

Effect of coconut shell powder filler on performance of polyester composites for ballistic application

G Maheswaran^{1,a}, R Murugan¹ & Abhijit Majumdar²

¹Department of Textile Technology, PSG College of Technology, Coimbatore 641 004, India

²Department of Textile and Fibre Engineering, Indian Institute of Technology Delhi,
New Delhi 110 016, India

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This work reports the use of coconut shell powder filler with polyester resin for the development of Nylon 6.6 fabric reinforced composite panels. The impact resistance of the prepared composites against 0.22 caliber projectile has been studied at four different weight proportions (10%, 20%, 30% and 40%) of coconut shell powder filler. With an increase in filler proportion, the depth created on the clay backing after ballistic impact is found to decrease from 7.62 cm to 4.60 cm in the 25 m range and from 7.62 cm to 2.39 cm in the 30 m range. Consequently, the area involved in impact energy absorption is also found to increase from 0.44 cm² to 2.27 cm² in the 25 m range and from 1.86 cm² to 4.9 cm² in the 30 m range. The increase in the area due to the absorption of impact energy ensures effective distribution of the impact energy over the panels. Coconut shell powder filler added with resin has a significant effect in improving the impact resistance of the composite panels due to the changes in the inter-yarn frictional force of the reinforced fabrics. Further, the impact test results are based on the findings of tensile strength test and Rockwell hardness test. There is an increase in tensile strength by 25% and hardness by 41.6% as compared to the control sample.

Keywords: Ballistic application, Coconut shell powder, Composite, Impact resistance, Nylon 6.6, Polyester resin

1 Introduction

Researchers and technologists over the years have been trying to develop protective systems that are efficient as well as light in weight. However, most armour materials are expensive and have limitations regarding weight. In this perspective, natural fibre-based fillers have gained attention due to their low density and high specific strength. Besides, they are eco-friendly, easily available and renewable. Body armours have been in use on the battlefields to safeguard the soldiers for the last three hundred years¹. Continuous improvements in their design are sought for empowering them against the increasing threat levels every day. While designing the protective armour systems for ballistic threats, the desired performance attributes need due consideration. Aspects, like resistance to multiple impacts without undergoing catastrophic failure and environmental stability, are also crucial. The standards laid down by the National Institute of Justice (NIJ), ranging from Level I to Level IV (NIJ 0101.04), take care of these requirements. Despite

being formulated specifically for personal body armour, these standards are frequently used to compare various other armour products.

Body armour may be categorized mainly into two types, namely soft armour and hard armour, which are used to resist impacts up to and beyond NIJ 0101.06 level IIIA, respectively². The hard body armours are used to protect the wearer from fragment, and the soft ones are used against the piercing projectiles. The modern soft body armours are made from high-performance fibres to achieve higher protection levels at less weight². In the case of hard armour, oxide ceramics are most popular. However, the determination of the ballistic performance of ceramics has been a difficult task due to reasons like the type of threat, projectile velocity, projectile geometry and nature of ceramics. In recent years, researchers have started utilizing natural fibre-based ballistic materials.

It is reported that the ballistic limit or V_{50} velocity of the natural fibre composites is increased non-linearly on increasing the areal density and thickness of flax, hemp and jute-reinforced polypropylene composites, with or without mild steel backing^{3,4}. There is an improvement in the ballistic performance of high-strength, high-modulus fabrics coated with

^aCorresponding author.
E-mail: mah.textile@psgtech.ac.in

natural rubber owing to higher inter-yarn friction in comparison to uncoated fabrics⁵. Also, there is a linear correlation between stress and filler content corresponding to tensile and flexural tests of composites prepared from agricultural wastes⁶. The decrease in weight and high performance for the economical manufacturing cost are the biggest assets for the great demand for natural materials in various industrial segments⁷.

