VII Međunarodna naučna konferencija
„Savremeni trendovi i inovacije u tekstilnoj industriji"
19-20. septembar 2024. Beograd, Srbija

IMPACT PROTECTION IN BODY ARMOUR USING SHEAR THICKENING FABRIC

Review scientific paper
DOI: 10.5937/CT_ITI24026D

Subrata Das[1], Sharmila Soundararajan[2]

[1]Bannari Amman Institute of Technology, Sathyamangalam, Erode, India
subratactl@gmail.com, ORCID 0000-0002-7118-5490
[2]Bannari Amman Institute of Technology, Sathyamangalam, Erode, India
sharmilasoundar3@gmail.com

ABSTRACT: *A brief discussion of body armour is provided in the current work, with a focus on the use of shear thickening fluid and the technological issues that prevent its widespread adoption. This paper first discusses the many categories of body armour. Furthermore, several methods for improvising energy absorption for body armour have been offered, along with assessment requirements for bullet-resistant jackets. The review covers the components of sheer thickening fluid as well as how it is incorporated into the fabric. Shear thickening fluid (STF) application amplifies the impact. The Kevlar fabric performs better in terms of impact resistance when shear thickening fluid (STF) is applied. Furthermore, several new STF-based applications are presented to illustrate the challenges that still need to be addressed and provide some more deterministic directions for future research.*

Keywords: *Sheer thickening fluid, energy absorption, thickness, body armour, impact resistance.*

TKANINA ZA ZAŠTITA OD UDARA U PANCIRIMA

APSTRAKT: *U ovom radu je dat kratka rasprava o pancirima, sa fokusom na upotrebu tečnosti za zgušnjavanje smicanjem i tehnološkim problemima koji sprečavaju njegovo široko usvajanje. Ovaj rad najpre govori o mnogim kategorijama pancira. Štaviše, ponuđeno je nekoliko metoda za improvizaciju apsorpcije energije za pancire, zajedno sa zahtevima za procenu jakni otpornih na metke. Pregled pokriva komponente čiste tečnosti za zgušnjavanje, kao i način na koji je ugrađen u tkaninu. Primena tečnosti za zgušnjavanje smicanja (STF) pojačava udar. Kevlar tkanina ima bolje performanse u pogledu otpornosti na udar kada se primeni tečnost za zgušnjavanje smicanja (STF). Štaviše, predstavljeno je nekoliko novih aplikacija zasnovanih na STF-u kako bi se ilustrovale izazovi kojima se tek treba pozabaviti i dali neki deterministički pravci za buduća istraživanja.*

Ključne reči: *Prozirna tečnost za zgušnjavanje, apsorpcija energije, debljina, pancir, otpornost na udar.*

1. INTRODUCTION

Body armour is a type of protective gear or clothing that is intended to ward against physical assaults from projectile bullets fired from contemporary weapons as well as sharp items [1]. The evolution of armour materials over time has coincided with advancements in weaponry threats. Throughout history, there has been a penetrating/defeating race between body armour and weaponry. In order to defend service personnel personally [2] from violence and the hazards of war, body armour is essential equipment. Although there is no such thing as completely bulletproof armour, ballistic-resistant body armour is capable of withstanding a variety of pistol and rifle ammunition. It is ideal to have lighter weight protective gear that offers adequate protection [3]. The continual advancements in weaponry and ammunition technologies have created a demand for more efficient body armour. Figure 1 & 2 illustrates several features of the body armour design and armour panel components respectively. The primary obstacle to producing successful bulletproof armour is creating lightweight vests that offer the best possible protection and optimum comfort.

