Development of non-Newtonian Composite Material for Bullet Proof Armor

Dilshan N. Kavinda
Department of Textile and Apparel Engineering
University of Moratuwa
Sri Lanka
kavindand.19@uom.lk

Harindu H. Gamage
Department of Textile and Apparel Engineering
University of Moratuwa
Sri Lanka
gamagehh.19@uom.lk

Sandun E.A.K. Fernando
Department of Textile and Apparel Engineering
University of Moratuwa
Sri Lanka
sandunf@uom.lk

Nilhan S. Niles
Department of Textile and Apparel Engineering
University of Moratuwa
Sri Lanka
niles@uom.lk

Gayani K. Nandasiri
Department of Textile and Apparel Engineering
University of Moratuwa
Sri Lanka
gayanin@uom.lk

Keywords – non-newtonian composite, shear stiffening gel, hydroxy-terminated polydimethylsiloxane, projectile

I. INTRODUCTION

The goal of this project is to create a novel, light-weight non-Newtonian composite material with improved resistance, especially for use in bulletproof armor. The main objective is to research and include advanced non-Newtonian materials with higher shear-thickening capabilities, which offer further protection against impacts with high velocities, as bullets. Hydroxy-terminated polydimethylsiloxane (PDMS-OH) is one of the main materials that used to develop the composite material. it will be analyzed together with other materials to produce an ideal composite structure. Creating a material that is appropriate for current ballistic applications in the military as well as civilian contexts while maintaining flexibility and comfort is the ultimate goal.

II. LITERATURE REVIEW

The non-Newtonian composite significantly improves bulletproof armor by overcoming issues with weight and movement related to conventional body armor. The new material has the potential to improve the comfort and efficiency of protective clothing used by military soldiers in high-risk situations by enhancing impact resistance and energy absorption. The foundation for future developments in ballistic-resistant materials is established by this study.

The shear stiffening non-Newtonian material exhibits higher viscosity as shear stress increases. This type of non-Newtonian material was developed in this study to achieve the project goal. There are two types of shear stiffening materials which are Shear stiffening gel (SSG) and Shear thickening fluid (STF). STF exhibits a few orders of magnitude rise in viscosity with increasing shear rate. When apply additional pressure to the fluid, it thickens and becomes more solidified. SSG is a viscous-elastic substance that increases its elastic modules and yield stress when subjected to external forces. As the strain rate increases, the condition of this STG changes from liquid to rubbery and ultimately to glassy. There are currently many developed solutions by using these materials. One study was in order to create a composite made of Kevlar, STF, and STG, the Kevlar yarns were filled with STF and coated with SSG [1]. Another one was development of ultra-high molecular weight polyethylene (UHMWPE) ballistic panel and shear stiffening gel (SSG), which has great flexibility and formability, were combined to create a UHMWPE/SSG composite body armor [2]. Some shear thickening fluid (STF) reinforced Kevlar fabric soft armor panel design techniques were created by dispersing silica particles with diameters of 500 nm and 100 nm, respectively, in polyethylene glycol (PEG) 200 [3]. Also, another development is forming polyurea/Kevlar composite fabric with STF into a honeycomb paper panel to reduce ballistic impact [4]. Another development was “Oobleck” is a mixture of corn starch and water and that was developed by using water and corn starch use as a layer with Dyneema fabric to design bullet proof clothing [5]. So those are some of the current available solutions.

The invention focuses on creating a shear stiffening gel (SSG), that uses a specific blend of ethanol, silicon oil, and boric acid to give the required non-Newtonian qualities.

With the impact load, these cross-links behaviors of B-O will change, and it can be categorized into four states [6].

Gel state (Viscous – liquid state) – When armor is not subjected to the bullet impact, the breaking energy of B-O crosslinks is higher than the bond forming energy, so they are in broken state which leads to un entanglement of molecular chains and shows gel behavior.

Glassy state – when armor subjected to bullet impact, the impact energy become high, and the breaking energy of B-O bonds become lower than forming energy and with that B-O bonds start to form which results in the entanglement of the molecular chains. With that, viscosity become increased, and gel become to a rigid state.

