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Sustainable innovation in ballistic vest design: Exploration of polyurethane-coated hemp fabrics and reinforced sandwich epoxy composites against 9 mm and .40 S&W bullets

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Abstract

This research aimed to evaluate the bulletproof capabilities of hemp fabrics and optimize the design factors for effective ballistic vests. Three main aspects were investigated: enhancing toughness with polyurethane-coated hemp fabrics, determining optimal placement of fabric-reinforced hemp epoxy composites in various configurations, and identifying the optimal number of fabric layers for performance against 9 mm and .40 S&W bullets. Penetration depth was measured in ballistic gelatin to analyze the results. The study showed strong statistical correlations between factor variables and penetration depth shifts. The most effective strategies included polyurethane-coated hemp on all layers and increased layering. The ammunition of 9 mm bullets exhibited the least penetration depth when tested against the sandwich-reinforced configuration. In contrast, the larger .40 S&W bullets demonstrated that the frontal arrangement yielded the minimum penetration depth. Notably, 9 mm bullets penetrated 1.25 times deeper than .40 S&W bullets. These findings emphasize hemp fabric's potential for reliable ballistic vests. Utilizing polyurethane-coated hemp fabric in epoxy composites within a sandwich reinforcement of at least 212 layers is recommended to stop 9 mm bullets effectively. The research contributes valuable insights to sustainable ballistic vest development, utilizing natural materials with exceptional bullet protection capabilities.

1. Introduction

This research is centered around the optimization of hemp fabric ballistic vests, with a specific emphasis on elevating their protective capabilities against 9 mm and .40 S&W ammunition. Hemp fabric is recognized for its exceptional tensile strength [1], lightweight properties, and cost-effectiveness, rendering it a highly suitable material for fashioning ballistic vests [2-4]. This study employs experimental methodologies to examine the intricate interplay of diverse parameters. These encompass the application of polyurethane-coated hemp fabrics, the strategic arrangement of hemp fabric reinforcements, the configuration of fabric layers, and the caliber of bullets 9 mm and .40 S&W impacting the overall performance of the ballistic vest. Through meticulous analysis of bullet penetration within ballistics gelatin, this research discerns critical factors significantly shaping the vest's efficacy. Particularly noteworthy are the findings that underscore the pronounced influence of bullet caliber and extrapolate the requisite minimum number of layers, thus furnishing indispensable insights for the meticulous design of ballistic vests proficient in consistently and reliably thwarting bullets of 9 mm and .40 S&W calibers. In essence, this investigation substantively contributes to the advancement of personal protective equipment, elevating the standard of defense against firearm-based threats, thereby ushering in a new era of enhanced personal safety [5,6].

In recent years, there has been a growing interest in exploring sustainable and high-performance materials for the fabrication of ballistic vests [7,8]. One such material is hemp fiber [9-14], which exhibits exceptional mechanical properties and can be reinforced with reinforced epoxy composites [2]. Hemp fabric is renowned for its remarkable tensile strength, lightweight nature, and environmentally friendly characteristics [1,8]. Incorporating hemp fabric into a ballistic vest design could potentially offer a cost-effective and sustainable alternative to traditional materials while maintaining the required level of protection.

The extant literature primarily focuses on the water-resistant and mechanical enhancement qualities of polyurethane-coated fabrics. The advantages of polyurethane coatings in comparison to other polymers are greater resistance to abrasion and splitting, increased strength and durability. The elongation in the course direction of the knitted fabric significantly increases after coating on average by about 102% and coating caused greater resistance to spherical bursting on average of 13% [15]. Scarce research has been dedicated to delineating the precise impact of polyurethane coating on the ballistic resilience of hemp fabrics. A comprehensive grasp of this aspect is imperative to evaluate the feasibility of its integration into ballistic vest designs.

The incorporation of hemp fibers into epoxy and polyester composites yields a statistically significant disparity in both tensile strength and elastic modulus, owing to a pronounced reinforcement effect. The research also notes that the integration of natural fibers into polymer matrix composites holds promise for mitigating the typical environmental impact associated with synthetic fibers. In doing so, this study significantly contributes to enhancing the overall sustainability of composite materials [1,4]. In their comprehensive inquiry, the investigators thoroughly examined the mechanical, thermal, and ballistic properties of epoxy composites reinforced with hemp fabric derived from Cannabis sativa. Employing a 30 vol% reinforcement strategy with hemp fabric, they achieved a notable enhancement in impact energy, tensile strength, and elastic modulus of the composites compared to the baseline epoxy. Of particular relevance to ballistic performance, the hemp fabric-reinforced composites exhibited superior energy absorption in comparison to counterparts reinforced with alternative natural fibers. This finding advances the potential suitability of these composites in the realm of ballistic armor, especially in terms of countering 0.22 ammunition [2]. Another investigation focused on identifying optimal parameters for the design of ballistic vests utilizing hemp fabric materials. It was determined that a minimum of 402 layers of hemp fabrics was requisite to effectively impede 9 mm parabellum bullets. These findings underscore the substantial potential of hemp fabrics in the development of dependable ballistic vests capable of reliably and securely withstanding 9 mm parabellum bullets [9].

Prior studies have extensively explored the integration of synthetic materials, such as Kevlar [16-19], Dyneema [20,21], Twaron [22,23], shear thickening fluid (STF) [24], polymeric composites [25,26], UHMWPE [27,28], metallic [29,30], and ceramics [31,32], into the composition of ballistic vests owing to their distinguished tensile strength and exceptional ballistic resilience. These materials have, over time, established themselves as the prevailing benchmarks in the realm of personal protection [33]. Researchers have diligently examined varied conceptual designs for ballistic vests, encompassing the gamut of soft armor, hard armor, and hybrid configurations amalgamating both material categories [34]. Notably, soft armor vests underscore enhanced flexibility and comfort, whereas their hard armor counterparts proffer elevated defense against armor-piercing threats [35].