Coconut shell powder is an effective filler for the development of composites owing to its inherent high strength and high modulus⁸. The coconut shell powder comprises lignin (29%), pentosans (28%), cellulose (27%), moisture (8%), solvent extractives (4%), uronic anhydrides (3.5%), and ash (0.5%)⁹. Coconut shell powder with mesh size 80 - 100 per inch² is recommended as filler in synthetic resin glues. Also, this mesh size finds applications in industries like automotive, aerospace, electrical and electronics¹⁰. Coconut shell powder reinforced HDPE (high density polyethylene) composites exhibit good bending, impact and tensile strength at moderate volume fractions of 10 to 20% rather than slightly higher volume fractions of 30-40% due to less interfacial bonding¹¹. Moreover, coconut shell powder mixed with polyurethane matrix (up to 6% volume fraction) shows a significant increase in the tensile strength, compression strength and impact energy. There is an increase in hardness and water absorption of polyurethane matrix, as the volume fraction of coconut powder was increased to 10%. Similarly, coconut shell powder mixed with unsaturated polyester matrix at different volume fractions from 0% to 50% shows good improvement in tensile and flexural strength of composites¹². A further enhancement in composite properties can be noticed upon treating coconut shell powder with alkali¹³. The strength and modulus of elasticity of the epoxy composite panels are retained even after 35% of the coconut shell powder reinforcement addition¹⁴.

Aramid group fibres, such as Kevlar®, Twaron®, Nomex® and Technora®, have been extensively studied and used for ballistic applications at a large scale^{15,16}. At present, ultra-high molecular weight polyethylene (UHMWPE) fibres have evolved as a better choice due to their lower density and higher strength-to-weight ratio in comparison to aramids^{17,18}. Their uses, however, are normally restricted to the sheet/laminate form and are less popular in fabric form⁵. However, despite being highly efficient, aramids and UHMWPE are very expensive and hence

unsuitable for highly populated growing nations where bulk manufacturing is required^{19,20}.

Decades back, Nylon 6.6 was the most preferred fibre for ballistic application due to its energy absorbing capacity, which is slightly higher than *p*-aramids. However, the high creep associated with it poses a limitation to its usage. Nevertheless, due to its features like high melting point (up to 265°C), high tenacity, less shrinkage in steam and resistance to heat and fracture with good dimensional stability, it finds numerous applications in seat belts, tire cords, ballistic cloth and military applications. Using good matrix and filler, Nylon 6.6 fabric reinforced composite panels may be utilised for a high-end application, like ballistics, which forms the basis for the present work. Many studies have been reported using epoxy resins and a little fewer with polyester resins. A subtle point is that, polyester resin possesses satisfactory physical properties, less curing time, cost-effectiveness, less dense and, therefore, in combination with the coconut shell powder, doesn't increase the weight much.

2 Materials and Methods

2.1 Materials

A plain woven fabric with an areal density (mass per unit area) of 212 g/m² was made on a sample loom using 840 denier multi-filament Nylon 6.6 yarns sourced from SRF, Chennai, India. The specifications of the produced fabric are given in Table 1. The unsaturated polyester resin for moulding was sourced from M/s AYPOS Polymers, Coimbatore; and coconut shell powder of mesh size 100 per inch² was sourced from M/s QZON India. The scanning electron microscopic (SEM) images of coconut shell powder are shown in Fig. 1.

2.2 Composite Manufacturing

The woven fabric was cut into samples of size 27 cm × 27 cm, approximately weighing 15 g each. Polyester resin (12.5g) was used to prepare the composite with a fibre weight fraction of 0.5. The coconut shell powder taken in different weight proportions, namely 0%, 10%, 20%, 30% and 40%, was thoroughly mixed with polyester resin using a

Table 1 — Specifications of Nylon 6.6 fabric

Parameter	Details
Yarn specifications	840 denier (120 filaments)
Weave	Plain
Warp density, cm ⁻¹	13
Weft density, cm ⁻¹	10
Areal density, gm ⁻²	212

