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Experimental study of bullet-proofing capabilities of Kevlar, of different weights and number of layers, with 9 mm projectiles

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ABSTRACT

Kevlar is the most commonly used material as armour for protection against bullets used in hand guns because of its impact resistance, high strength and low weight. These properties make Kevlar an ideal material to be used in bullet-proof vests as compared to other materials. In the present study, different numbers of layers of Kevlar with different weights are tested to determine the weights and the number of layers needed to design a safe bullet-proof vest. For this purpose, several ballistic tests were performed on combinations of ballistic gel and Kevlar layers of different weights. Ballistic impacts are generated by 9 mm Parabellum ammunition. The objective is to assess the characteristics of high-speed ballistic penetration into a combination of a gel and Kevlar and determine the number of layers needed to safely stop the 9 mm bullet and thereby contribute to the design of safe bullet-proof vests. The tests provide information on the distances the bullets can travel in a gel/Kevlar medium before they are stopped and to identify the resistance capabilities of Kevlar of different grams per square meter (GSM). The tests were conducted with the use of a chronograph in a controlled test environment. Specifically, results identify the number of layers of Kevlar required to stop a 9 mm Parabellum projectile, and the effectiveness of using different number of layers of GSM Kevlar material.

1. Introduction

The concept of body armour was developed in 1538 and comprised of steel plates. Fully steel bullet proof vests were progressively used and improved up until the 20th century [1]. Today's body armour systems may still incorporate steel (but at a minimal amount), but consist mostly of Kevlar [2]. The use of Kevlar was integrated into vests in the mid-1970's and a fully developed vest was produced in 1976 after the discovery of Kevlar by Stephanie Kwolek in 1971 [3]. This new material greatly reduced the overall weight of the body armour system and drastically improved the mobility of the person wearing the vest, resulting in the modern bulletproof vests utilised today.

Kevlar used in the vests is comprised of a woven fabric consisting of synthetic fibres made through polymerisation. It is a high strength material known for its high strength to weight ratio, and in comparison to the strength to weight ratio of steel, Kevlar is five times stronger [4]. The lightweight property of Kevlar in conjunction with its high tensile strength (3620 MPa) [5] and its capacity for energy absorption [6] in comparison to other materials, makes it an ideal material for use in body armours. Ballistic applications of Kevlar based composites mostly include protective clothing [7,8]. The effect of ballistic impact on Kevlar and other composites, and the mechanical properties of the material, have been investigated in several studies [9–18] with a view towards assessing its characteristics and effectiveness under impact loading. These studies involved both experimental testing [9–18] and numerical modelling [19–21] and established the effectiveness of Kevlar as an impact resistance material. Experimental ballistic tests performed with the samples of the Kevlar-Phenolic composite, used in Ref. 18, showed that the results did not correlate with the ones given in current publications, and they therefore indicated that further controlled experiments were needed. In the previous experimental studies, various methods of impact were used including gas guns [9,12], 9 mm bullets [10,14] and armour piercing projectiles [11]. An active area of research concerning the impact resistance of Kevlar materials involved the study of the effect of shear thickening fluids

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on the ballistic performance of Kevlar reinforced composites [22–25]. Reviews on shear thickening fluids and their applications were given in a number of publications [26–28]. A number of high velocity projectile tests have been performed before as noted above, but in many cases, different methods of inducing motion, such as compressed air, or dropped weight [29] were implemented. These motion induction methods do not correlate with the uncertainty characteristics of ammunition, the explosion of gun powder, and the rifling used in the firearm barrels.

The present study aims at investigating the ability of Kevlar fabric of different weights to stop a projectile of common calibre, and the distance the projectile can travel through a gel/Kevlar combination to prevent life-threatening incidents. The contributions of this paper can be summarized as follows:

1) Identify the effectiveness of different layers of three grades of Kevlar layered, namely 160 GSM, 200 GSM and 400 GSM Kevlar fabrics.
2) Investigate the relationship of GSM with the number of layers needed to stop a 9 mm bullet.
3) Investigate the relationship of the type of ammunition with its penetration depth
4) Assess the number of Kevlar layers needed to stop a projectile.