Rubber state – with the reduction of ballistic impact, the B-O chains start to break, and molecular chains will start to dis entangle and gradually convert to a rubbery state.

Gel state – After the rubbery state, now SSG has much low shear rate and most of the B-O crosslinks broken and chains were untangled. So again, converts to the initial gel state.

According to research, the optimal ratio of ethanol, silicon oil, and boric acid is 3:15:1. Rheological testing has confirmed the efficiency of this ratio in real-world ballistic settings, which increases energy absorption while retaining structural integrity.

III. MATERIALS AND METHODS

The project was carried out in four stages, beginning with the creation of a composite material that contained necessary characteristics to withstand ballistic impacts, such as viscoelasticity, energy absorption, and storage modulus. Shear stiffening gel (SSG) composite material was layered into a Dyneema layered structure and, for additional protection, coated with a waterproof knitted fabric. Various ratios of boric acid, silicon oil, and ethanol were used in ballistic impact testing (from 1.5:15:1 to 3.5:15:1). The best ratio, 3.0:15:1, showed a significant reduction in projectile depth along with better energy dissipation. Reducing penetration depth and enhancing the armor's overall protective properties were achieved by sandwiching the SSG within two layers of Dyneema.

The material production stage involves heating the boric acid until it reaches 160 degrees and takes around two hours. When boric acid is heated (H_3BO_3), it decomposes into meta boric acid (HBO_2) and to a water molecule around 100^0C to 145^0C.

$$H_3BO_3 \rightarrow HBO_2 + H_2O \tag{1}$$

Then continue heating up to 160^0C and meta boric acid dehydrated into pyroboric acid ($H_2B_4O_7$) and water.

$$4\,HBO_2 \rightarrow H_2B_4O_7 + H_2O \tag{2}$$

The materials are mixed with ratio obtained from the previous research studies. According to these the pyroboric and PDMS-OH are mixed with ratio of 2:15 [7]. The ratio of pyroboric acid to PDMS-OH causes to the change of the shear thickening property of the material [8].

The reaction between these two materials is below here.

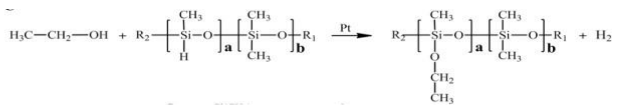

Fig. 1: PDMS Ethanol Reaction

The materials manage to be mixed despite this difficulty of boric acid, and the mixture is then heated further until the oven temperature is raised to 240 degrees.

In this process the PDMS-OH reacts with pyroboric acid and as a result the Si-O bonds in the PDMS-OH break, and the boron is simultaneously introducing into the chains to form polyborodimethylsiloxane (PBDMS). Under normal conditions B atom last orbital has electrons shortage and O atom has electron surplus and therefore they attracted and create weak B-O bonds with each other, and the specialty of this weak bonds is they can be continuously broken and formed because the bond energy is low. Mainly there can be 3 types of B-O bond structures which are shown in following figure [9].

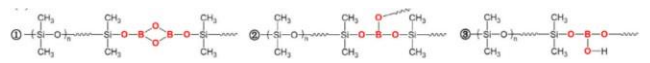

Fig. 2: Boric acid bond formation

After this process, the raw SSG is formed. The property of this shear thickening gel can be identified by using the rheological testing and using these results the ratio can be analyzed. And this will change the energy dissipation values of the material as well [10]. So, by changing the ratio, the best properties can be identified to achieve the final product performance.

By changing 5 parameters the material development is carried out.

TABLE I. RATIO AND TEMPERATURES OF EACH SAMPLE

Ex No	Boric acid (g)/Temp	Silicon Oil (g)	Ethanol (ml)	Ratio/Temp. (BA:SO: Eth)
1	18 160^0C	180	12	1.5:15:1 240^0C
2	24 160^0C	180	12	2.0:15:1 240^0C
3	30 160^0C	180	12	2.5:15:1 240^0C
4	36 160^0C	180	12	3.0:15:1 240^0C
5	40 160^0C	180	12	3.5:15:1 240^0C

The experiment also highlights how significant it is to have an adequate cover textile for the SSG that is made to stop leaks and continue operating in difficult conditions. The water-repellent properties of low melt nylon yarn were chosen to add to the armor's durability. The thorough attention to detail needed to make dependable protective gear is highlighted by the method of production, which is intricate and involves layer separation and heat pressing.