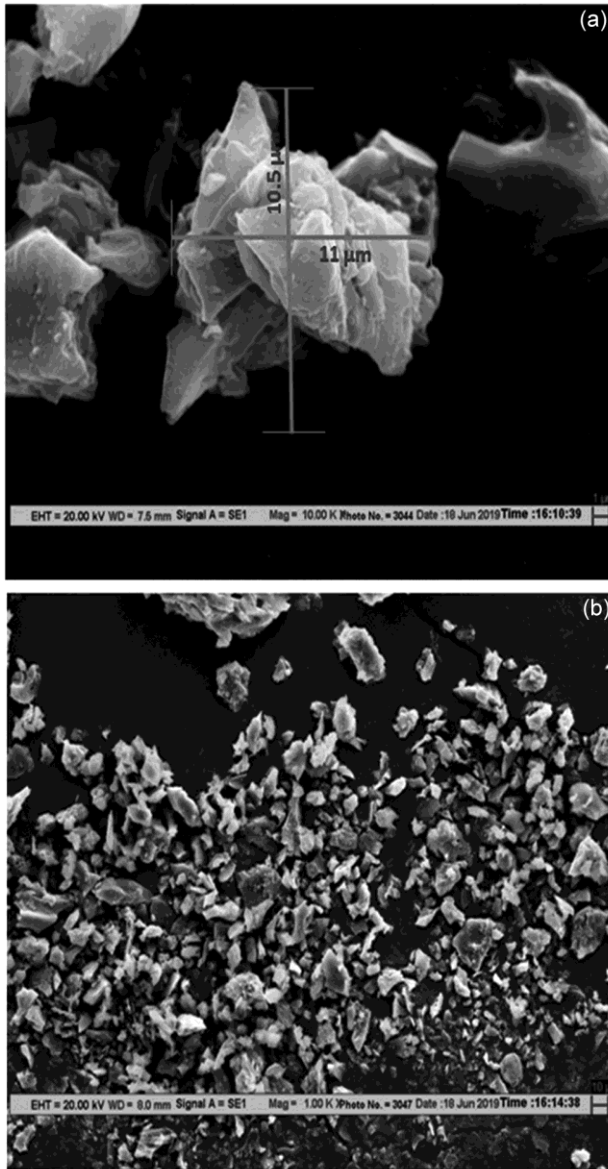


Fig. 1 — SEM images of coconut shell powder (a) ×10000 magnification (b) ×1000 magnification

mechanical stirrer (to make a homogenous mixture) at 27°C in weight fractions of 100:0, 90:10, 80:20, 70:30 and 60:40 (polyester resin:coconut shell powder). The resultant weight of resin mixture was maintained at 10 g for all five combinations. Each of the five resin mixtures was applied separately on both sides of the fabric sample using a brush over the fabric surface. After the resin application, the hand consolidation roller was used to distribute the resin mixture throughout the fabric surface and excess resin was squeezed to remove the voids. This was done before the samples were taken for compression moulding. The coated fabrics were then arranged into a

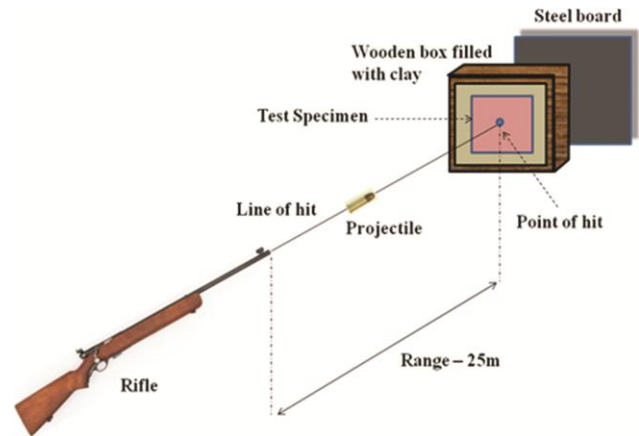


Fig. 2 — Schematic view of the shooting range

Table 2 — Coding of composite panels

Sample code	Coconut shell powder, %	Polyester resin, %	Fabric weight, %
P1 (Control)	0	50	50
P2	10	40	50
P3	20	30	50
P4	30	20	50
P5	40	10	50

4-layered assembly/panel, prepared with a 90° phase shift between each successive layer to impart higher resistivity during impact²¹. The prepared multi-layered fabric panels or ensembles were then converted to composite panels in a compression moulding machine under 1 kg(f)/cm² pressure at 80°C, and the sample was cured for 24 h at 27°C. Compression was applied to keep the 4 layers intact and heating reduces the viscosity of resin, thereby improving its flow to cover the entire specimen. The details of the developed panels with 3 mm thickness and 3700 g/m² areal density are listed in Table 2. All panels (P1 – P5) comprised 50% reinforcement content, i.e. Nylon 6.6 fabric.