Preceding research has dissected the correlation between bullet caliber and penetration depth across diverse ammunition types [36]. Researchers have also delved into the ramifications of distinct design layouts on the ballistic performance of ballistic vests [6]. Comparative analyses have juxtaposed the protective capabilities of frontal, medial, rear, and sandwich configurations, revealing the influential role of reinforcement material placement in shaping penetration resistance [37].

This study delves into the bullet protection capabilities exhibited by polyurethane-coated hemp fabrics and fabric hemp-reinforced epoxy composites, to devise proficient designs for ballistic vests. Systematic experimental assessments were carried out to investigate the influence of diverse parameters on the penetration resistance of 9 mm and .40 S&W caliber bullets. These evaluations encompassed various configurations, including frontal, rear, and sandwich arrangements, to effectively intercept projectiles of standard calibers. This proactive approach is instrumental in mitigating potential life-threatening incidents. The salient outcomes of this research can be succinctly outlined as follows:

1. Elucidation of the efficacy of polyurethane-coated hemp fabrics in bolstering bullet penetration resistance.
2. Thorough evaluation of distinct fabric hemp-reinforced epoxy composite designs, encompassing frontal, rear, and sandwich configurations.
3. Comprehensive explication of the impact exerted by the penetration resistance of 9 mm and .40 S&W bullets on resultant penetration depths.
4. Investigating the intricate relationship of polyurethane-coated hemp fabrics, the optimal placement of fabric hemp-reinforced epoxy composites, and the requisite number of layers necessary to effectively impede the trajectory of bullets.

2. Experimental

2.1 Firearms and ammunitions

The firearms used for testing comprised Glock 19 and Beretta Px4 Storm. The study employed a Glock 19 with a barrel length of 102 mm (4.02 inches) for testing the 9 mm firearm ammunition. Similarly, the Beretta Px4 Storm with a barrel length of 102 mm (4.02 inches) was used for testing the .40 S&W firearm ammunition. Notably, the authors remained independent of any financial compensation from firearm manufacturers throughout the testing process. This deliberate separation aimed to ensure the impartiality and integrity of the findings articulated within this research publication. It is crucial to underscore that the presented findings remain untainted by financial bias, meticulously reflecting solely the outcomes of rigorous experimental observations. Given the inherent variability in missile tests, a rigorous approach was undertaken, with multiple experiments being repeated throughout the study to enhance the reliability of the conclusions.

This section provides in-depth insights into the attributes of the ammunition employed in our experimental trials. Table 1 offers a comprehensive overview of the diverse kinds and brands of ammunition deployed, representative of those commonly utilized by a significant portion of firearm users. Our primary aim encompassed the comparative analysis of the ramifications arising from varying bullet dimensions, specifically the 9 mm and .40 S&W full metal jacket (FMJ). It merits highlighting that the ammunition's weight was quantified in grains (grs), with a conversion rate of 1 g equating to 15.432 grains.

Table 1. The attributes and specifications of the ammunition used in the conducted tests.

Ammunition	Bullet weight (grains)	Bullet diameter (inches)	Velocity ($ft\cdot s^{-1}$)	Energy (J)
1) Winchester USA 9x19 mm FMJ	115	0.35	1,212	509
2) Bullet Master .40 S&W FMJ	180	0.40	947	486

2.2 Ballistics gelatin block

The testing protocol involved discharging ammunition into a ballistic gelatin medium, aiming to authentically emulate the impact characteristics commonly associated with gunshot wounds, with a specific focus on the exposed chest area. To meet the stringent density and consistency requirements set forth by the Federal Bureau of Investigation (FBI), a meticulously prepared block of ballistics gelatin was employed. The chosen material for this purpose was unflavored gelatin, renowned for its precision and reliability. This procedural approach strictly conformed to the specifications and directives outlined in References [38], a protocol that emerged in the aftermath of the 1986 Miami shootout.

The precise density of this gelatin closely imitates crucial attributes of muscle tissue, establishing it as the preferred choice for terminal ballistics testing both within the FBI and other law enforcement domains. The gelatin block, sourced from Clear Ballistics in Greenville, South Carolina, USA (http://clearballistics.com), as depicted in Figure 1 was handled with meticulous attention to detail. Subsequent testing iterations were conducted to thoroughly validate strict adherence to the performance standards delineated in Reference.

The application of synthetic ballistic gelatin offers a discernible advantage due to its reusability, achievable through melting and reshaping. This synthetic gelatin, developed by Clear Ballistics, effectively functions as a practical substitute for conventional gelatin across a diverse spectrum of applications. It features prominent attributes including complete transparency, stability on shelves within a temperature range spanning from -23.3°C (-10°F) to 35°C (95°F), absence of odor and color, and the exclusion of organic components. While its initial conception was geared toward terminal ballistic applications, its adaptability extends to various alternative uses.

The density of the ballistic gelatin block employed in this study was meticulously calculated to be 0.906 $g{\cdot}cm^{-3}$. By comparison, average densities of human blood, fat, and muscle are reported as 1.004 $g{\cdot}cm^{-3}$ [39,40]. This places the gelatin's density at approximately 90.3% of the referenced average density, effectively emulating the tactile characteristics of human flesh. This precision facilitated the replication of varying densities within the ballistic gelatin block, enabling faithful emulation of human tissue properties. The technical specifications of the block encompass dimensions of 50.80 cm in length, 15.24 cm in width, and 15.24 cm in height, with a corresponding weight of 16.32 kg, two blocks are interconnected.

