STF hybrid	415.71
50% STF hybrid	698.94
70% STF hybrid	909.52

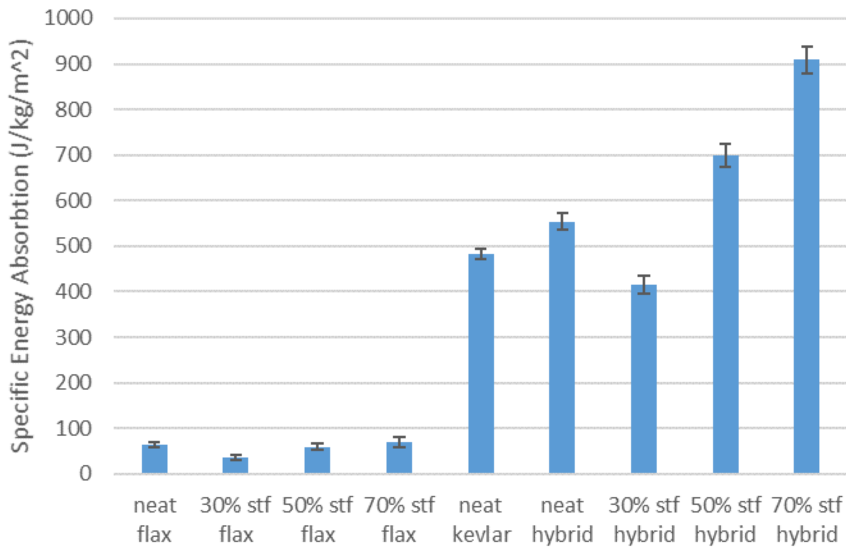

Figure 33: Comparison of specific ballistic impact energy absorption per layer.

4.5. SEM imaging

Scanning electron microscope images were taken as describe in Section 3.3.4. Figure 34 shows the SEM images of the STF impregnated flax fabric samples. As is common when working with nanoparticles agglomerations of the nanosilica particles are seen throughout the samples, with larger agglomerates seen at the higher STF concentrations. The nanosilica/PEG STF suspension can be seen to be relatively well dispersed throughout the fabric.

