Tensile and Flexural Properties of a Newly Developed Bulletproof Vest Using a Kenaf/X-ray Film Hybrid Composite

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In terms of manufacturing cost and weight, current bulletproof vests are simply not optimized. This means that consumers and manufacturers alike desire a bulletproof vest that is more user-friendly, cheaper, and lighter. This study considered the tensile and flexural characterization of new lighter and cheaper hybrid composite materials to replace the existing insert panel for the currently available bulletproof vest. The materials chosen included a natural fibre, *i.e.,* kenaf fibre, chemically treated with sodium hydroxide solution, and, as a means of recycling, used x-ray films with a surface treatment. Using the traditional hand lay-up method, the materials were fabricated into seven layers of different configurations, which were then subjected to tensile and flexural tests. The findings showed that one of the configurations that consisted of both treated materials had a tensile strength of 396.9 MPa, which is quite strong, and a flexural modulus of 6.24 GPa, which makes it flexible enough to be made into wearable equipment. This configuration was then chosen to be the base design for the specimen subjected to impact test. The interfacial bond between the two distinct materials proved to be a major issue, even with the help of fibre treatment. Therefore, some improvements need to be made for the material to be comparable to existing materials performance-wise hence making this configuration suitable for ballistic application. However, the design did show promising results by stopping a bullet with speed up to 230 m/s.

Keywords: Kenaf fibre; X-Ray; Chemical treatment; Surface treatment; Tensile test; Flexural test; High-velocity Impact Test

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INTRODUCTION

Other than stopping speeding bullets, the purpose of ballistic-resistant material also includes protecting the individual from fragmenting devices, such as mortars, grenades, and artillery shells. All ballistic-resistant equipment, such as bulletproof vests and helmets, are known to contain high-strength fibres such as aramid, ultra-high-molecular-weight polyethylene (UHMWPE), nylon, and glass, which are among the fibers conventionally used (Lee *et al*. 2003; Wambua *et al*. 2007; Kumaravel and Venkatachalam 2014; Luz *et al*. 2015). In most cases, the fibres are used for many applications, such as vests or parts of vests in a woven or knitted fabric. In some cases, the fibres are encapsulated or embedded in a composite material.

Depending on the manufacturer, the ballistic-resistant panels used in body armours can consist of different materials. For currently available panels, the materials generally would be one of the following: para-aramids, ultra-high-molecular-weight polyethylene (UHMWPE), or hard armour materials. Aramids are synthetic man-made fibres that are heat-resistant and extremely strong, with exceptional strength-to-weight ratios. The first para-aramid, introduced in 1973, was the famous Kevlar. Para-aramid materials introduced the idea of manufacturing lightweight and flexible body armour that provides a high level of protection. Another popular choice for ballistic-resistant panels is UHMWPE. Even though it has many similar attributes to the para-aramids, it is a kind of polyolefin, made up of very long chains of polyethylene. The most common types of hard body armour panels were made from metals, such as steel, but they are heavy and often ineffective. Similar to soft body armour panels, modern hard body armour can be produced from a range of materials. The newer types of hard body armour panels are made from ceramics or ceramic composites, usually with a para-aramid support such as Kevlar (ARMOR^{TM} 2009).

Researchers have become aware of the significance of natural fibre application. Many researchers have started focusing on natural fibres, not just for ballistic cases, but for other applications as well (Hamdan *et al*. 2016; Salman *et al*. 2016). X-ray waste and fibre-reinforced biocomposites are employed in this research to promote the green composite concept. By impregnating a shear thickening fluid (STF) into the fabric, Lee *et al*. (2003) found that it helped to enhance the ballistic properties of the fabric significantly due to its better capacity to absorb and dissipate kinetic energy. Da Luz *et al*. (2015) found that the ballistic performance of an epoxy composite reinforced with jute fabric can even compete with Kevlar. Through comparing the level of energy absorption, Wambua *et al*. (2007) found that hybrid structures have an obvious advantage over mild steel and plain flax, as well as hemp and jute composites. Moreover, natural fibre costs and weighs considerably less, apart from the environmental and societal benefits from using natural fibre (Brouwer 2013).

Due to consumer, industry, and government regulations in various countries on environmental awareness, researchers and industries have focused on Kenaf fibre for use in different polymer composites. Reinforced with epoxy resin, Kenaf fibres form fibre-reinforced polymeric composites that improve the strength of the composites (Bharath *et al*. 2015).