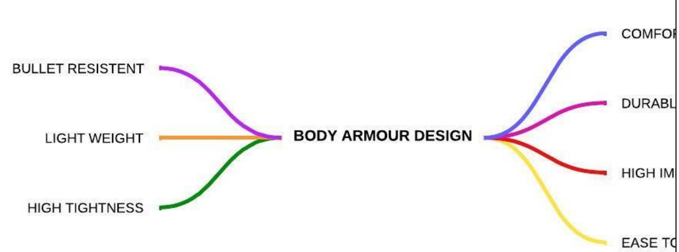

Figure 1: Body armour design

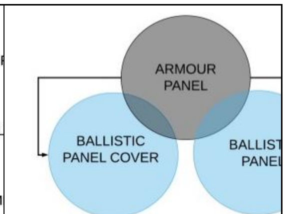

Figure 2: Components of body armour panel

Body armour can be categorized according to the risks posed by projectiles, sharp objects [4], and bullets.

1. Bullet resistant
2. Splinter resistant and
3. Stab resistant [5].

Bullet resistant body armours can be further classified into two categories [6] such as

1. Hard body armour and
2. Soft body armour.

Ceramic plate composite or metal is used to make hard body armour. Usually, aluminium oxide, silicon carbide, or boron carbide is used to make ceramic tiles. The decision between different kinds of ceramic materials is influenced by a number of factors, among the most significant of which are cost, weight limitations, and threat level [7]. The primary component of soft body armour is layers of high-performance fiber-based fabric. The primary use of soft body armours by soldiers on the battlefield either for small-arms ammunition [8] or is in conjunction with hard body armour to provide sufficient ZZ ballistic protection. Low-modulus binding materials, such as elastomers or soft polymers, are employed to sew or glue (Figure 4) which has many stacked layers of high-strength woven fibre textiles to create soft armour.This armour's fundamental function is to shield against ballistic strikes without impairing wearer's ability to move [9]. Law enforcement officers, who are more likely to encounter lower levels of ballistic threat, also wear soft body armour alone.As a result, there are three main categories of armour materials that need to be reviewed, understood, and described: Formable, technical textiles, fiber-reinforced polymeric laminates, and hard, brittle, strike-face materials such as high-hardness steels and ceramics are the three categories. These three components are displayed in Figure 3 along with consistent camouflage material [10].

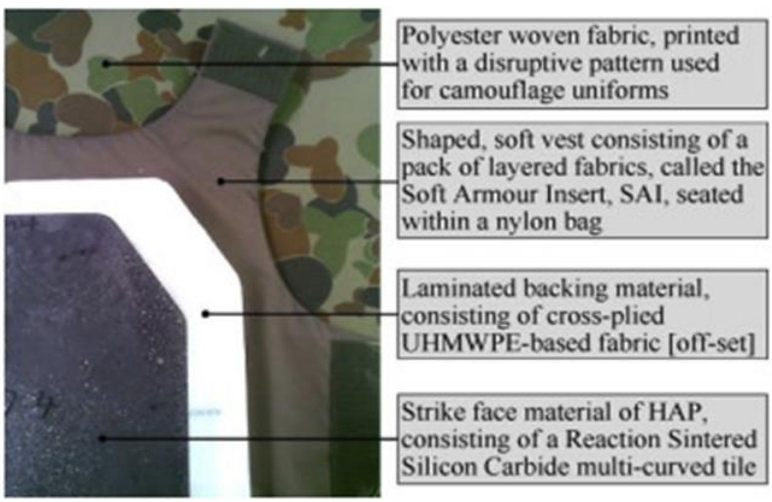

Figure 3: Categories of armour materials [10]

2. EVOLUTION OF BODY ARMOUR

Depending on what kind and speed of the attack, several manufacturing techniques were used to create effective body armour. The various forms and methods of body armour panel production are depicted in Figure 4. There are two types of personal body armour: soft armour and hard armour. Stitched and stiff body armour is other classifications for soft armour [11]. Table 1 displays the progress of soft body armour. Figure 5 reflects the time line diagram illustrating the emergence of high altitude platform system (HAPs) and, specifically, the impact of novel compounds and threat level on the final product's areal density.