2.3 Hemp fabrics sample

The production process of hemp samples holds paramount significance. The fabrics undergo a meticulous machine-weaving procedure, adhering rigorously to the highest standards of quality and precision. This meticulous approach assures the integrity and dependability of ensuing experimental validations. The weight of hemp fabric, polyethylene-coated hemp fabric, and reinforced epoxy composites are detailed in Table 2. The fiber characteristics, including the measurement of the fiber diameter employed in the test, reveal a fiber size of 251.16 μm, as illustrated in Figure 2.

The primary focus of the study revolved around a thorough evaluation of two distinct fabric classifications: Type 1, characterized by its utilization of uncoated hemp fabrics, and Type 2, recognized for its elevated durability resulting from the inclusion of polyurethane-coated hemp fabrics. Subsequently, the analysis proceeded intending to determine the most favorable number of fabric layers through Factor Analysis. In addition, a separate Factor Analysis was employed to identify the optimal configuration for fabric-reinforced hemp epoxy composites. These analytical endeavors were undertaken within the broader context of advancing the design of sustainable ballistic vests.

The procedure for preparing polyurethane-coated hemp fabrics involves laying the hemp fabric along the length of the fiber and uniformly applying polyurethane across the entire sheet. The liquid polyurethane effectively permeates the hemp fabric during this stage. Subsequently, allowing it to partially dry, typically within 30 min, and then using a roller to iron it ensures a smooth and even application. This process is repeated thrice, with an approximately one-day interval to allow the polyurethane to thoroughly dry before conducting further tests. The chosen polyurethane solution is Beger polyurethane 1K supreme outdoor crystal clear, it is a thermoset plastic and designed for outdoor woodwork. Upon drying, it achieves a film thickness of 50 μm. The resulting polyurethane-coated hemp fabric exhibits a weight of 336 $g{\cdot}m^{-2}$.

Figure 1. Ballistics gelatin block.

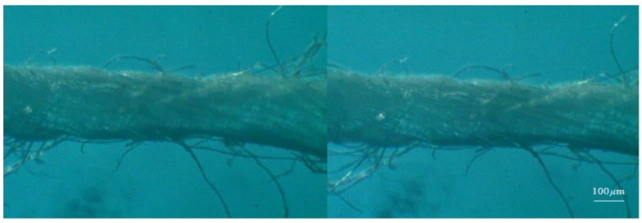

Figure 2. The characteristics of hemp fabric fibers.

Table 2. The weight of the fabrics.

Types of fabrics	Gram per square meter (GSM)
Hemp fabric	230.40
Polyethylene-coated hemp fabric	336.00
Hemp fabric-reinforced epoxy composites	684.80

The optimal utilization of hemp fabrics entails their alignment in the 0-90 direction to harness maximal strength. To enhance energy absorption during impacts, a composite approach involves amalgamating multi-directional configurations to augment transverse strength and rigidity. This strategy proves conducive to fostering cohesiveness and endurance within pressure vessels, along with promoting uniform material hardness. This organizational framework adheres to the 0/±90/0/±90 paradigm [41,42], where meticulous layering ensues systematically, ultimately achieving the desired layer count, as depicted in Figure 3.

The fabrication process of epoxy composites involves the integration of hemp cloth and Epoxy Putty Stick as a bonding agent between layers. The assembly is meticulously sealed in ten layers, resulting in a total thickness of approximately 10 mm. The method entails placing the initial sheet horizontally, evenly applying Epoxy Putty Stick, and then positioning the subsequent sheet vertically. The layers are meticulously aligned and ironed to achieve a smooth, even surface. The molding process occurs at room temperature. The liquid Epoxy Putty Stick effectively permeates each hemp cloth sheet during application. Following a brief drying period, approximately 30 min, the process is repeated until 10 layers of epoxy composites are achieved. Importantly, each layer adopts alternating horizontal and vertical orientations. It is crucial to arrange the fibers meticulously on a straight template to prevent warping during the drying phase, ensuring the integrity of the epoxy composites. The final step involves leaving the composite undisturbed for approximately one day to allow the adhesive to thoroughly dry before it can be subjected to testing.

Once these precisely orchestrated layers are harmonized, they undergo meticulous alignment to commence the subsequent series of assessments. The selection of testing layers adheres to an incremental model, initially employing 30 layers. Subsequently, experimental outcomes are subjected to regression analysis to quantify the extent of penetration at the core. This analytical endeavor aims to ascertain the optimal configuration of ballistic vest layers, a critical factor in ensuring both safety and efficacy.

The optimal strategy for positioning fabric-reinforced hemp epoxy composites involves systematic arrangements in front, back, and sandwich configurations, as illustrated in Figure 4. The initial trial employs solely hemp fabric, organized sets of 150 layers for testing. The second trial, wherein a configuration of 30 layers of fabric-reinforced hemp epoxy composites is employed on the front, complemented by 120 layers of hemp fabric on the rear. In this particular arrangement, each set comprises a cumulative total of 150 layers. During the third experiment, fabric-reinforced hemp epoxy composites were partitioned into three sets, each consisting of 10 layers, strategically configured in a sandwich arrangement.

2.4 Experiments procedure

The research investigated the performance characteristics of hemp fabric across various compositions and types. The analysis encompassed an evaluation of two distinct fabric categories: Type 1, consisting of non-polyurethane-coated hemp fabrics, and Type 2, featuring increased durability through polyurethane-coated hemp fabrics. The investigation included both factor analysis for the number of fabric layers and Factor Analysis for the placement of fabric-reinforced hemp epoxy composites.