In the tests, the layers of Kevlar that a projectile can penetrate are considered as the layers that are damaged. The calibre of the ammunition used is 9 mm Parabellum ammunition as they are used extensively. The tests were performed with a Glock 17 handgun inside a Roni carbine conversion kit. It is noted that the authors are not associated with the companies manufacturing the ammunition and obtained no financial gain for performing the tests. The results given are unbiased, and are purely as observed in the tests conducted. Due to many uncertainties in ballistic tests, many of the tests conducted in the present study had to be repeated numerous times, for example, when the projectiles deviated out of the ballistic gel, or external interference was observed that might have an effect on the results.

2. Ballistic gel and Kevlar samples

The description of how the ballistic gel and the Kevlar samples were constructed are described below.

2.1. Ballistic gel

The ballistic gel was made from unflavoured gelatine. The density and consistency of the gel have to be the same as that used by the Federal Bureau of Investigation (FBI). To achieve the same consistency, instructions given in Ref. [30] were followed and it has been tested against the standards described in Ref. [31].

8 cups (250 ml) of unflavoured gelatine powder (approximately 1.25 kg) is mixed with 8 L of water (1 part gelatine for every 4 parts of water) until all the powder is dissolved. After the solution was poured into the containers (2×5 L containers were used for the above mixture), 5 drops of essential oil (cinnamon leaf essential oil) was poured over the solution and gently stirred into it. The reason for the essential oil is to allow for the bubbles in the solution to dissipate, and to give the ballistic gel an improved smell. The solution is set in the containers placed in a fridge. The ballistic gel was ready to be used 36 h after it was made and then it was wrapped in cellophane wrapping. A video showing the details to make the ballistic gel is available from https://www.youtube.com/watch?v=0nLWqJauFEw.

Density of the ballistic gel was calculated as 996 km/m^3 (99.6% of water density). The average density of human blood, fat and muscle [32], which is the consistency of the human flesh, is 1004 kg/m^3. A 0.8% difference in the densities is considered as acceptable for the ballistic gel to replicate the flesh of a human body.

2.2. Kevlar samples

Three weights of Kevlar fabric were used in the tests, namely, 160 GSM, 200 GSM and 400 GSM. Since Kevlar can be used as a woven material, the highest strength of the material could be utilised in a 0–90 orientation. The samples were stacked with a −45/+45 (quasi-isotropic) orientation which absorbs more energy upon impact than 0–90 orientations stacked on each other [33]. The samples that were used in the tests were made in multiples of 3 layers where each sample was layered in the order of 90/±45/90. When two or three samples were placed on top of each other, it was done such that the last layer of one sample was placed at 45° to the next layer of the next sample.

The Kevlar sheets were divided and cut into A4 size sheets to prepare them to be bound together using the recommended epoxy resin and hardener. The samples were left to dry. The samples were cut after the resin had set and bolted to each other and were placed into position for the tests to be conducted.

3. Tests and experiments

The experimental setup and ammunition used are discussed next followed by the experimental results that were obtained.

3.1. Experimental setup

Ballistic tests were carried out using two different kinds of ammunition, namely, full metal jacket (FMJ) and jacketed hollow point (JHP) of the 9 mm Parabellum (P or Para for short) calibre. The method used to test the samples is described next:

1) A firearm chronograph was set up to measure bullet speeds. The chronograph was placed 2 m from the muzzle of the firearms to prevent the muzzle flame to give inaccurate readings.
2) A baseline test was performed to determine the bullet velocity directly into the ballistic gel. The kinetic energy equation $E = (1/2)mv^2$ was used to determine the energy and distance of penetration into the ballistic gel.
3) The Kevlar samples were then placed in front of the ballistic gel and this was placed 1 m away from the chronograph. The reason for the distance of 1 m is to replicate the worst case scenario where a person or object is shot at a close distance.
4) The sample was shot with the projectile going through the chronograph to determine its initial speed. After this, the sample is penetrated and the projectile is lodged in the ballistic gel. The velocities of the tests were used to obtain an average velocity reading which was used to update the values in step 2.
5) The distance of penetration into the ballistic gel was measured and recorded.
6) Step 2 was repeated for each type of ammunition used in the tests. Step 3 to step 5 was repeated for each Kevlar sample. A test with specific ammunition was repeated if the projectile did not travel straight within the ballistic gel, or if it penetrated the Kevlar sample in an area that was considered not to be structurally sound.

The setup configuration is shown in Fig. 1.

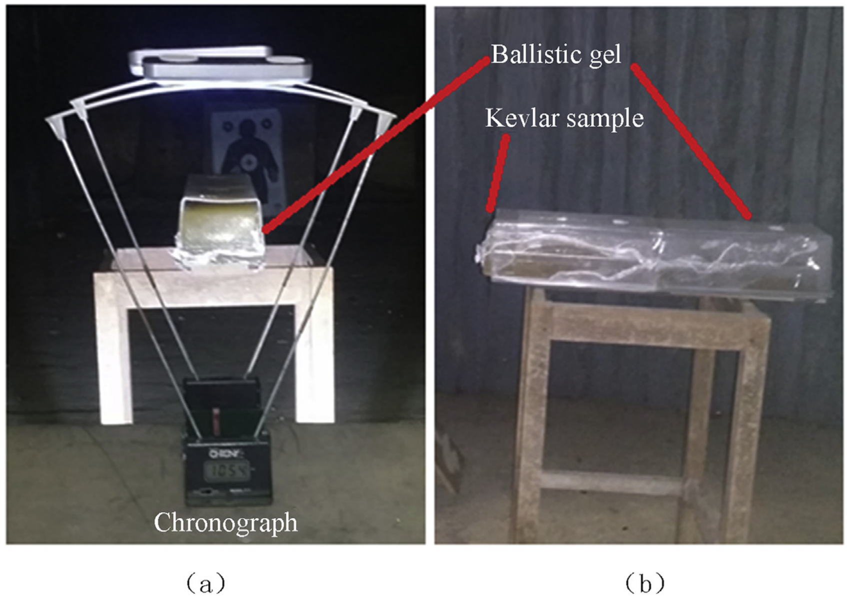

Fig. 1. Front (a) and side (b) view of the chronograph and ballistic gel for the experiments.

3.2. Ammunition characteristics

Information on the ammunition is given in Table 1. The ammunitions used in the tests are of common types and makes, used by the majority of firearm users. To compare the effects of different 9 mm Parabellum projectiles, different makes and types are considered. It is noted that the weight of ammunition is measured in grains (grs), where 15.432 grs is equal to 1 g. The weight indicated on the ammunition box is the weight of the projectile only and does not include the gun powder or cartridge. The characteristics of the ammunition are shown in Table 1. The velocities indicated in Table 1 are average velocities recorded in the experiments. The number correlating to each ammunition in Table 1 is used for the respective results in the graphs in this paper.

Tests were conducted by means of shooting the ammunition into the ballistic gel to replicate the characteristics of the impact in the event that a person was shot (bare chest). The pictures of different projectiles recovered from the ballistic gel can be seen in the YouTube video available at: https://www.youtube.com/watch?v=WvWsfDiVUiA. The distances that the projectiles travelled into the ballistic gel with no Kevlar are shown in Fig. 2.