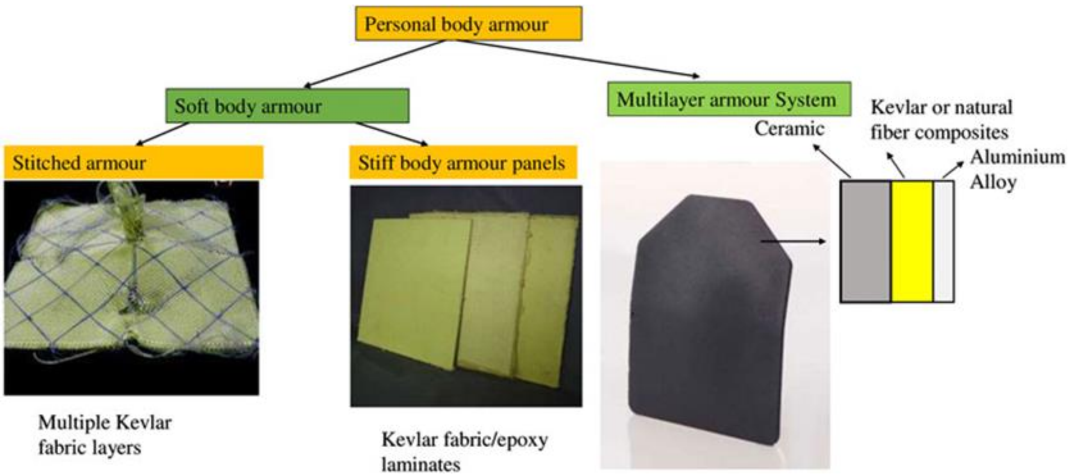

Figure 4: Classification of body armour system [12]

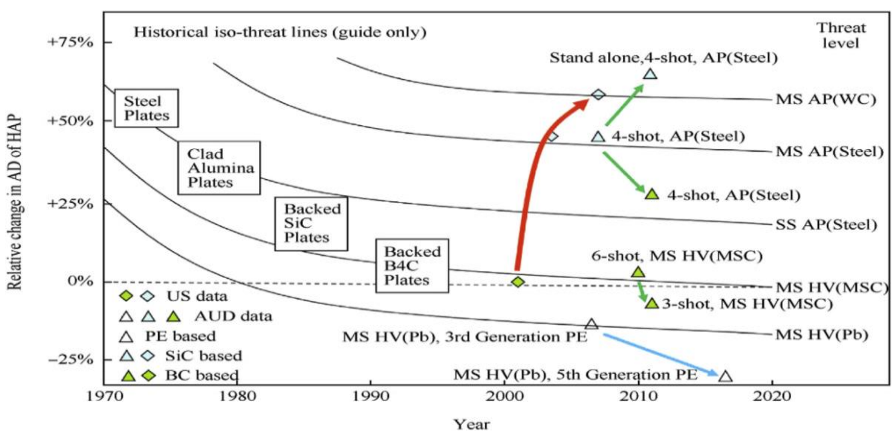

Figure 5: Evolution of Hard Body armour [10]

Table 1: Evolution of soft body armour [13]

Timeline	**Material**	**Threat**	**Fabric structure**
World war I	Silk	Low velocity Projectiles ~120 m/s to 180 m/s	Woven fabric
World War II	Nylon Flak	Munition fragments failed against pistol and rifle rounds	Woven fabric

Post World War II 1960 to 2020	Para aramid, UHMWPE**, Zylon, M5, PBO	NIJ* level IIIA, III and III+(in conjunction with HAP)	Woven fabric and unidirectional fabric
Future	Shear Thickening fluid coated fabric, Nano particles+STF coated fabrics	NIJ level IIIA, III and III+(in conjunction with HAP) in less weight	Impregnated woven fabric 3d woven fabric STF pads

NIJ*: National Institute of Justice (NIJ)
UHMWPE**: Ultra-High Molecular Weight Polyethylene