Furthermore, a thorough examination was carried out to establish the most appropriate regression equation linking the independent and dependent variables, as referenced in sources [9,36]. To determine the optimal configuration, an advanced Regression Analysis was employed. This analysis aimed to identify the ideal number of layers and the suitable hemp weave type required to impede the trajectory of both a 9 mm and .40 S&W bullet.

The primary objective of the study was to ascertain the precise quantity of hemp fabric layers essential for effectively stopping the motion of a Glock 19 caliber 9 mm parabellum pistol. The testing employed a Beretta Px4 Storm, chosen due to its widespread use for concealed carry purposes. Both pistol types feature a consistent barrel length of 102 mm (equivalent to 4.02 inches). Subsequently, the focus will transition towards elucidating the details of the experimental setup, encompassing specific information regarding the utilized ammunition. This will be followed by a comprehensive presentation of the acquired experimental findings.

This section offers an extensive overview of the ammunition utilized in the experimental trials. The ammunition was chosen to reflect commonly employed types and reputable brands within the firearms community. Specifically, the Winchester USA 9 mm Luger 115 grain FMJ and the Bullet Master .40 S&W 180 grain FMJ were chosen as representatives.

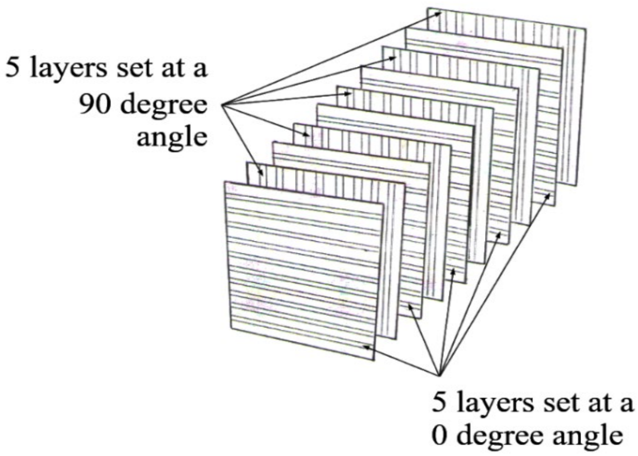

Figure 3. Alignment of hemp fabrics [42].

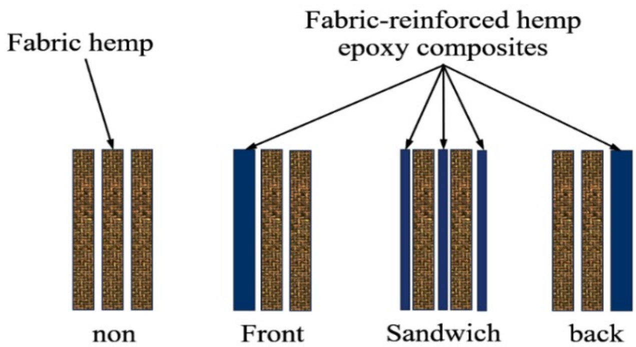

Figure 4. Position fabric-reinforced hemp epoxy composites.

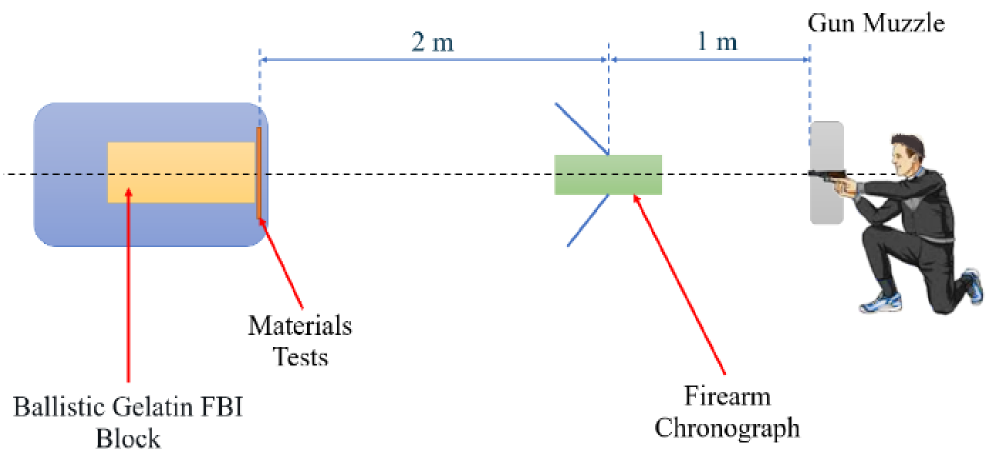

Figure 5. Experimental layout and device positioning.

Following this overview, the description proceeds to outline the testing methodology applied to the specimens as follows:

1. A firearm chronograph was positioned at a distance of 1 m from the muzzle of the firearm [36], depicted in Figure 5. The chronograph was configured to measure bullet velocities within the 20 $ft\cdot s^{-1}$ to 9,999 $ft\cdot s^{-1}$ range, ensuring precise measurements and mitigating potential interference from muzzle flame.

2. This measurement was conducted to directly assess the bullet velocity upon entry into the ballistic gelatin. Precision Measurement of Penetration Depth Using a Laser Distance Meter. The laser distance meter employs a fundamental principle based on laser light emission and subsequent reflection on the device. Through this process, the meter effectively calculates the distance accurately, offering a tolerance level of merely ±1.5 mm. The kinetic energy equation was utilized to determine both the energy imparted and the penetration depth within the ballistic gelatin medium. The relationship between kinetic energy and an object's properties is encapsulated by the Equation (1), wherein kinetic energy exhibits direct proportionality to the object's mass and the square of its velocity.

$$K.E. = (1/2)\ mv^2 \qquad (1)$$

3. The hemp fabric samples were situated 3 m away from the firearm's muzzle and were strategically positioned in front of the ballistic gelatin block, which was placed at a distance of 2 m from the chronograph. This setup replicates a worst-case scenario, simulating close-range firearm engagement.