2.3 Ballistic Performance Evaluation

The composite panels were tested for compliance within NIJ 0101.04 level I standard using a 0.22 LR rifle firing projectiles at 130 m/s with 5 fair hits per panel. The mass and kinetic energy of the projectile were 40 grain and 141 J respectively. The ballistic impacts were made from two distances, (25 m and 30 m). The schematic of the basic test setup is shown in Fig. 2, and the details of the rifle and projectile are mentioned in Table 3. The test specimens were fixed in front of a Roma plastilina clay mould, which simulated the physiological nature of the human body. The depth of an indentation in the clay post impact or back face signature (BFS) and the area of wave propagation were measured using a vernier scale. For

Table 3 — Details of rifle and projectile

Component	Value
Parent case	0.22 long
Case type	Rimmed, straight
Bullet mass, grain	40
Bullet diameter, mm	5.7
Neck & Base diameter, mm	5.7
Rim diameter, mm	7.1
Rim thickness, mm	1.1
Case length, mm	15.6
Overall length, mm	25.4
Rifling twist	1:16
Primer type	Rim fire

comparison between different panels, the shot corresponding to the maximum BFS was considered for each panel.

2.4 Tensile Strength Testing

ASTM D 3039 universal tensile testing was used to test the tensile strength of the prepared composites. The force necessary to break a polymer composite specimen and the extent to which the specimen stretches or elongates to that breaking point are measured using tensile testing. The sample with the dimension of 250 mm length and 25 mm width was used for the composites for the tensile strength test. Tensile tests were carried out with a strain rate of 0.02 inch/min. The elongation can be read by the provided strain gauge. As the elongation value is directly proportional to the tensile modulus value (in MPa), it is more than enough to evaluate the specimen strength.

2.5 Hardness Testing

ASTM E18–22 was followed to test the hardness of the prepared composites. A ball indenter with a diameter of 1.588 mm was used to press the specimen with a load of 100 kgf. The load exerted by the sample can be directly taken from the display. The B scale is used to measure the hardness of the sample. Hardness Rockwell B-scale value is termed as HR_B . The test was carried out at three different places of the specimen to achieve an average value of the hardness. Hardness Rockwell B-scale value is measured from the depth of the indent created on the sample and the force applied. This is a simple method and widely used in industry. The hardness value has no units. Here, the number is directly proportional to the hardness of the specimen.

3 Results and Discussion

3.1 Ballistic Test

The bullets and panels are observed for damage analysis. Generally, the nature and number of layers

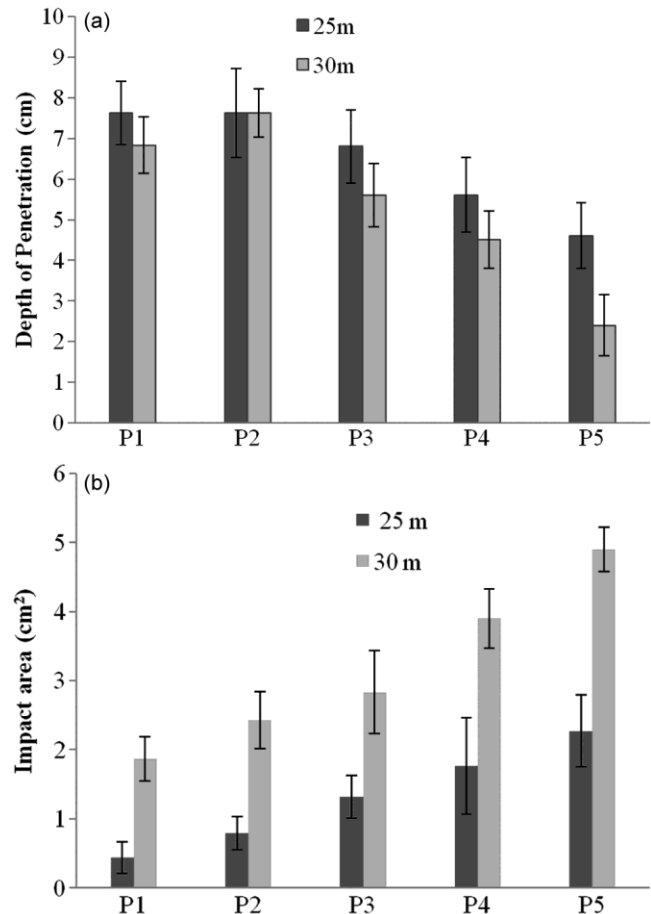


Fig. 3 — (a) Depth of penetration and (b) area of impact by the projectile on the composite panels

of the backing material, type of adhesive and the bonding technique strongly affect the ballistic performance. The ballistic performance of various composite samples is shown in Fig. 3.