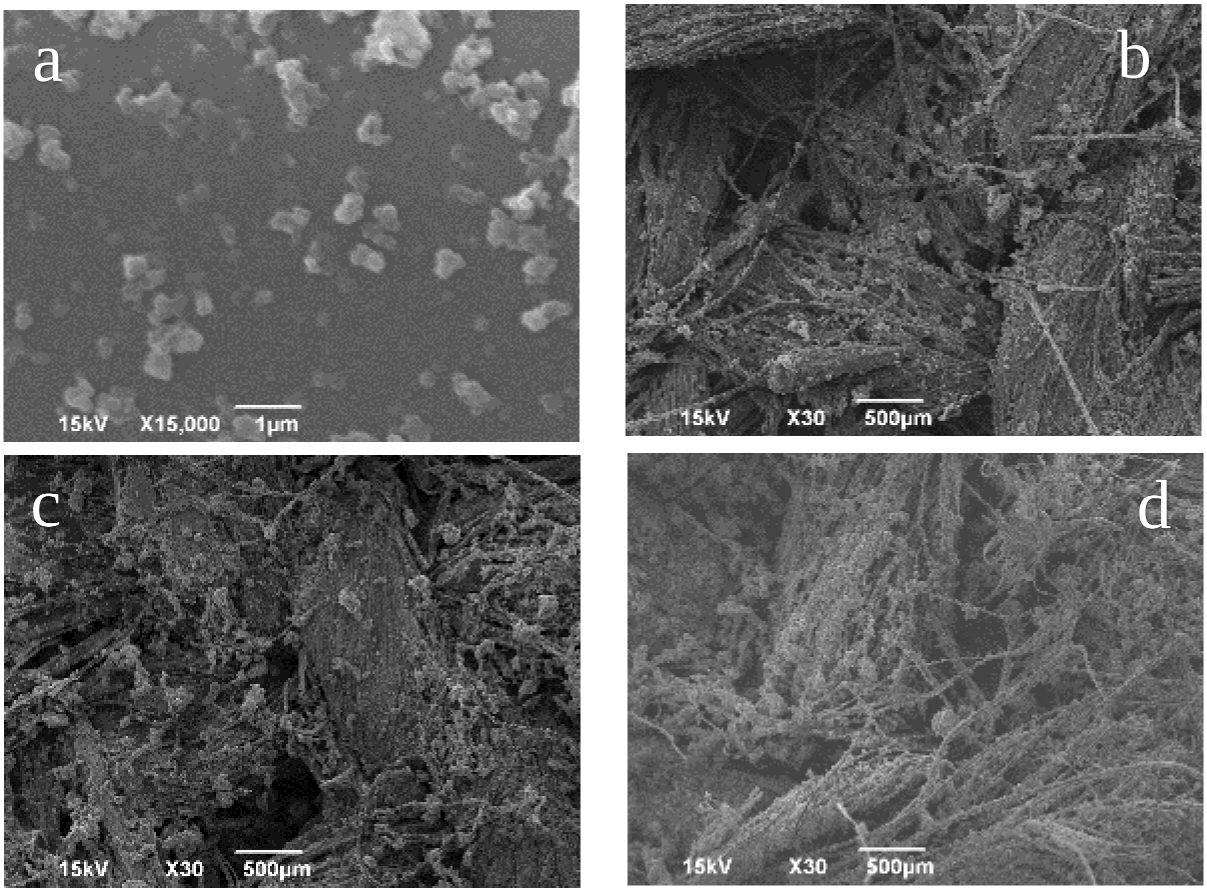

Figure 34: SEM images of (a) nanosilica particle agglomerates (b) 30% STF flax (c) 50% STF flax (d) 70% STF flax.

Figure 35 shows the nanoparticle adherance to indiviual fibers in the fabric materials. At all STF concentrations it was seen that the fibers were never completely coated in nanoparticles leaving some bare surface area. It was observed that at concentrains of 30% and 50% nanosilica STF the nanoparticle agglomerates and fiber surface coverage are similar. At 70% nanosilica concentration the fiber surface is more completely covered and there are more agglomerates.

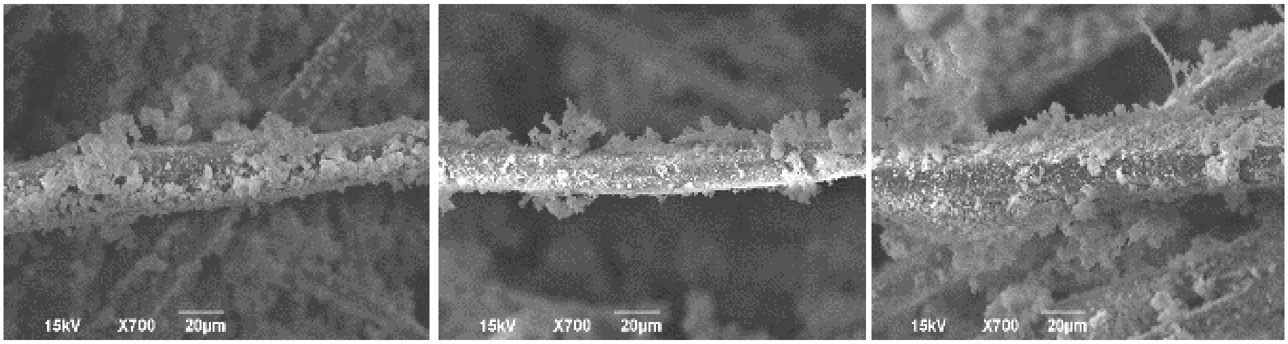

Figure 35: Nanosilica adherence to individual fibers. (left) 30% STF flax (center) 50% STF flax (right) 70% STF flax.

5. CONCLUSIONS AND FUTURE RECOMMENDATIONS

STF samples were studied and shown to have a non-Newtonian behavior which is dependent on shear rate and temperature. At a critical shear rate if the concentration of nanosilica in the STF is great enough the viscosity of the STF begins to increase. As temperature was increased the viscosity of the STF was decreased and the critical shear rate required to induce shear thickening was increased. As the concentration of the STF increased the viscosity was shown to increase and the critical shear rate required to induce shear thickening was reduced.

STF impregnated flax fabrics exhibited significant increases in puncture resistance. As the concentration of the STF used to impregnate the flax fabrics was increased the puncture resistance was also increased. Although the addition of STF to the flax fabrics adds a significant amount of weight to the sample, the STF treated flax fabrics still showed significant increases in specific puncture strength, or puncture strength per unit weight per unit area. STF treated flax fabrics also showed an increase in ballistic energy absorption, although with the significant increase in weight from the STF, the treated flax samples did not exceed the performance of the neat flax in terms of specific impact energy absorption.