4. The samples were subjected to gunfire, with the projectile passing through the chronograph to capture its initial speed. Subsequently, the projectile penetrated the sample and lodged within the ballistic gelatin. The acquired velocities from these tests were then utilized to compute an average velocity.

5. Laser distance measurement was utilized to quantify the penetration depth into the ballistic gelatin, with the results recorded accordingly.

6. Each sample underwent a repeated process involving steps 3 to 5. In instances where the projectile deviated from a linear trajectory within the ballistic gelatin or led to penetration of the hemp fabric sample at structurally compromised regions, a subsequent test was conducted using the same ammunition.

To replicate the impact characteristics arising from a point-blank shot to an unshielded chest, the conducted experiments encompassed the discharge of ammunition into a block of ballistic gelatin. These comprehensive testing steps collectively contribute to the robustness of the experimental approach, ensuring accurate and repeatable results in the evaluation of hemp fabric's ballistic vest performance.

3. Results and discussion

3.1 The experimental findings from the development of a prototype bulletproof armor plate for testing are presented

Table 3 illustrates the outcomes derived from the executed experiments. The categorizations entail non-coated (NC) and representing the Coated condition (C), denoting polyurethane-coated hemp fabrics. The layer count in the tests was progressively increased to 90, 120, and 150 layers, selected to prevent bullet penetration into the ballistics gelatin block. Both 9 mm and .40 S&W bullets were utilized for testing actual scenarios. The experimental protocol encompassed evaluating two distinct variations in bullet penetration depth, specifically focusing on 9 mm and .40 S&W ammunitions.

Statistical significance denotes the association between alterations in the independent variable and corresponding modifications in the dependent variable. Notably, the presence of polyurethane coating results in a reduction in drilling depth. Across all trials involving both 9 mm and .40 S&W ammunitions, a direct correlation has been established between the number of layers and the depth of penetration. Specifically, an escalation in the number of layers leads to a reduction in penetration depth. This observation further validates the significant role these factors play in explaining the observed variability in drilling depth.

These findings underscore the pronounced influence wielded by each of these variables. Furthermore, an examination of the combined effects of these two factors has been conducted, revealing a substantial interplay between them that significantly contributes to the observed outcomes. The obtained results from this study have enabled the computation of the mean response, along with a comprehensive evaluation of the principal effects. A visual representation of these analytical insights is provided in Figure 6.

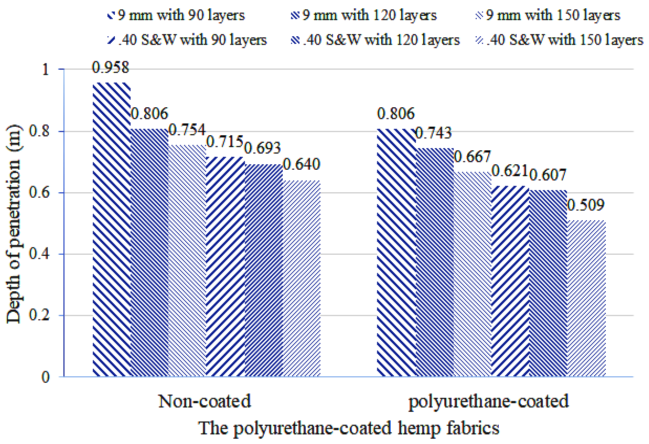

Figure 6. The depth of penetration in both polyurethane-coated and non-polyurethane-coated hemp fabric.

Furthermore, while assessing disparities in penetration depth between 9 mm and .40 S&W ammunition, the results demonstrated a notably greater depth of penetration for the 9 mm rounds compared to the .40 S&W rounds. Based on the experimental findings presented in Table 3, it is observed that the average depth of penetration for the 9 mm bullet across all experiments was 0.789 m. This value surpasses the corresponding average depth of penetration for the .40 S&W bullet, which amounted to 0.631 m. The analysis reveals that the average depth of penetration for the 9 mm bullet is 1.25 times greater than that of the .40 S&W. This emphasizes the significance of incorporating ammunition type as a pivotal element in body armor design considerations. Subsequent post-testing enables the derivation of dependable inferences, grounded in the statistical significance of our experimental data. This robustly bolsters the efficacy of the selected design configuration and underscores the impact of bullet type on penetration resistance.

The obtained experimental findings from configurations involving 90, 120, and 150 layers reveal a consistent trend of enhanced penetration resistance as the layer count increases, holding for both 9 mm and .40 S&W ammunition. These outcomes emphasize the significant role played by all contributing factors in defining penetration depth. Notably, the main effects plot prominently showcases the experimental scenarios featuring polyurethane-coated hemp fabrics with 150 layers, as in Figure 7. This finding aligns with prior research, A direct relationship was evident between the number of layers and the anti-penetration performance. This indicated that increasing the number of layers improved the capacity to withstand projectiles [9,36].

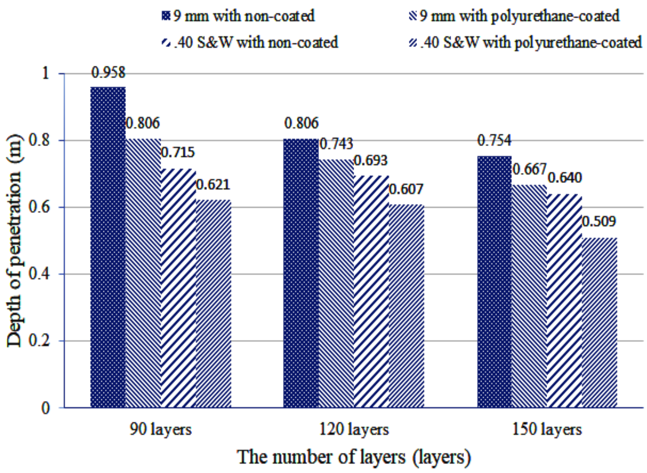

Figure 7. The penetration depth of layers within a hemp fabric.