Figure 3 (a) shows that the depth of penetration of projectile in composite samples decreases linearly with an increase in the percentage of coconut shell powder. The depth of penetration created by the projectile varies from 4.60 cm to 7.62 cm at 25 m firing distance, and from 2.39 cm to 6.98 cm at 30 m, indicating a decrease in the ballistic impact at greater firing distances. Besides, a significant difference exists in BFS between control panel and coconut shell powder reinforced panels. This may be attributed to the enhancement in friction between fibres on addition of coconut shell powder, thereby resembling the fibres could be held tightly together and may have significantly absorbed the energy through friction and extension, leading to lesser penetration depths.

Figure 3 (b) shows the area involved in impact energy absorption corresponding to different composite

panels. This area, at or around the point of ballistic impact, increases from 0.44 cm² to 2.27 cm² in the 25 m range and from 1.86 cm² to 4.9 cm² in the 30 m range. The area involved in impact energy absorption is indicative of the effectiveness of the composite panel in restraining the projectile. For the panel to efficiently resist the projectile efficiently, it must propagate the stress waves generated upon impact at a fast rate around the point of impact²². Therefore, the involvement of a larger area in stress wave propagation signifies higher ballistic resistance²³. Figure 3 (b) shows that the area participating in impact energy absorption increases linearly with an increase in filler percentage for both the firing distances. This observation is corroborated by the larger deformation of projectiles in the case of filler reinforced panels in comparison to that in the control panel (Fig. 4). A closer look at Fig. 5 shows all composite panels post ballistic impact, and also augments this finding. The origin of the loci of cracks from the impact point is distinctly visible in all panels. A clear case of penetration is seen in the control panel (P1). For panels P2 – P5, a gradual increase in the spread of the area of stress wave propagation is seen at around impact points with the increase in filler concentration.

3.2 Failure Mechanism under Ballistic Impact on Developed Composite and Crack Propagation

The top layer of the composite, when hit by the projectile, undergoes compression apart from the cone formation. The extent of compression is dependent on the stress at the point of impact. At the beginning of impact, strain in the top layer is more than that in the

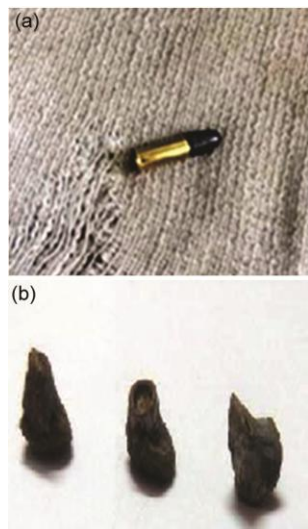


Fig. 4 — Projectile deformation (a) before and (b) after hitting the panel

bottom layer. Whether the projectile strikes the target at the point of intersection of warp and weft or the gap formed between two adjacent parallel warp or weft yarns plays an important role in the energy absorption process. Primary yarns take the direct force and fail if the strain exceeds the maximum strain limit. Failure of these yarns results in the absorption of some energy. The secondary yarns deform and absorb some energy, which depends on the strain distribution within the secondary yarns. There will be a sequential failure of yarns starting with the yarns in the top layer and then proceeding towards the bottom layer. Delamination and matrix cracking would absorb some energy. The schematic image of reinforced composite failure mechanism is shown in Fig. 6.

3.3 Tensile Strength Test

The tensile strength of the samples ranges from 60 MPa to 84 MPa as shown in Fig. 7 (a). Each sample undergoes three tests. The control sample (P1) exhibits an average value of 55.53MPa, while samples P2, P3, P4 and P5 exhibit average values of 68.67MPa, 73.40MPa, 79.09MPa and 83.13MPa respectively. The variation in the values shows the