3. COMPOSITES

Body armour is divided into types called disruptors and absorbers. Bullet Resistant Vests are classified as absorbers because they have a trauma cushion and many layers of ballistic materials. In that order, disruptors and absorbers are bullet resistant jackets with ceramic plates and high-performance fabric panels [14]. Strong, durable materials like ceramics disrupt, whereas polymer composites absorb. Composites are described here as the joining of hard ceramic and high performance (HP) fabric layers compacted into panels. Ceramic plates come in three different shapes: flat, curved, and monolithic [15]. For multiple performances, tiles are recommended. Epoxy or polyurethane-based bonding solutions are recommended for joining ceramic plates and HP panels together.
Types of ceramics used in body armours are alumina, boron carbide, silicon carbide, and titanium diboride. Ceramics are the preferred strike face materials as it is kept in front of body armours to distort the shape of bullets by the hardness of the ceramics. Nowadays although alumina is not as popular as it once was because of its high density, it is still used in vehicle armouring. In body armour, silicon carbide and boron carbide are utilised; while silicon carbide performs better overall, boron carbide is more expensive and lighter[16].Their properties of ceramics are given in Table 2.

Table 2: Properties of ceramics

Class of material	**Density ($kg.m^{-3}$)**	**Hardness (GPa)**	**Elastic modulus(GPa)**	**Flexural strength (MPa)**	**Fracture toughness ($MPa.m^{-1/2}$)**
Alumina	3920	14.1	370	375	4-5
Silicon carbide	3200	23.5	460	570	7
Boron carbide	2500	25.5	460	410	4

The selection of textile materials for soft body armour is accessible. The two fibres that are favored for body armour are Ultra High Molecular Weight Polyethelene (UHMWPE) and

Para Aramid. Para aramid is produced by Teijin (Japan) under the brand name Twaron and Dupont (US) under the Kevlar trademark. DSM (Netherlands) produces UHMWPE under the Dyneema brand. Honeywell (US) produces it under the Spectra brand [17]. Manufacturers provide a range of grades with varying GSM, width, and roll length that are appropriate for varying danger levels. General characteristics of both fabrics are listed in the table 3.

Table 3: Para aramid and polyethelene fabric characteristics

Fibre type	**Density kg/m3**	**Tensile strength MPa**	**Specific strength m2/s2**	**Elastic modulus GPa**	**Failure strain %**
Para aramid (low modulus)	1440	2900	$2.01*10^6$	60	3.6
Para aramid (high modulus)	1450	2900	$2.00*10^6$	120	1.9
Polyethelene (low modulus)	970	2700	$2.78*10^6$	89	3.5
Polyethelene (high modulus)	970	3200	$2.30*10^6$	79	3.7

Fabric structures preferred for body armours are

1. Woven fabrics
2. Unidirectional laminated (UD).

There are three different configurations of woven fabrics: 1 ×1 plain, 2 ×1 twill, and 2 ×2 matt. Plain weave is often favoured because to its increased cover factor [18]. Numerous crossing points in the structure of woven fabric limit the yarn's transverse deflection during projectile contact, which is a drawback. A lower weave density may enable the projectile to pass through, whereas a greater weave density will restrict traverse deflection more. This is woven ballistic material's main disadvantage [19]. Unidirectional (UD) laminated technology was created as a solution to this issue.

Every fibre layer of a cross plied UD material, referred to as the lamina, is orientated in opposition to the layer before it. The final laminated fabric is created by bonding the fibre layers together using a matrix of thermoplastic or thermoset resin. Depending on the needs, ballistic UD materials typically comprise of two, four, six, etc. plies with an orientation of either 0/90 or 0/90/45 degrees. In addition to maximising traverse deflection, this orientation lowers the likelihood of projectile penetration due to each ply's increased fibre density. In general, armour solutions made using UD textiles weigh less than those made with traditional woven material systems [20]. Currently, this method is used by the majority of manufacturers to create lightweight composite materials for ballistic applications.