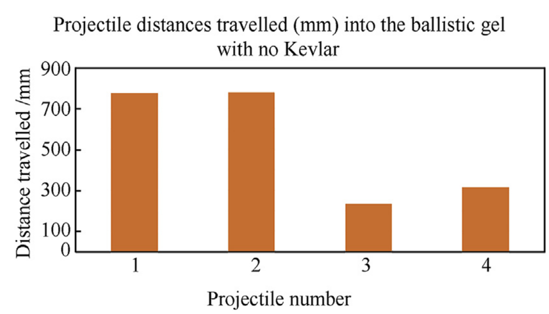

Fig. 2. Distances projectiles travelled into the ballistic gel with no Kevlar to penetrate.

3.3. 160 GSM Kevlar

The 160 GSM Kevlar tests were performed with samples of 3, 6, 9 and 12 layers, and the results are presented in Fig. 3. As the samples of Kevlar were of multiples of 3, the results are also shown in multiples of 3 on the *x*-axis.

With the 3 layer samples, the 9 mm Parabellum FMJ projectiles travelled slightly less in comparison to the case with no Kevlar. The hollow point projectiles travelled further as compared to the no

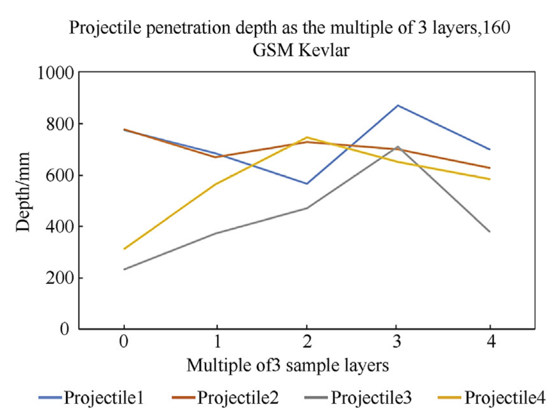

Fig. 3. Distances travelled by the projectiles after penetrating different layers of 160 GSM Kevlar.

Table 1
Characteristics of the ammunition used in the tests.

Ammunition	Bullet weight/grains	Bullet diameter/inches	Velocity/($m \cdot s^{-1}$)	Energy/kJ
1) Sellier and Bellot (S&B) 9 × 19 115 grs full metal jacket (FMJ)	115	0.35	373.4	519.507
2) Diplopoint 9 × 19 124 grs full metal jacket (FMJ)	124	0.35	354.5	504.893
3) Federal HST 9 × 19 147 grs jacketed hollow point (JHP)	115	0.35	327.1	398.661
4) Sellier and Bellot (S&B) 9 × 19 115 grs jacketed hollow point (JHP)	147	0.35	347.5	575.138

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Kevlar case. The 9 mm Parabellum projectile (number 4) did not deform much, but the brass jacket started to rip off the projectile.

The tests that were conducted with 6 layers of 160 GSM Kevlar indicated that the 9 mm Parabellum hollow point projectiles went further compared to no Kevlar penetration tests with projectile number 4 going almost the same distance as that of a FMJ projectile.

With the 9 layers of 160 GSM Kevlar, the corresponding distances travelled by the projectiles in the gel showed that projectile numbers 1, 3 and 4 went further after it went through the 9 layers of 160 GSM Kevlar, compared to the projectiles shot into the ballistic gel (no Kevlar).

The tests conducted with 12 layers of 160 GSM Kevlar show that all projectiles show a decreasing trend of penetration depth compared to 9 layers.

As seen in Fig. 3, the penetration depths of the projectiles fluctuate with depth as the number of layers increases, yet a decrease is observed from 9 to 12 layers in all cases. It was observed that the hollow point projectiles penetrated the Kevlar layers and in the process the hollow point was blocked with the Kevlar material. Once these hollow point projectiles reach the ballistic gel, they perform in the same manner as a FMJ projectile. Due to the above-mentioned reason with the Kevlar samples used, the projectiles penetrated further into the ballistic gel compared to the tests performed with no Kevlar. Only once sufficient layers of Kevlar were penetrated to absorb sufficient energy, did the projectile show characteristics of a decreased penetration into the ballistic gel. This characteristic was observed in the other tests, with the different weights Kevlar as presented in this paper.