Table 1. Properties of Kenaf Fibre (Bharath *et al*. 2015)

Fibre	Diameter (mm)	Ultimate Stress (MPa)	Density (kg/m^3)	Specific Stress (dynes)	Water Absorption for 24 h (%)
Kenaf	0.15 to 0.30	350 to 600	1500	0.22 to 0.44	0.95

A research study by Bharath *et al*. (2015) showed that a kenaf composite is suitable for high-performance applications compared to other natural fibre composites because of its superior mechanical strength and thermal properties.

Table 2. Development of the Bulletproof Vest

Design	Materials Used	Reference
Ballistic impact resistance of graphite epoxy composites with shape memory alloy and extended chain polyethylene spectra™ hybrid components	Shape memory alloy (SMA), spectra	(Ellis 1996)
The ballistic impact characteristics of Kevlar® woven fabrics impregnated with a colloidal shear thickening fluid	Kevlar, Nissan chemicals (MP4540)	(Lee *et al*. 2003)
Ballistic resistance capacity of carbon nanotubes	Carbon nanotubes	(Mylvaganam and Zhang 2007)
The response of natural fibre composites to ballistic impact by fragment simulating projectiles	Polypropylene, flex, hemp, jute	(Wambua *et al*. 2007)
Ballistic performance of coconut shell powder/Twaron fabric against non-armour piercing projectiles	Coconut shell powder-epoxy composite (COEX), Twaron fabric	(Risby *et al*. 2008)
Development of a green combat armour from Rame-Kevlar-polyester composite	Ramie, Kevlar, polyester	(Radif *et al*. 2011)
Finite element modeling of ballistic impact on a glass fiber composite armor	Glass fiber	(Davis 2012)
Aspects regarding the use of polyethylene fibers for personal armor	Endumax, alumina	(Alil *et al*. 2013)
Ballistic properties of hybrid thermoplastic composites with silica nanoparticles	Multi-axial aramid, Twaron, polymer powder poly, absolute ethanol	(Obradovic *et al*. 2014)
Development of nylon, glass/wool blended fabric for protective application	Nylon, glass, wool, multi-walled carbon nanotube	(Kumaravel and Venkatachalam 2014)
Ballistic test of multilayered armor with intermediate epoxy composite reinforced with jute fabric	Nb_2O_5 doped Al_2O_3 impact resistant ceramic, Kevlar, jute fabric reinforced epoxy matrix composite	(Luz *et al*. 2015)
Bullet proof vest using non-Newtonian fluid	Kevlar, bootblack, polyethylene glycol and silica mixture	(Seshagiri and Alexander 2015)
Combination of natural fiber *Boehmeria nivea* (Ramie) with matrix epoxide for bullet proof vest body armor	Ramie, cotton-rayon	(Anggoro and Kristiana 2015)
Design of a bullet-proof vest using shear thickening fluid	Shear thickening fluid, dyneema	(Fernando *et al*. 2015)
Experimental and numerical analysis of bulletproof armor made from polymer composite materials	Kevlar, Al_2O_3	(Oleiwi *et al*. 2015)
Giant bamboo fiber reinforced epoxy composite in multilayered ballistic armor	Nb_2O_5 doped Al_2O_3 brittle ceramic, aramid fiber, giant bamboo fibers reinforced epoxy matrix composite	(Pereira *et al*. 2015)
Natural curaua fiber-reinforced composites in multilayered ballistic armor	Curaua fiber-reinforced composites, Al_2O_3 ceramic, aluminum alloy	(Neves Monteiro *et al*. 2015)

Based on various research studies, outstanding mechanical properties allow kenaf bast fibres to replace glass fibres as the reinforcement element in polymer composites because they are taken from the pith, bast, and core; which makes them suitable for various applications (Tahir *et al*. 2011; Faruk *et al*. 2012; Karimi *et al*. 2014). Apart from natural fibre composites, hybrid composites between natural fibre and synthetic fibre are also widely studied and used in various applications. X-ray films are a synthetic fibre made from polymer which are a non-biodegradable waste and needs an innovative way to be recycled. An x-ray film shows a radiographic image and is produced from either a single or double emulsion of silver halide, usually silver bromide, which produces a silver ion (Ag^+) and an electron when exposed to light. The electrons attract the silver ion when they become attached to the sensitivity specks. Subsequently, clumps of metallic silver are formed when the silver ions attach (Curry *et al.* 1990; Mosby and Bushong 2009).