Bullet resistant Jackets evaluation standards [21] are given below:

International Standards:

1. USA National Institute of Justice (NIJ): NIJ 0101.06,
2. NATO STANAG 4569,
3. Home Office Scientific Development Branch (UK),
4. European Ballistic Standards (EU),

5. GOST Ballistic Standards (Russia),
6. German SCHUTZKLASSE standard,
7. International Ballistic Standards,

Indian Standards:

1. MHA GSQR
2. BIS IS 17051:2018
3.

Figure 6 & 7 depict the different threat levels in NIJ and BIS respectively.

Armor Type	Weapom Type	Test Round	Test Bullet	Bullet Mass	Conditioned ArmorTest Velocity*	New ArmorTest Velocity*	HitsPer Panel at 0 Angle	Maximum BFS Depth	Hits Per Panel at 30 or 45Angle†	Shots Per Panel	Panel Size	Panel Condition	Panels Required	Shots Required	Total Shots Required
IIA		1	9mm FMJ RN	8.0g (124gr)	355m/s (1165ft/s)	373m/s (1225ft/s)	4	44mm (1.73in)	2	6	Large Small	New Conditioned	4 2 4 2	24 12 24 12	144
		2	.40 S&W FMJ	11.7g (180gr)	325m/s (1065ft/s)	352m/s (1155ft/s)	4	44mm (1.73in)	2	6	Large Small	New Conditioned	4 2 4 2	24 12 24 12	
II		1	9mm FMJ RN	8.0g (124gr)	379m/s (1245ft/s)	398m/s (1305ft/s)	4	44mm (1.73in)	2	6	Large Small	New Conditioned	4 2 4 2	24 12 24 12	144
		2	.357 Magnum JSP	10.2g (158gr)	408m/s (1340ft/s)	436m/s (1430ft/s)	4	44mm (1.73in)	2	6	Large Small	New Conditioned	4 2 4 2	24 12 24 12	
IIIA		1	.357 SIG FMJ FN	8.1g (125gr)	430m/s (1410ft/s)	448m/s (1470ft/s)	4	44mm (1.73in)	2	6	Large Small	New Conditioned	4 2 4 2	24 12 24 12	144
		2	.44 Magnum SJHP	15.6g (240gr)	408m/s (1340ft/s)	436m/s (1430ft/s)	4	44mm (1.73in)	2	6	Large Small	New Conditioned	4 2 4 2	24 12 24 12	
III		1	7.62mm NATO FMJ	9.6g (147gr)	847m/s (2780ft/s)	-	6	44mm (1.73in)	0	6	All	Conditioned	4	24	24
IV		1	.30Caliber M2 AP	10.8g (166gr)	878m/s (2880ft/s)	-	1 to 6	44mm (1.73in)	0	1to6	All	Conditioned	4 to 24	24	24

Figure 6: Details of Threat levels in NIJ standard

Threat levels

Threat Level	Ammunition	Impact Velocity, m/s	Bullet weight, g	Remarks
1	9 × 19 mm, SM, MP-5, Carbine)	430 ± 15	7.4 - 8.2	For all flexible panels
2	7.62 × 39 mm, AK 47, MSC	710 ± 15	7.45 - 8.05	—
3	7.62 × 51 mm, NATO ball, SLR/BAR	840 ± 15	9.4 - 9.6	In addition, shall be compliance with threat level 2
4	5.56 × 45 mm, INSAS	890 ± 15	3.5 - 4.0	In addition, shall be compliance with threat level 3
5	7.62 × 39 mm, AK 47, HSC	700 ± 15	7.45 - 8.05	
6	7.62 × 54R, API	830 ± 15	10.3 -10.5	

Figure 7: Details of Threat levels in BIS IS 17051:2018

3. APPROACHES FOR IMPROVING ENERGY ABSORPTION OF BODY ARMOURS

The development of armour necessitates striking a compromise between protective requirements and requirements for low weight, comfort, and flexibility. A material that can deliver the same ballistic performance as current body armour materials while being noticeably more compact and flexible is required to increase comfort and flexibility of the armour [22]. The several layers of ballistic materials used in current body armour make it stiff and hefty. In order to distribute projectile energy over the body armour in a perpendicular direction, energy absorption is crucial. Some of the methods being researched to increase textiles' ability to absorb energy are listed below[23].