3.4. 200 GSM Kevlar

The 200 GSM Kevlar tests were performed with samples of 3, 6, 9, 12 and 15 layers. Since 200 GSM Kevlar is commonly used for bulletproof vests, it was decided to perform tests with 15 layers. The results of the penetration into the ballistic gel are shown in Fig. 4.

The tests conducted with 3 layers of 200 GSM Kevlar shows that the 9 mm Parabellum FMJ projectiles went through the ballistic gel and the distances they travelled in comparison with the no Kevlar case were not reduced. The 9 mm Parabellum hollow point projectiles mushroomed out as expected, and the 9 mm Parabellum projectile number 4 had the brass jacket lodged into the ballistic gel, yet the lead projectile continued and stopped as recorded in Fig. 4.

With 6 layers of 200 GSM Kevlar, it was observed that the penetration distance of projectile 1 into the ballistic gel decreased while projectiles 2, 3 and 4 went further into the ballistic gel in comparison to the no Kevlar case.

The tests conducted with 9 layers of 200 GSM Kevlar show that projectile number 2 travelled further into the ballistic gel compared to the no Kevlar case. It was observed that projectiles 3 and 4 had Kevlar blocked in the hollow point which prevented it from mushrooming. Projectiles 3 and 4 travelled further into the ballistic gel after penetrating 9 layers of 200 GSM Kevlar in comparison to the no Kevlar case.

With the tests conducted with 12 layers of 200 GSM Kevlar, it was observed that 9 mm Parabellum FMJ projectiles, number 1 and 2, had a flatter head after penetrating. Projectile number 4, even though not mushroomed much with the hollow point blocked with Kevlar, was flattened more in the head. Projectile number 3 did not mushroom much, but there was evidence of the tip of the head being deformed.

The tests conducted with 15 layers of 200 GSM Kevlar, had both FMJ projectiles indicating signs of mushrooming. Projectile numbers 1 and 2 show a decrease in penetration depth into the ballistic gel compared to the no Kevlar case. In the present case, projectiles 3 and 4 were stopped by the Kevlar layers.

As seen in Fig. 4, when the averages between the points are considered, it seems to indicate a linear gradient of decreasing penetration into the ballistic gel to occur, once a peak at approximately 6 layers of 200 GSM Kevlar has been reached. The 200 GSM Kevlar is showing a better performance in comparison to the 160 GSM Kevlar, as expected. At 15 layers of the 200 GSM Kevlar, projectiles number 3 and 4 have been stopped, but not projectiles number 1 and 2. Following the average gradient, it is estimated that projectiles number 1 and 2 will be stopped using possibly 18 and 21 layers of 200 GSM Kevlar, respectively.

3.5. 400 GSM Kevlar

The 400 GSM Kevlar tests were performed using samples of 3, 6, 9 and 12 layers, as indicated by the results shown in Fig. 5.

The tests that were conducted with 3 layers of 400 GSM Kevlar, showed that projectiles 1, 2 and 3 kept mostly their original shapes. As seen in Fig. 5, projectiles 3 and 4 travelled further into the ballistic gel after it penetrated 3 layers of 400 GSM Kevlar, while the other projectiles showed a shorter distance of penetration.

The tests that were conducted with 6 layers of 400 GSM Kevlar, indicated that projectiles 1 and 2 penetrated a shorter distance with the 6 layers 400 GSM Kevlar, in comparison to the no Kevlar case.