In order to assess the efficiency of the armor, the final performance of these gels was evaluated using a projectile setup that would shoot bullets at high speeds. The projectile is consisting with two individual springs and the spring constant (k) for each of the two individual springs used in the projectile configuration was 500 N/m. Potential energy was retained in the system when the springs were compressed. The 7g bullet used during the testing. The system was designed such that the bullet would shoot towards the gel sample when the springs were released.

1. The bullet was held at the release point while the springs compressed and fixed in the same point.
2. The bullet was shot in the direction of the gel after the springs were released.
3. The impact of the bullet was noted and its effect on the gel was observed. And the depth of the bullet effect is calculated.

IV. RESULTS AND DISCUSSION

In ballistic impact testing, various ratios of boric acid, silicon oil, and ethanol were evaluated to optimize material performance. Ratios ranged from 1.5:15:1 to 3.5:15:1, but the 1.5:15:1 ratio was excluded due to its tendency to melt within hours, while the 3.5:15:1 ratio was discarded because it lost its viscoelastic properties and became too stiff. Consequently, the final testing phase focused on three other ratios to refine the material's ballistic performance.

The resistance and performance of the three distinct types of gels were evaluated using the impact energy of 61.25 Joules and using the bullet that has speed of 132.29 m/s. To identify the effect of the gel, Dyneema fabric sample was setup and tested without using gel in the projectile setup. To get the best non-Newtonian gel composition for optimum bulletproof effectiveness, the findings were analyzed. We were able to see clear variations in the gel's capacity to absorb and disperse impact energy by adjusting the boric acid ratio, that provides main information for the production of bulletproof armor.

TABLE II. BULLET IMPACT FOR THE DIFFERENT SAMPLES

Sample	Depth 1 (mm)	Depth 2 (mm)	Depth 3 (mm)	Mean Depth (mm)	Std Dev (mm)
Without gel, only fabric sample	4.8	4.6	5.1	4.83	0.21
2.0 w/w boric acid	2.4	2.9	2.8	2.70	0.22
2.5 w/w boric acid	2.3	2.5	2.1	2.30	0.16
3.0 w/w boric acid	1.1	0.8	0.9	0.93	0.12

The findings show that the depth of the hole made by the bullet impact is considerably reduced when the non-Newtonian gel is added to the fabric. The gel becomes more efficient at absorbing and dispersing impact energy as the boric acid ratio rises to 3.0 level. With the lowest depth of hole and the highest level of protection, the gel with 3.0 w/w boric acid ratio performed the best.

V. CONCLUSION

In conclusion, the creation of this non-Newtonian composite material for bulletproof armor represents a significant leap forward in personal protective equipment. By addressing the challenges of conventional armor, such as weight and flexibility, this development promises a more comfortable and reliable defense against ballistic threats, enhancing safety for those in high-risk environments.

To provide the required non-Newtonian qualities, pyroboric acid, silicon oil, and ethanol must be precisely mixed in certain ratios throughout the SSG's manufacturing process. Researchers have determined the ideal composition 3:15:1 of ethanol, silicon oil, and boric acid, respectively that maximizes energy absorption while preserving structural integrity by careful modifying of these ratios and intensive rheological testing. This testing is essential to confirming the material's efficacy in actual ballistic situations, where its capacity to disperse kinetic energy efficiently may save lives.

The study also emphasizes how crucial it is to create a strong cover cloth that will safely enclose the SSG and stop leaks or performance deterioration. Because low melt nylon yarn is water-repellent, it was selected for the cover fabric. This important barrier helps to maintain the SSG's integrity and functionality under harsh circumstances. The thorough attention to detail needed to make dependable protective gear is highlighted by the method of production, which is intricate and involves layer separation and heat pressing. Further suggestions for potential enhancements include the use of Dyneema and polypropylene sheets to improve the flexibility of the SSG and the cover fabric. The most important methods for assessing the material's performance under varied circumstances and assisting in the identification of the ideal thickness and composition for maximum energy absorption are impact testing and drop hammer testing.