Table 3. The results of the experiments involved polyurethane-coated hemp fabrics.

No.	Polyurethane-coated hemp fabrics	The number of layers (layers)	Typical bullet diameter	Depth of penetration (m)
1	NC	90	9 mm	0.991
2	NC	90	9 mm	0.924
3	NC	90	.40 S&W	0.689
4	NC	90	.40 S&W	0.741
5	NC	120	9 mm	0.818
6	NC	120	9 mm	0.794
7	NC	120	.40 S&W	0.736
8	NC	120	.40 S&W	0.649
9	NC	150	9 mm	0.733
10	NC	150	9 mm	0.775
11	NC	150	.40 S&W	0.663
12	NC	150	.40 S&W	0.617
13	C	90	9 mm	0.799
14	C	90	9 mm	0.813
15	C	90	.40 S&W	0.661
16	C	90	.40 S&W	0.580
17	C	120	9 mm	0.782
18	C	120	9 mm	0.704
19	C	120	.40 S&W	0.601
20	C	120	.40 S&W	0.613
21	C	150	9 mm	0.699
22	C	150	9 mm	0.634
23	C	150	.40 S&W	0.547
24	C	150	.40 S&W	0.471

Moreover, the analytical findings consistently underscore that an increase in layer count and the adoption of larger bullet sizes correlate with a consistent reduction in penetration depth. Particularly noteworthy is the independent impact of larger bullet sizes on reducing penetration depth. These interwoven relationships offer valuable insights into the nuanced dynamics of penetration depth, providing guiding principles to ascertain optimal parameters that ensure the effective safeguarding capability of ballistic vests.

The experimental methodology involved the utilization of polyurethane-coated hemp fabric, which was then supplemented with a sandwich-layered arrangement comprising hemp fabric. Notably, this amalgamation demonstrated the utmost efficacy in terms of ballistic protection. The ensuing experimental outcomes were subjected to an in-depth analysis to evaluate their efficacy in countering 9 mm projectiles, which exhibit a penetration rate 1.25 times higher than that of .40 S&W bullets.

3.2 The experimental results of the arrangement of fabric-reinforced hemp epoxy composites are detailed.

Based on the outcomes of the experiment outlined in section 3.1, it was determined that the most optimal variable within the experimental setup was the utilization of hemp fabric coated with polyurethane, combined with a layer count of 150 hemp fabric layers. This combination exhibited the highest level of protection against both 9 mm and .40 S&W ammunition.

Subsequently, employing the identified optimal factors, the experiment was extended to explore the optimal positioning of the reinforcing plate. The arrangement of fabric-reinforced hemp epoxy composites was defined as follows: "F" denoting the Front position, "B" representing the Back position, and "S" indicating the Sandwich configuration.

Table 4 displays the experimental findings concerning the arrangement of epoxy hemp fabric-reinforced composites about the factors of polyurethane-coated hemp fabric and variations in layer count. This information was sought to unravel the intricate interplay between multiple factors, including polyurethane-coated hemp fabric, variations in layer count, and the arrangement of fabric-reinforced hemp epoxy composites. The outcomes consistently demonstrated that the sandwich configuration yielded a reduced penetration depth within the ballistic gelatin block.

Upon assessing the placement of the fabric-reinforced hemp epoxy composite, the analysis discerns a discernible hierarchy in terms of penetration depth. In the evaluation involving 9 mm bullets, it is evident that the sandwich design exhibited the lowest penetration depth, followed by the front and rear configurations, respectively. Similarly, experiments conducted with larger .40 S&W bullets indicated that employing a reinforced epoxy hemp composite at the front position resulted in the least penetration depth, followed sequentially by the sandwich and rear configurations, as depicted in Figure 8.

In the investigation of the physical characteristics of epoxy-cast hemp fiber cloth reinforcement sheets, a notable observation emerges from the ballistic impact analysis. When a projectile penetrates the front surface, it exhibits a smooth entrance, contrasting with more pronounced damage upon exit, as depicted in Figure 9. This phenomenon was consistently observed across multiple trials for both 9 mm and .40 S&W bullets.

A significant revelation arises from the examination of Figure 10, highlighting the substantial trajectory deviation caused by the positioning of the bullet within the reinforcement layer. This deviation consistently deviates from the implant material, as evidenced by the need for repeated trials to ascertain the reliability of this occurrence. The positioning of the sandwich reinforcement layer emerges as a critical factor, not only mitigating force but also demonstrating a commendable ballistic deflection pattern.

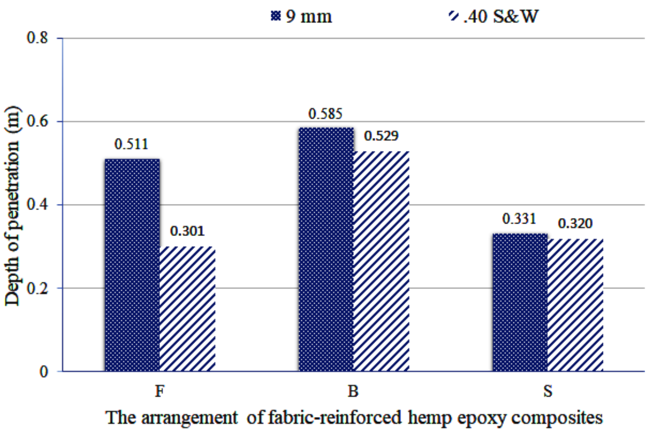

Figure 8. The penetration depth within the arrangement of fabric-reinforced hemp epoxy composites.