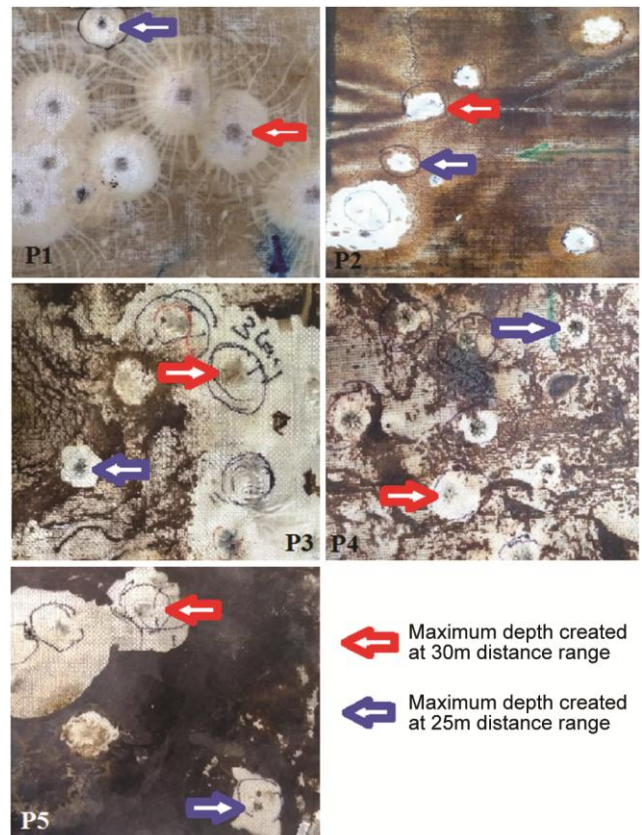


Fig. 5 — Post impact images of composite panels (a) 0%, (b) 10%, (c) 20%, (d) 30% and (e) 40% filler composites

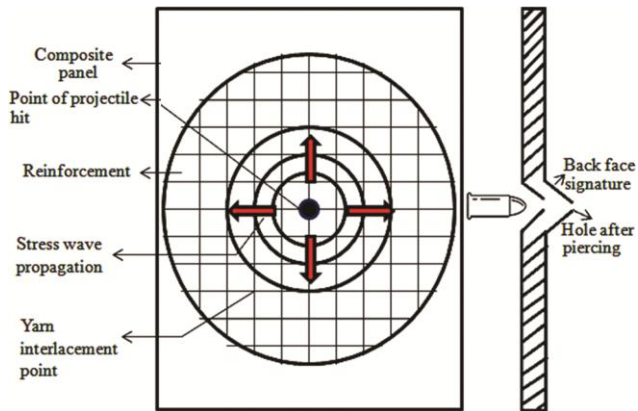


Fig. 6 — Schematic view of failure mechanism of fabric reinforced composite

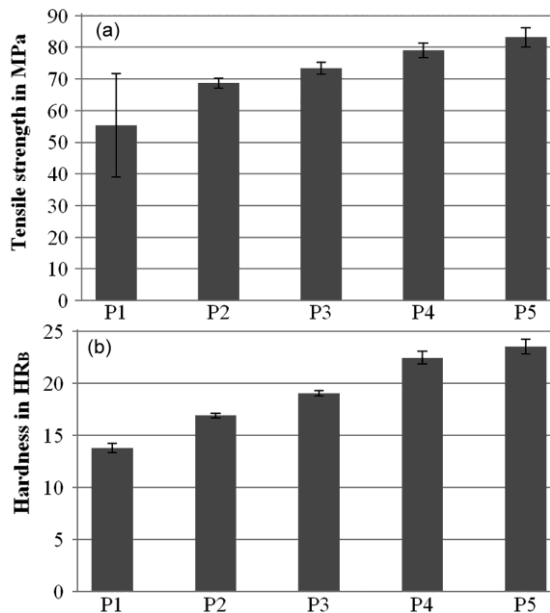


Fig. 7 — (a) Tensile strength and (b) hardness of the composite panels

linearly increasing trend of the tensile strength with respect to the increase in the filler percentage.

3.4 Hardness Test

The hardness tested by Rockwell hardness tester exhibits the results ranging from 14 to 24. Three tests are carried out for each sample and the average of P1 (control sample) is found 13.77HR_B. For P2, P3, P4 and P5 samples, the hardness values increase with the increase in filler weight fraction, ranging from 16.90 HR_B to 23.53 HR_B. The results supplement the ballistic and tensile strength test [Fig.7 (b)].

4 Conclusion

Composite panels have been made using plain-woven Nylon 6.6 fabrics as reinforcement, polyester resin as matrix and coconut shell powder as filler.

These panels are tested for ballistic resistance using a 0.22 LR rifle at two different distances. It is found that as the coconut shell powder content increases, the impact resistance of the composite panels improves. A decrease in the back face signature is found with the increase in the filler content. Similarly, the area of impact energy absorption expands with the increase in filler content. The fibres rupture around the piercing point increases with the increase in filler content. The tensile strength and the hardness of the composite panels are also found to increase with the increase in filler content. This ensures that there is an increase in the resistivity of panels towards the projectile due to the efficient energy distribution between fibres. Thus, the addition of filler has the potential to improve the impact resistance of fibre reinforced composites.

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