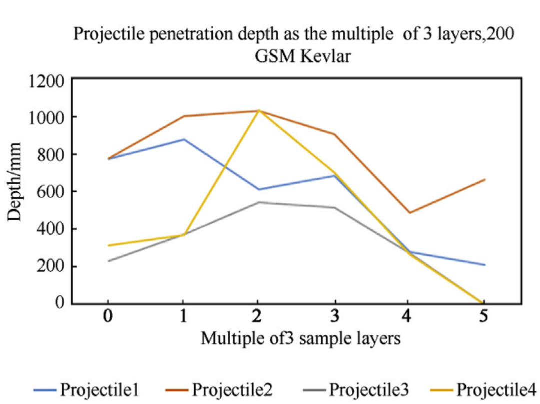

Fig. 4. Distances travelled by the projectiles after penetrating different layers of 200 GSM Kevlar.

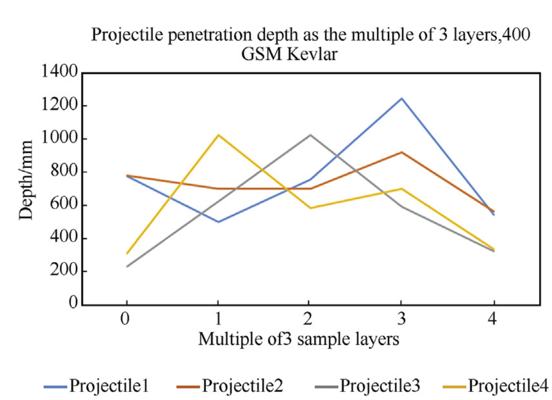

Fig. 5. Distances travelled by the projectiles after penetrating different layers of 400 GSM Kevlar.

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The tests conducted with 9 layers of 400 GSM Kevlar indicate that all the 9 mm Parabellum projectiles travelled further into the ballistic gel after penetrating 9 layers of 400 GSM Kevlar, in comparison to penetrating the ballistic gel only.

As with the 12 layers of 400 GSM Kevlar, travel of the 9 mm Parabellum FMJ projectiles decreased in distance into the ballistic gel, in comparison to the no Kevlar scenario. The 9 mm Parabellum hollow point projectiles travelled still further in comparison to the no Kevlar case.

As per the overall results shown in Fig. 5, the projectiles' penetration distances peaked, but all showed a decrease in penetration of 12 layers of Kevlar. Projectiles 1 and 2 would possibly be stopped with 15 layers or 18 layers of 400 GSM Kevlar if the gradients between 9 and 12 layers, in Fig. 5, are extrapolated.

4. Analysis and discussion of results

Fig. 6 shows the comparison of penetration depths of different projectiles into 3 layers of 160 GSM, 200 GSM and 400 GSM Kevlar. As seen in Fig. 6, with the 9 mm Parabellum hollow point projectiles, 3 layers of 200 GSM Kevlar stopped the projectiles in the shortest distance. 3 layers of 400 GSM and 160 GSM Kevlar stopped projectiles 1 and 2 the most, respectively.

Fig. 7 shows the corresponding results for 6 layers of 160 GSM, 200 GSM and 400 GSM Kevlar. From Fig. 7 it is observed that projectile 1 was stopped in the shortest distance with 6 layers of 160 GSM Kevlar while projectile 2 was stopped the most by 6 layers of 400 GSM Kevlar. As for the 9 mm Parabellum hollow point projectiles, 6 layers of 160 GSM Kevlar stopped projectile 3 the most while the 400 GSM Kevlar stopped projectile 4 the most.

Fig. 8 shows the comparison of 9 layers of 160 GSM, 200 GSM and 400 GSM Kevlar. As seen in Figs. 8 and 9 mm Parabellum FMJ projectile 1 has a decreased distance travelled into the ballistic gel with 9 layers of 200 GSM Kevlar. Projectile 2 shows a decreased distance of travelling into the ballistic gel with 9 layers of 160 GSM Kevlar. As for the 9 mm Parabellum hollow point projectiles, projectile 3 travelled less distance into the ballistic gel with 9 layers of 200 GSM Kevlar while projectile 4 has less distance of travel with 9 layers of 160 GSM Kevlar.