Table 4. The results of the experiments arrangement of fabric-reinforced hemp epoxy composites.

No.	The arrangement of fabric-reinforced hemp epoxy composites	Typical bullet diameter	Depth of penetration (m)
1	F	9 mm	0.493
2	F	9 mm	0.528
3	F	.40 S&W	0.306
4	F	.40 S&W	0.331
5	B	9 mm	0.518
6	B	9 mm	0.651
7	B	.40 S&W	0.497
8	B	.40 S&W	0.560
9	S	9 mm	0.343
10	S	9 mm	0.318
11	S	.40 S&W	0.309
12	S	.40 S&W	0.294

Figure 9. Depicts front and back face damage post projectile impact.

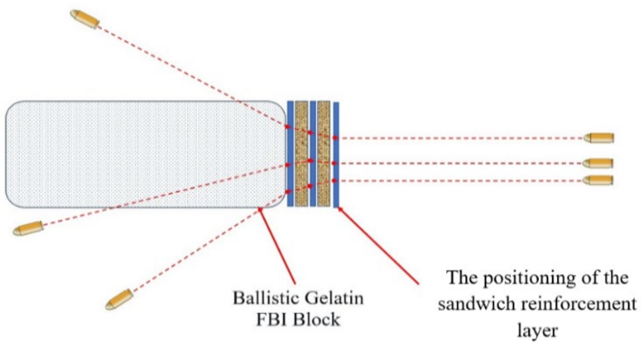

Figure 10. The bullet trajectory deviation is shown with the strategic placement of the sandwich reinforcement layer.

This outcome can be attributed to the heterogeneous nature of the materials employed, featuring alternating layers of both rigid and pliable substances. The resultant unevenness significantly influences the refraction of the bullet's trajectory, surpassing the performance of a uniform material.

3.3 The experimental results concerning a prototype ballistic armor plate

The research endeavors are directed towards a comprehensive exploration of the nuanced dynamics associated with polyurethane-coated hemp fabric, particularly in conjunction with the optimal configuration of hemp fabric-reinforced epoxy composites within a sandwich structure. The study meticulously addresses the determination of the optimal number of layers essential for effectively intercepting the trajectory of a projectile. Table 5 presents the experimental results of a prototype ballistic armor plate tested with a 9 mm projectile, chosen for its superior penetration characteristics. At 210 layers, the experimental results demonstrate effective penetration resistance. The 9 mm bullet exhibits non-penetration in ballistics gelatin, yielding a recorded depth value of 0 m

Examining the prototype ballistic armor plate composed of polyurethane-coated hemp fabric and determining the optimal configuration of hemp fabric-reinforced epoxy composites within a sandwich structure is the central focus of the ongoing research. The analysis, by regression Equation (2), highlights the critical necessity of employing a minimum of 212 layers to ensure sufficient protection against 9 mm projectiles. This configuration is expected to provide effective safeguarding against bullets, resulting in zero penetration.

$$\text{Depth of penetration} = 1.2169 - 0.005762\ (N) \qquad (2)$$

The derived regression equation (2) yielded a calculated R-Square coefficient of 94. 83% and an adjusted R-Square (R-Sq(adj)) of 93.97%, according to the data presented in Table 6. These values, surpassing the 75% threshold, affirm that the correlation equation employed in this experiment accurately characterizes drilling depth. This outcome underscores the robust fit of the correlation equation to the experimental data, thereby augmenting the reliability and precision of the conducted experiment.

3.4 Discussion

Moreover, the pertinent literature derived from prominent scholarly investigations [1,2,36,43], has seamlessly complemented the current research endeavor, thereby endowing it with invaluable insights into the mechanical attributes inherent to hemp-based materials. This insight extends to their potential utility within the domain of ballistic vest design. In synergy with our empirical findings, these scholarly contributions coalesce to expand the burgeoning repository of knowledge concerning sustainable resources for ballistic safeguarding.

Table 5. The results of the experiments were a prototype ballistic armor plate.

No.	The number of layers comprising polyurethane-coated hemp fabric and reinforced epoxy composites in a sandwich configuration (layers)	Depth of penetration for 9 mm bullets (m)
1	150	0.343
2	150	0.318
3	170	0.307
4	170	0.242
5	190	0.134
6	190	0.093
8	210	0.000
9	210	0.000

Table 6. Model summary of regression.

S	R-sq	R-sq (adj)	R-sq (pred)
0.0347473	94.83%	93.97%	91.88%

This study was meticulously conducted to evaluate polyurethane-coated hemp fabric's intrinsic ballistic protection prowess. This investigation further encompassed the augmentation of the number of layers to an optimal configuration while strategically positioning fabric-reinforced hemp epoxy composites to underpin the formulation of efficacious ballistic vest prototypes. An array of empirical assessments comprehensively underpinned these efforts. Consequently, this research endeavors to elucidate the multifaceted impact of various parameters on the resistance to penetration posed by intricate 9 mm and .40 S&W projectiles.

The outcomes of the experimentation notably indicated that the implementation of polyurethane coating across each stratum of hemp fabric led to a discernible enhancement in its tensile strength [43]. The augmentation of fabric layers similarly correlated with augmented tensile strength and enhanced puncture resistance. Noteworthy antecedent work coupled with strategic reinforcement material placement [36], underscored that the positioning of fabric-reinforced epoxy hemp composites significantly influenced penetration depth. The 9 mm sandwiched bullet configuration exhibited the shallowest penetration depth [37]. Meanwhile, the larger .40 S&W projectile registered minimized penetration depth when deployed in a frontal configuration, attributing this result to the expanded cross-sectional dimensions of the bullet, resulting in diminished penetration due to the bullet's deceleration and dissipated energy upon encountering semi-solid obstructions.