1. Application of polymer coating to cloth to increase friction
2. Shear thickening fluid (STF) use on textiles
3. Fabric surface modification by the creation of metal oxide nanorods and
4. Application of STF and 3D woven textiles

4. SHEAR THICKENING FLUIDS

Shear thickening fluids, also known as non-Newtonian fluids, are characterised by concentrated colloidal dispersions that display a dramatic increase in viscosity above a critical shear rate [24]. This transformation of a liquid dispersion into a substance with solid-like qualities is a common indicator of shear thickening behaviour. The behaviour of shear thickening is reversible with strain rates associated with the wearer's typical motion, shear-thickening fluid (STF) is intended to have a low viscosity but to stiffen rapidly under the high strain rates associated with a ballistic impact [25].When a projectile strikes cloth coated with STF, the shear rate suddenly increases, causing the fluid to instantly become more viscous and harden. This strengthens the armour and accelerates its absorption of energy. A bullet event will finish its impact in about 100 milliseconds. It should be planned such that the shear thickening is finished in the least amount of time.
Mechanisms for improved energy absorption in STF treated fabric [26] are Greater friction (yarn pull out energy) between yarns; improved coupling and load transmission between yarns; and energy dissipation as a result of shear thickening behavior

5. MATERIALS USED IN STF

The two phases of STF are the dispersed phase and the dispersion medium, often known as the carrier [27]. The dispersion medium of STF can be water, silicon oils, polyethylene glycol (PEG), polypropylene glycol (PPG), or 1-butyl-3-methylimidazolium tetrafluoroborate. The dispersed phase of STF is composed of nano-scale or sub-micron particles of silica, calcium carbonate, or polymethylmethacrylate (PMMA), among other materials. 50% of the phase volume is maintained for shear thickening [28]. Before being applied to the Kevlar textiles, these dispersions are diluted with ethanol to increase the wettability of the Kevlar fabrics with STFs. Dilution improves STF penetration into the

Kevlar fabric structure by lowering both the viscosity and surface tension of the material [29]. The ratio of STF to ethanol solvent can range from 3:1 to 5:1, dependent on the STF quantity. Figure 8 depicts the procedures involved in process of STF incorporation to fabric. The table 4 shows that the target's ability to create ballistic resistance is greatly enhanced by the STF's presence within it.

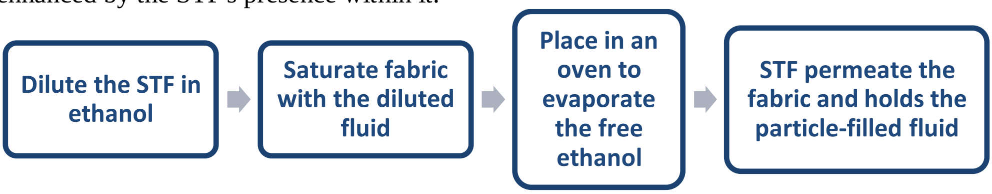

Figure 8: Process of STF incorporation to fabric

Table 4: Ballistic performance of targets with 4 layers of KEVLAR and different volumes of impregnated STF.