STF impregnated hybrid samples of flax/Kevlar fabrics also showed significant increases in puncture resistance far beyond those of just the flax treated with STF. The hybridization of Kevlar with flax fabrics significantly improves the flax fabrics puncture resistance and also its specific puncture strength of the flax fabric. The STF treated hybrid fabrics also absorbed significantly more energy than untreated flax, Kevlar, and hybrid samples. The specific impact energy absorption per layer the samples treated with 50% and 70% STF was also measured to be significantly greater than any untreated samples.

The results from this novel study show that treating flax fabrics with STF does indeed affect their puncture resistance and ballistic impact resistance. The hybridization of Kevlar with flax fabric and treatment with STF lead to significant increases in the properties of the material allowing it to outperform neat Kevlar fabric, making the hybrid material a candidate for further study in body armor applications as the material can be easily encased inside a tactical vest or if needed vacuum sealed inside a plastic film and then inserted in tactical vest pouches.

The limited results of impregnating flax and Kevlar with cornstarch were also very promising. Both fabric types were able to show significant increases in their resistance to puncture when impregnated with cheap, and readily available corn starch and water suspensions. These promising results warrant further investigation into the effectiveness of cornstarch as a puncture resistant enhancer for fabric materials. These results also show that a shear thickening fluid itself is not needed to increase a materials puncture resistance, rather only that particles be dispersed throughout the fabric material, thus increasing the inter-yarn friction.

It is the opinion of the author that in order to improve the puncture and ballistic impact properties of fabric type materials that it is not necessary to incorporate a shear thickening fluid into the fabric, only disperse particles inside the fabric material. The dispersion of particles increases the puncture resistance and impact resistance by increasing the inter-yarn friction within the fabric, or severely reducing any individual fibers ability to move when particles are dispersed and holding them in place. More irregularly shaped particles dispersed in a fabric could lead to enhanced properties relative to a more regularly shaped particles like nanosilica spheres, provided the particles have a similar or greater hardness than nanosilica. It is also possible that the particles were able to embed themselves into the fibers when force is applied to the fabrics, helping to increase the friction force required to move fibers in the fabric. It is hypothesized that the effect the particles have on the increase in puncture and ballistic resistance is greater in hybrid impregnated samples because the particles have a greater reinforcing effect in Kevlar fabric. This may be because the Kevlar fibers are tougher and particles are able to embed into them more readily as compared to flax fibers which may be more easily crushed. The synthetic Kevlar fabric also has a much tighter and more consistent weave in the fabric which may lead to particles being able to embed into multiple fibers more easily.

Future work suggested in this area includes exploring the hybridization of different fabric materials treated with STF such as glass fiber/Kevlar, flax/glass fiber, carbon fiber/flax, or hemp/Kevlar to name a few. Natural fibers especially warrant further study in this application as they have not been studied before, although the lack of consistency with natural fibers may prove a challenge as many conditions such as weather can affect properties of the fibers. The study of hybrid fabrics treated with STF remains a promising avenue of research as there is currently very little research that has been performed on the topic.

Another avenue of future research believed to be worth exploring is in varying the particles and carrier fluids used to create the STF. As the STF is essentially just a suspension with a high enough particle loading to cause a jamming effect when shear force is applied at a sufficient rate, an STF material could potentially be made of many different combinations of particles and carrier fluids. If for example a higher M.W. of PEG fluid is used it should result in a higher viscosity suspension. To date the STF composed of nanosilica and PEG is by far the most heavily studied, but there may exist a better performing or even cheaper combination of particles and carrier fluid to create a STF.

As previously mentioned, it is the author’s belief that only a dispersion of particles inside a fabric material is required for enhancing properties. Taking this idea there is great potential for different types of particles to be impregnated into fabric materials to enhance properties. This can also be done with relative ease and short time requirements. One must simply use a particle, for example cellulose nanocrystals, hallosyte nanoclay, diamond nanoparticles, and even micro sized particles of the same materials, and disperse them in a liquid to form a relatively stable colloidal suspension. Then the fabrics would be soaked in the suspension and fluid dried off.

The functionalization of particles may also be of interest when attempting to improve particle impregnated fabric properties. If one is able to optimally functionalize a chosen particle in order to make it most compatible with a given fabric material enhanced properties may be seen. A study on the surface energies of fabrics, particles, and various treatments to the particles could lead to interesting and beneficial results.