A salient discovery was the substantial trajectory deviation induced by the sandwiched reinforcement pattern. Upon striking the sandwiched reinforcement material, the bullet underwent pronounced deflection away from the ballistic gelatin block, necessitating multiple reloads for measurement, particularly evident in the 9 mm rounds, which demanded three to four reloads per trial.

In summation, the 9 mm projectile, characterized by greater velocity and energy compared to the .40 S&W counterpart, exhibited superior penetration characteristics. This observation aligns with the FBI's decision in October 2016 to transition from .40 S&W pistols and ammunition to 9 mm variants. This inquiry casts illumination on the efficacy of polyurethane-coated hemp fabric and fabric-reinforced hemp epoxy composites as pivotal constituents in the progression of cutting-edge ballistic vest technology. Integration of these sustainable materials offers a promising avenue toward the creation of environmentally conscientious and high-performance protective equipment. As societies gravitate toward heightened sustainability and resilience, this research seeks to substantively enrich the missile defense domain, thereby augmenting the understanding of hemp-based materials' potential in safeguarding the lives of law enforcement and military personnel.

Previous studies, as referenced in the Introduction [1,2,4], examined the properties and applications of epoxy composites reinforced with hemp fabric to enhance the performance of hemp fabric. However, these investigations did not include live ammunition testing. In a separate study [1], hemp fabric was tested against real bullets. The assessment aimed to determine the optimal number of layers required for effective bullet protection, without subjecting the hemp fabric to additional strengthening processes [9]. The findings revealed that polyurethane-coated hemp fabrics exhibited superior bullet resistance performance, necessitating fewer protective layers compared to prior research [15,43]. Moreover, a prototype ballistic armor plate analysis revealed a consistent reduction in penetration depth when there was an augmentation in the number of layers, consistent with previous research. The findings demonstrated the linear behavior association between the number of layers and penetration depth in the ballistic gelatin block [44]. These correlations yielded valuable insights into the intricate nature of penetration depth and furnished guidance for discerning the optimal parameters to ensure the effective protection of ballistic vests.

Experimental assessments of a ballistic armor plate prototype, incorporating live ammunition, underscore the imperative requirement for a minimum of 210 layers to ensure effective protection against 9 mm projectiles. The analysis, employing regression Equation (2), further accentuates that a minimum of 212 layers is necessary for adequate defense against 9mm ballistic missiles. Both methodologies yield congruent experimental outcomes, as the accuracy of the regression equation aligns consistently with that observed in experiments utilizing live ammunition [36].

4. Conclusions

This research aimed to assess the ballistic resistance of hemp fabrics and optimize the pertinent design parameters for developing efficient ballistic vests. The study encompassed three key focal points: the enhancement of durability through the integration of polyurethane-coated hemp fabrics, the identification of the optimal arrangement of fabric-reinforced hemp epoxy composites across varied configurations, and the determination of the most suitable number of fabric layers for effective performance against 9 mm and .40 S&W bullets. To evaluate outcomes, penetration depth was quantified within gelatin blocks, to encapsulate the essence of these findings concisely:

1. Utilizing polyurethane-coated hemp fabric across each layer demonstrates a marked enhancement in penetration resistance compared to uncoated variants.
2. When assessing 9 mm bullets, the sandwich configuration displayed the most favorable performance in terms of limiting penetration depth, succeeded by the front and rear configurations, respectively. Likewise, experiments utilizing larger .40 S&W bullets indicated that employing a reinforced epoxy hemp composite in the frontal position yielded the least penetration depth. The sandwich configuration sequentially followed this and then the rear configuration.
3. Noteworthy is the fact that 9 mm bullets showcased penetration depths 1.25 times greater than those of their .40 S&W counterparts.
4. Investigating the nuanced interrelationship between polyurethane-coated hemp fabric and the optimal configuration of hemp fabric-reinforced epoxy composites within a sandwich structure constitutes the primary focus of the current research. Empirical trials utilizing live ammunition underscored a crucial necessity for a minimum of 210 layers to afford effective protection against 9 mm projectiles. The analysis, as per the regression Equation (2), underscores the imperative requirement of a minimum of 212 layers to provide adequate protection against 9 mm projectiles.

This research is specifically designed to ascertain the optimal number of layers required to effectively intercept the trajectory of a projectile. These identified findings underscore the significant potential of hemp fabrics in the manufacturing of reliable ballistic vests. Specifically, the recommendation is to combine polyurethane-coated hemp fabric. To provide adequate protection against both 9 mm and .40 S&W bullets, it was advisable to increase the number of layers as a precautionary measure.

This research contributes valuable insights into the advancement of sustainable ballistic vest technology, harnessing the intrinsic capabilities of natural materials to provide exceptional bullet resistance. In the context of future research endeavors, it is prudent to note that while the current experimental parameters encompassed a diverse array of design configurations and bullet variants, an expanded investigation that takes into account a spectrum of environmental conditions and engages in long-term durability assessments would undoubtedly provide a holistic and nuanced understanding of the performance dynamics exhibited by hemp-based materials in practical, real-world scenarios. Overall, the significance of this research extends beyond its findings. By advancing the development of ballistic vest designs that embrace eco-friendly materials like hemp, this study makes a notable contribution to the field of ballistic protection and sustainable armor design. The integration of natural materials in protective gear aligns with contemporary environmental considerations, paving the way for a safer and more sustainable future.

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