S.No.	Description	Sample Weight(g)	Impact Velocity(m/s)	Penetration Depth (cm)
1.	4 layers of KEVLAR	1.9	244	2.12
2.	2 ml STF impregnated in 4 layers of KEVLAR	4.8	243	1.23
3.	4 ml STF impregnated in 4 layers of KEVLAR	7.9	244	0.886
4.	8ml STF impregnated in 4 layers of KEVLAR	13.9	253	0.673

5. EXAMINATIONS OF STF-TREATED TEXTILES

1. Test for yarn pull-out

In 2019, Baiet all performed a quasi-static test called yarn pull-out, which simulates yarn-to-yarn friction in a woven fabric is used to carry out. The Instron tensile tester's fixed jaw gripped one end of the cloth strip. Subsequently, the moveable jaw extracted a single free yarn at a consistent speed from the cloth, since it was not caught by the fixed jaw. The maximum force necessary to extract the yarn from the cloth is noted and the strength is calculated [30].

2. Test of dynamic impact

In accordance with ASTM D3763, Majumdar et all performed dynamic impact tests with a drop-weight testing apparatus (CEAST). Ballistic tests were conducted in aero ballistic range facility [31]. The impact velocity was 8 m/s. Pneumatic pressure was used to clamp the fabric samples that were placed on the circular jaws with an inner diameter of 7.6 cm. The impact features a hemispherical head and measures 13 cm in diameter [32]. The impact energy was measured by the device in Joules.

The results indicated that the elastic zone in the STF-treated samples was found to be broader than in the unprocessed samples, indicating a greater absorption of impact energy and an accumulation of force in the elastic zone [33].

3. Ballistic impact test at low velocity

In 2014, Majumdar et all tested tThe single layer Kevlar textiles (200 g/m^2) underwent a low velocity ballistic impact test using the apparatus depicted in Figure 9. The ammunition weighed 11.62 g and was fired at a mean velocity of 165.2 m/s using a 0.380 calibre revolver. There were nine rounds fired for every sample. The before and after impact bullet velocities were measured using four optical screen-based velocity measuring units. In order to evaluate the pre impact velocity, two optical screens (screens 1 and 2) were positioned before the test sample, and two more optical screens (screens 3 and 4) were positioned after the test sample to measure the post impact velocity. When there was no sample, it was discovered that the bullet's velocity dropped by less than 1 m/s across a distance of 4 m, and as a result, the energy lost to air resistance was disregarded. The following equation was used to determine the ballistic energy absorbed by the sample [34].

$$E = \frac{1}{2} m(v1^2 - v2^2)$$

Where, E is the energy absorbed (J), m is the mass of the bullet (kg), v 1 is the pre impact velocity (m/s) and v 2 is post impact velocity (m/s).

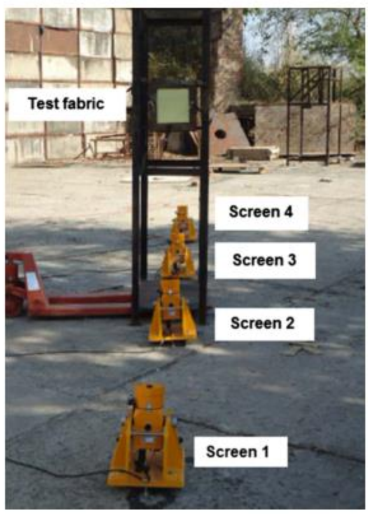

Figure 8: Low velocity ballistic impact test set up

6. SHEAR THICKENING FLUIDS APPLICATION IN BODY ARMOUR RESEARCH BY COMMERCIAL AND ARMY OF DIFFERENT COUNTRIES

1. United States Army Research Laboratory - At the US Army Research Laboratory in Adelphi, Maryland, in 2002. Norman Wagner, a chemical engineering professor at the University of Delaware, and Eric Wetzel, a laboratory employee, headed the development team. The patent for "Advanced Body ArmourUtilising Shear Thickening Fluids," US Patent No. 7,226,878, was filed in 2003 and granted four years later [35].