Different applications of STF could also be explored in future research. Currently STF materials of nanosilica/PEG are almost exclusively studied as candidate materials for body armor applications. Other applications for these materials must certainly exist. For example, it could possibly be used in protective sporting applications such as a football helmet to prevent injuries to athletes. An STF suspension could also be used to create a type of custom resistance device based on STF composition for medical rehabilitation purposes. There exist many potential applications of this material that have not yet been explored.

REFERENCES

[1] Boersma WH, Laven J, Stein HN. "Shear thickening (dilatency) in concentrated dispersions". AIChE J 190;36:321-32.

[2] Lee YS, Wagner NJ. "Dynamic properties of shear thickening colloidal suspensions". Rheol Acta 2003: 42: 199-208.

[3] Seshimo K. "Viscoelastic damper": 1988. US 4759428.

[4] Williams T et al. "Surgical and Medical Garments and Materials Incorporating Shear Thickening Fluids"; 2008. US 2007000440086.

[5] Gurgen S, Kushan MC, "High performance fabrics in body protective systems" Mater Sci Forum. 2016;880:132-5.

[6] Tarig A. Hassan et al. "Synthesis and characterization of shear thickening fluid (STF) impregnated fabric composites." Materials Science and Engineering A. 527. 2010. 2892-2899.

[7] Eric D. Wetzel et al. "The Effect of Rheological Parameters on the Ballistic Properties of Shear Thickening Fluid (STF)- Kevlar Composites." NUMIFORM. 2004. June 13.

[8] Brian A. Rosen et al. "Multi-Threat performance of Kaolin-based shear thickening fluid (STF)- treated fabrics" Proceedings of SAMPE 2007. Baltimore, MD. 3-7 June 2007.

[9] Dennis P. Kalman et al. "Effect of Particle Hardness on the Penetration behavior of fabrics intercalated with dry particles and concentrated particle-fluid suspensions." Applied Materials and Interfaces. Vol 1. No 11. 2602-2612. 2009.

[10] J. Gassan, A study of fibre and interface parameters affecting the fatigue behavior of natural fibre composites, Composites par A: applied science and manufactureing 33(3) (2002) 369-374.

[11] Wagner NJ. Brady JF. “Shear thickening in colloidal dispersions.” Phys Today. 200;62:27-32.

[12] Cheng X et al. “Imaging the microscopic structure of shear thinning and thickening colloidal suspensions.” Science. 2011;333:1276-9.

[13] Hoffman RI. “Discontinuous and dilatant viscosity behavior in concentrated suspensions. I. Observation of a flow instability.” J Rheol. 1972; 16:155-73.

[14] Hoffman R. “Discontinuous and dilatant viscosity behavior in concentrated suspensions. II. Theory and experimental tests.” J Colloid Interface Sci. 1974. 46. 491-506.

[15] Luan HM. “Rheology of extremely shear thickening polymer dispersions a) (passively viscosity switching fluids).” J Rheol 1991; 35: 999-1034.

[16] Luan HM. “Rheological and small angle neutron scattering investigation of shear induced particle structures of concentrated polymer dispersions submitted to plane Poiseuille and Couette flows.” J Rheol 1992; 36:743-87.

[17] Bossis G, Brady JF. “The rheology of Brownian suspensions.” J Chem Phys. 1989; 91:1866-74.

[18] Bender Jw, Wagner NJ. “Optical measurement of the contrubutions of colloidal forces to the rheology of concentrated suspensions.” J Colloid Interface Sci 1995; 172: 171-84.

[19] D’Haene P. et al. “Scattering dichroism measurements of flow-Induced structure of a shear thickening suspension.” J Colloid Interface Sci.

[20] Maranzano BJ, Wagner NJ. “Flow-small angle neutron scattering measurements of colloidal dispersion microstructure evolution through the shear thickening transition.” J Chem Phys 2002; 117: 10291-302.

[21] Seto R et al. “Discontinuous shear thickening of frictional hard-sphere suspensions.” Phys Rev Lett 2013;111:218301/1-5.

[22] Lin NYC. Et al. “Hydrodynamic and contact contributiions to continuous shear thickening in colloidal suspensions.” Phys Rev Lett 2015;115:228304/1-5.

[23] Pednekar S, Chun J, Morris JF. “Simulation of shear thickening in attractive colloidal suspensions.” Soft Matter. 2017. Volume 13. Pgs 1773-1779.

[24] Mari R. et al. “Shear thickening, frictionless and frictional rheologies in non-Brownian suspensions. Journal Rheology.” 2004. Vol 58. 1693-1724.

[25] Barnes HA. “Shear thickening (‘Dilatency’) in suspensions of nonaggregating solid particles dispersed in Newtonian liquids.” J Rheology. 1999. Vol 33. Pgs 329-366.