Fig. 9 shows the comparison of 12 layers of 160 GSM, 200 GSM and 400 GSM Kevlar. The least penetration into the ballistic gel with all projectiles occurred with 9 layers of 200 GSM Kevlar.

Fig. 10 shows the number of layers of Kevlar which were able to stop the different projectiles. From Fig. 10, it can be observed that 200 GSM Kevlar stops the projectiles more on average. Fig. 10 also shows that except for projectile 1 and 2, all projectiles were stopped with 9 layers of 200 GSM Kevlar. 160 GSM and 400 GSM Kevlar did not perform satisfactorily and did not stop any of the tested projectiles, and therefore no data for these specific weights Kevlar are shown in Fig. 10.

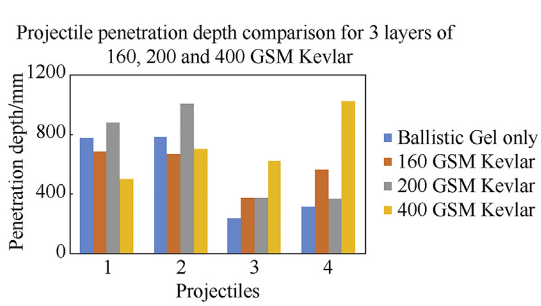

Fig. 6. Penetration depth comparisons for 3 layers of 160 GSM, 200 GSM and 400 GSM Kevlar.

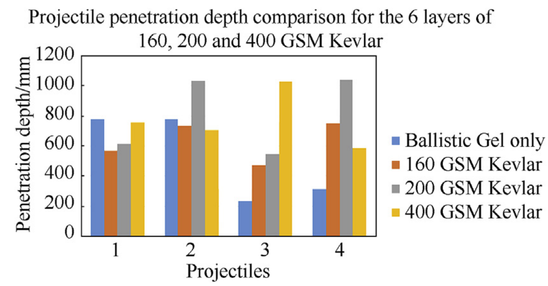

Fig. 7. Penetration depth comparisons for 6 layers of 160 GSM, 200 GSM and 400 GSM Kevlar.

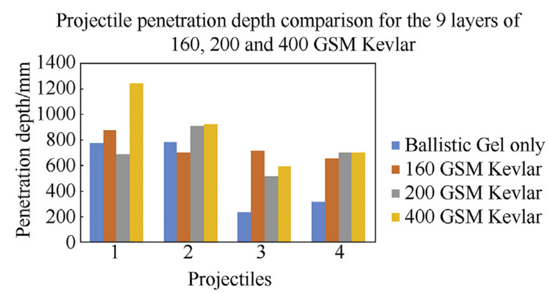

Fig. 8. Penetration depth comparisons for 9 layers of 160 GSM, 200 GSM and 400 GSM Kevlar.

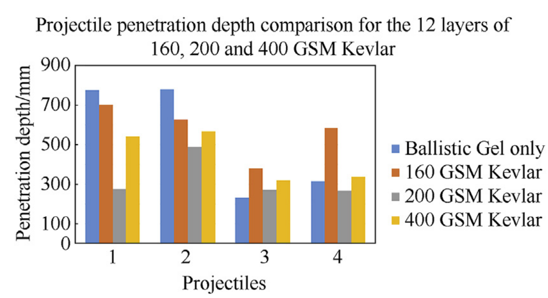

Fig. 9. Penetration depth comparisons for 12 layers of 160 GSM, 200 GSM and 400 GSM Kevlar.

Figs. 7 and 9 indicate that there are no similar characteristics with different projectiles for two different numbers of layers of similar GSM. An example is 12 layers of 200 GSM Kevlar and 6 layers of 400 GSM Kevlar. Both of these samples have a total of 2400 GSM Kevlar each. When comparing these two different samples, they do not decrease the distance of the projectiles by a similar amount. Similar correlations and conclusions can be observed from 3 layers of 400 GSM Kevlar and 6 layers of 200 GSM Kevlar. Each of these cases has 1200 GSM samples, but do not have similar characteristics in the results.