2. Armour holdings - During 2006, Patent STF was created by the Centre for Composite Materials at the University of Delaware, in collaboration with the U.S. Army Research Laboratory's Weapons and Materials Research Directorate. Armour Holdings is the only licensee of STF. American company ArmourHoldings, Inc. produced equipment for police enforcement, the military, and personnel safety. Renamed BAE Systems Mobility & Protection Systems, it was bought by BAE Systems on July 31, 2007 [36].
3. BAE systems - Body armour composed of Kevlar and shear-thickening fluid was introduced by BAE in 2010. A Memorandum of Understanding (MoU) was signed in 2017 between Helios Global Technologies and BAE Systems to further the development of liquid armour technology. British multinational military, security, and aerospace corporation BAE Systems plc. With activities all around the world, its headquarters are in London and Farnborough, United Kingdom. The business is Europe's biggest defence contractor. Technology for safety and survival is provided by Helios Global Technologies. They are working on projects including sensors for danger detection from a distance and sophisticated materials for protection against blasts and ballistics [37].
4. The Military Institute of Armament Technology and Institute of Security Technologies in Poland (Moratex) created a specifically formulated shear thickening liquid in 2015 and stopped using fibres for impact applications and body armour [38].
5. A UK-based business called D3O applies armour using STF gel. D3O is an energy-absorbing polyurethane substance with several additives and polyborodimethylsiloxane, a non-Newtonian dilatant fluid [39].

7. PRACTICAL ISSUES IN STF TREATED FABRIC

Variables such the employment of different sized silica and other particles, their added weight to textiles, fabric weaves, fabric materials, layer arrangements, bullets and fsps, varying velocity, energy absorption, etc. are all covered in research publications.
Following issues with respect to practical usage require some insight [40].

1. During usage or shelf life, the gravity action causes the bottom of the fabric or garment to get thicker.
2. STF leakage from treated cloth under stress during use, regardless of whether protective coverings were placed over the treated fabric by the researchers
3. Degradation/evaporation when exposed to the environment
4. Humidity sensitivity.

8. CONCLUSION

According to YueXu (2016) in her master's thesis, STF-impregnated fabric was retained both horizontally and vertically for 30 days, with an increase in thickness (0.3 to 0.49 mm) at the bottom of the material. UPTTI - STF specialists have suggested that STF be kept in situ to prevent it from flowing due to gravity by incorporating it into 3D woven materials.

Following a conversation with STF experts at IIT Delhi, the thickness of the cloth treated with STF is only a few microns, and the STF coating is incredibly stable.
Since the critical shear rate for the initiation of shear thickening reduced with lowering temperature, research on shelf life and in various settings is necessary. Furthermore, a body armour must pass the service life evaluation, which entails a ballistic test following conditioning in an environmental room with temperature and humidity controls (65 ± 5°C and 80 ± 5%, respectively) and a tumbling apparatus (with a rotation speed of 5 ± 1 rpm and a total rotation of 72000 ± 1500). According to the research, chemical adjustments must be made so that STF impregnated materials can endure the impacts of temperature and humidity.
Another method was also proposed in this study, to retain the shear thickening properties of STFs. In this, the STFs were preserved by two different methods: in the first method, the STF was kept in a closed jar under nitrogen atmosphere at ambient temperature, whereas in the second method the STF was encapsulated in silicone and placed in a chamber with 100% RH. It was found that the encapsulated STF behaved rheologically similar to the freshly synthesized STF, whereas a slight change in the rheological behavior was observed for the STF stored under the nitrogen environment. Hence, this study revealed the ideal storage conditions and methods for STFs to maintain their shear thickening properties with time.
This study also suggested a different approach to preserve STFs' shear thickening characteristics. The STFs in this were maintained using two distinct techniques: in the first, they were stored at room temperature in a closed jar with nitrogen atmosphere, and in the second, they were sealed in silicone and kept in a chamber with 100% relative humidity. The rheological behaviour of the newly synthesised STF and the encapsulated STF were found to be identical, but the STF kept in a nitrogen environment showed a minor deviation in rheological behaviour. As a result, this study identified the best ways to store STFs and how long they can keep their shear thickening qualities.

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