[26] Srivastava A. et al. “Improving the impact resistance of textile structures by using shear thickening fluids: a review.” Critical Review Solid State Material Science. 2012. Vol 37. Pgs 115-129.

[27] Beazley K. “Industrial aqueous suspensions.” In: Walters K. Editor. Rheometry. Industrial Applications Chichester. John Wiley & Sons Inc. 1980. Pgs 339-407.

[28] Yurim Park et al. Empirical study of the high velocity impact energy absorption characteristics of shear thickening fluid (STF) impregnated Kevlar fabric. International Journal of Impact Engineering. 72. (2014) 67-74

[29] Yue Xu et al. Stabbing resistance of body armour panels impregnated with shear thickening fluid. Composite Structures. 163. (2017) 465-473.

[30] Yurim Park et al. High Velocity Impact Characteristics of Shear Thickening Fluid Impregnated Kevlar Fabric. International Journal of Aeronautical & Space Science. 14(2), 2013, 140-145.

[31] Masoud Fahool and Ali Reza Sabet. Parametric study of energy absorption mechanism in Twaron fabric impregnated with a shear thickening fluid. International Journal of Impact Engineering. 90 (2016) 61-71.

[32] Xi-Qiang Liu et al. Temperature induced gelation transition of a fumed silica/PEG shear thickening fluid. RSC Adv. 2015, 5, 18367-18374.

[33] H. Mahfuz, F. Clements, and J. Stewart. Development of Stab Resistant Body Armor using Fumed SiO2 Nanoparticles Dispersed into Polyethylene Glycol (PEG) through Sonic Cavitation. NSTI-Nanotech. 2006. Vol 1, 358-361.

[34] Vijaya k. Rangari et al. Synthesis of Shear Thickening Fluid Using Sonochemical Method. NSTI-Nanotech. 2006. 637-640.

[35] Seyed Hossein Amiri Afeshenjani et al. Energy Absorption in a Shear-Thickening Fluid. Journal of Materials Engineering and Performance. Volume 23(12) December 2014. 4289-4297.

[36] A. Khodadadi et al. "Ballistic performance of Kevlar fabric impregnated with nanosilica/PEG shear thickening fluid. Composites Part B: Engineering." Volume 162, 1 April 2019. Pgs 643-652.

[37] Shu-Kai Yeh et al. Light shear thickening fluid (STF)/Kevlar composites with improved ballistic impact strength. Journal of Polymer Research (2019) 26. 155-167.

[38] Young S. Lee, E. D. Wetzel, and N. J. Wagner. The ballistic impact characteristics of Kevlar woven fabrics impregnated with a colloidal shear thickening fluid. Journal of Materials Science. 38. (2003) 2825-2833.

[39] Abhijit Majumdar, Bhupendra Singh Butola, and Ankita Srivastava. An anlysis of deformation and energy absorption modes of shear thickening fluid treated Kevlar fabrics as soft body armour materials. Materials and Design. 51. (2013) 148-153.

[40] R. G. Egres Jr. et al. Stab Resistance of Shear Thickening Fluid (STF)-Kevlar Composites for Body Armor Applications. Transformational Science and Technology for the Current and Future Force. 2006. 264-271.

[41] Harish Rao et al. Stab Characterization of Hybrid Ballistic Fabrics. Proceedings of the SEM Annual Conference. June 1-4. 2009. Transformational Science and Technology for the Current and Future Force. 2006. 264-271.

[42] Tae Jin Kang, Kyung Hwa Hong, and Mi Ran Yoo. Preparation and Properties of Fumed Silica/Kevlar Composite Fabrics for Application of Stab Resistant Material. Fibers and Polymers. Vol. 11. No. 5. 2010. 719-724.

[43] Xinya Feng et al. Effects of different silica particles on quasi-static stab resistant properties of fabrics impregnated with shear thickening fluids. Materials & Design. 64. December 2014. 456-461.

[44] Jianbin Qin et al. Dynamic/quasi-static stab-resistance and mechanical properties of soft body armour composites constructed from Kevlar fabrics and shear thickening fluids. RSC Advances. 7. 2017. 39803-39813.

[45] Edison E. Haro, Jerzy A. Szpunar, and Akindele G. Odeshi. Ballistic impact response of laminated hybrid materials made of 5086-H32 aluminum alloy, epoxy, and Kevlar fabrics impregnated with shear thickening fluid. Composites: Part A (2016) 54-65.