Looking ahead, rheological testing should be the main emphasis of future research to better understand the properties of the composite material. Through the examination of variations in shear frequency, storage modulus, loss modulus, and loss factor, scientists may determine the rate of phase transition and assess the composite material's stiffness characteristics. The preparation of the most accurate and appropriate material for the finished product will be guided by this data. However, the testing showed that the bullet force utilized was insufficient to identify the minimal number of layers of Dyneema fabric required. This points out a topic that needs further investigation to improve the armor's design.

In summary, the development of a non-Newtonian composite material for bulletproof armor has great potential to improve the protective gear that law enforcement officials and people in high-risk scenarios utilize. By addressing the drawbacks of conventional body armor, such as weight and mobility restrictions, the suggested system seeks to provide a more comfortable and reliable defense against ballistic threats.

REFERENCES

[1] Q. He, S. Cao, Y. Wang, S. Xuan, P. Wang, and X. Gong, "Impact resistance of shear thickening fluid/Kevlar composite treated with shear-stiffening gel," Compos. Part Appl. Sci. Manuf., vol. 106, pp. 82–90, Mar. 2018, doi: 10.1016/j.compositesa.2017.12.019.

[2] C. Zhao, X. Gong, S. Wang, W. Jiang, and S. Xuan, "Shear Stiffening Gels for Intelligent Anti-impact Applications," Cell Rep. Phys. Sci., vol. 1, no. 12, p. 100266, Dec. 2020, doi: 10.1016/j.xcrp.2020.100266.

[3] M. Bajya, A. Majumdar, B. S. Butola, S. K. Verma, and D. Bhattacharjee, "Design strategy for optimising weight and ballistic performance of soft body armour reinforced with shear thickening fluid," *Compos. Part B Eng.*, vol. 183, p. 107721, Feb. 2020, doi: 10.1016/j.compositesb.2019.107721.

[4] "Polymers | Free Full-Text | Preparation and Ballistic Performance of a Multi-Layer Armor System Composed of Kevlar/Polyurea Composites and Shear Thickening Fluid (STF)-Filled Paper Honeycomb Panels." Accessed: Dec. 03, 2023. [Online]. Available: https://www.mdpi.com/2073-4360/13/18/3080

[5] S. E. A. K. Fernando, "Design of a Bullet-proof Vest using Shear Thickening Fluid," *Int. J. Adv. Sci. Tech. Res.*, vol. 01, pp. 434–444, Feb. 2015.

[6] F. Tang *et al.*, "Protective performance and dynamic behavior of composite body armor with shear stiffening gel as buffer material under ballistic impact," *Compos. Sci. Technol.*, vol. 218, p. 109190, Feb. 2022, doi: 10.1016/j.compscitech.2021.109190.

[7] Q. He, S. Cao, Y. Wang, S. Xuan, P. Wang, and X. Gong, "Impact resistance of shear thickening fluid/Kevlar composite treated with shear-stiffening gel," *Compos. Part Appl. Sci. Manuf.*, vol. 106, pp. 82–90, Mar. 2018, doi: 10.1016/j.compositesa.2017.12.019.

[8] B. Liu, C. Du, S. Jiang, G. Zhou, and J. Sun, "The influence of the curing process on the shear thickening performance of RMG and property optimization," *RSC Adv.*, vol. 10, pp. 12197–12205, Mar. 2020, doi: 10.1039/D0RA00319K.

[9] Y. Tan, Y. Ma, and Y. Li, "Shear thickening fabric composites for impact protection: a review," *Text. Res. J.*, vol. 93, no. 5–6, pp. 1419–1444, Mar. 2023, doi: 10.1177/00405175221126746.

[10] B. Liu *et al.*, "Study on the shear thickening mechanism of multifunctional shear thickening gel and its energy dissipation under impact load," *Polymer*, vol. 247, p. 124800, Apr. 2022, doi: 10.1016/j.polymer.2022.124800.