Average curves for projectiles 1 and 2, shown in Fig. 4, indicate that the projectiles would stop with 6 and 7 multiples of 3 layers of the 200 GSM Kevlar, respectively (i.e. 18 and 21 layers of 200 GSM Kevlar). There is a trend that approximately double the number of layers of Kevlar which is needed, in comparison to the actual damaged Kevlar to stop the projectiles. With 18 and 21 layers of 200 GSM Kevlar, it will result in the projectiles 1 and 2 to stop in approximately 9 and 10 layers of Kevlar. This number of layers correlates with the number of layers of Kevlar that commercially available Kevlar-only bullet proof vests contain.

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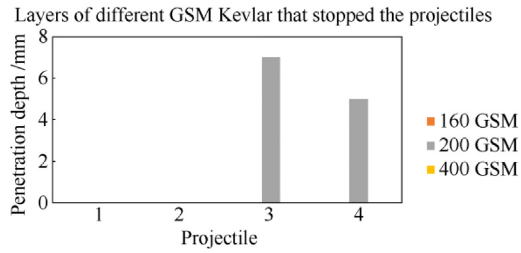

NB: Data for 160 GSM and 400 GSM results are not shown in this figure as none of the projectiles were stopped by layers of Kevlar for these specific weights.

Fig. 10. Layers of different GSM Kevlar that stopped the projectiles.

5. Conclusions

Comparisons of 160 GSM, 200 GSM and 400 GSM Kevlar under ballistic impact have been made with the ballistic tests carried out with 9 mm Parabellum ammunition and with different number of Kevlar layers. It was observed that a few layers of Kevlar are not effective in stopping the projectiles, but rather forces the projectiles to travel further into the ballistic gel. Only once the number of layers is increased, the decrease in the projectile penetration into the ballistic gel was observed. The reason for this peak in penetration, especially with the hollow point projectiles, was due to the hole filling up with Kevlar material and making it perform as a FMJ projectile. Similar averaged negative gradients were observed between the FMJ and hollow point projectiles, once the peak has been reached.

Summarising the contributions of this paper, it can be concluded:

1) The effectiveness of different layers of 160 GSM, 200 GSM and 400 GSM grades of Kevlar layered with ballistic gel was investigated, and it was found that 200 GSM Kevlar was more effective for stopping a 9 mm Parabellum projectile.
2) It was found that there is no linear relationship between two different types of Kevlar with different weights (such as 200 GSM and 400 GSM Kevlar), layered in such a way that they have the same combined weight.
3) Four different types of 9 mm Parabellum ammunition were tested, and their penetration depths into the ballistic gel were identified for different layers of Kevlar.
4) It was assessed that for a 9 mm Parabellum ammunition, which are most commonly used around the world, 21 layers of 200 GSM Kevlar is required as a minimum to stop the projectile. It is suggested that, as a safety precaution, an additional safety factor is included as the penetration is dependant also on the projectile profile.

Based on the results presented above for the characteristics of Kevlar layers of different weight, it is hoped that these characteristics can be used to develop and design safe and effective bulletproof vests.

The general trend that double the amount of layers of Kevlar is needed as compared to the actual amount of layers damaged, would be worthwhile to explore in further research with different ammunition. Future research would also be able to indicate the penetration effect that smaller calibre projectiles and ammunition have on Kevlar in comparison to that of 9 mm Para ammunition. Similarly, future research will be able to identify how different ammunition and projectiles penetrate 200 GSM Kevlar such as the Kevlar used only in bulletproof vests. With the characteristics observed with the hollow point projectiles penetrating deeper into the ballistic gel, after the hollow point is blocked with Kevlar, future research would allow to identify if a similar effect would be experienced in a scenario where the projectile penetrated clothing, before penetrating flesh.

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