The base, the emulsion, and the protective coating are the three main parts that make up an x-ray film. The base is where the other materials are applied and exists in all x-ray films. Usually, the base is made from a clear, flexible plastic such as cellulose acetate. The base's main purpose is supporting the emulsion. The softer layers of the gelatin coating are called the emulsion. An emulsion holds something in suspension. It is this material that is sensitive to radiation and forms the latent image on the film in suspension. Lastly is the protective layer, whose main function is to protect the softer emulsion layers below. In simpler terms, it is a very thin skin of gelatin protecting the film from scratches throughout handling. To film manufacturers, it has very important properties that include shrinkage (during drying this forms glassy protective layers) and dissolution in warm water. If it is dissolved in cold water, it will absorb the water and swell (NDT Resource Center 2001).

Table 2 shows that extensive research has been performed on composite materials regarding their ballistic application, whether with natural fibre or synthetic fibre composites. However, it can also be observed that there have not been many studies on kenaf fiber, and certainly much fewer, if any, on x-ray films. In addition, these studies give a strong impetus for replacing existing materials with a natural fibre composite. Therefore, due to the materials' properties and the gap in the research related to ballistic performance, this study focused on determining the mechanical characteristics of hybrid composites between kenaf fibre and x-ray films and how different configurations affect it.

EXPERIMENTAL

Materials

The materials chosen as the test specimens were x-ray films and a kenaf fibre-reinforced polymeric composite. The x-ray films (Hospital Universiti Kebangsaan Malaysia (HUKM), Kuala Lumpur, Malaysia) were a flexible and transparent blue-tinted base coated on both sides with an emulsion-gelatine that carries radiation sensitive silver halide crystals, usually either silver bromide or silver chloride. The surfaces of some of the x-ray films were punctured by consistent holes 2 cm apart, which is considered as a surface treatment. The epoxy resin (ZKK Sdn. Bhd, Selangor, Malaysia) was reinforced with kenaf fibre (ZKK Sdn. Bhd, Selangor, Malaysia) which was in woven mat form, producing a fibre-reinforced polymeric composite. Part of the kenaf fiber was treated using a sodium hydroxide solution with 6% concentration for 3 h immersed in a water bath at 95 °C (Edeerozey *et al*. 2007). As shown in Table 3, the specimens were fabricated using the traditional hand lay-up method into eleven different configurations with seven layers. The configurations were based on the intention to study the interfacial bond between the two distinct materials. A configuration consisting of fully treated x-ray films was intended, but the specimen immediately delaminated when attempts were made to cut them into the respective specimens.

Table 3. Configurations Layering Sequence

Configuration	Name	Layers
1	Alternate (treated x-ray)	K-TX-K-TX-K-TX-K
2	Sandwich (treated x-ray)	K-K-TX-TX-TX-K-K
3	Alternate (treated kenaf)	TK-X-TK-X-TK-X-TK
4	Sandwich (treated kenaf)	TK-TK-X-X-X-TK-TK
5	Full kenaf (treated)	TK-TK-TK-TK-TK-TK-TK
6	Alternate (fully treated)	TK-TX-TK-TX-TK-TX-TK
7	Sandwich (fully treated)	TK-TK-TX-TX-TX-TK-TK
8	Full kenaf (untreated)	K-K-K-K-K-K-K
9	Full x-ray (untreated)	X-X-X-X-X-X-X
10	Alternate (untreated)	K-X-K-X-K-X-K
11	Sandwich (untreated)	K-K-X-X-X-K-K

Note: K- kenaf fiber reinforced composite; TK- treated kenaf fiber reinforced composite; X- x-ray film; TX- treated x-ray film

Testing Methodology

Figure 1 below shows the process done prior to the testing, which is the cutting and shaping of specimen as well as the testing setup itself or tensile and flexural test.


a b c

Fig. 1. Testing process: a) specimen cutting; b) tensile test setup; c) 3-point bending setup

The specimens were cut to size according to the ASTM D3039 (2014) standard, which is 250 mm × 25 mm for the tensile test, and the ASTM D790 (2017) standard, which is 250 mm × 20 mm for the flexural test. The tensile test was conducted using a Shimadzu AG-IS ultimate testing machine (Selangor, Malaysia), and the flexural test was a 3-point bending test conducted using an Instron 4204 flexural testing machine (Selangor, Malaysia). For the flexural tests, the mean thickness and span separations can be seen in Table 4.

Table 4. Mean Thickness and Span Separation for Respective Configurations

Configuration	Mean Thickness (mm)	Span Separation (mm)
Alternate (1, 3, 6, 10)	6.35	101.6
Sandwich (2, 4, 7, 11)	6.40	102.4
Full Kenaf (5, 8)	8.15	51.2
Full X-ray (9)	1.60	130.4

The impact test was conducted using a single stage gas gun (Universiti Malaysia Pahang, Malaysia) with blunt/flat mild steel bullets. The speed of the bullet was varied by varying the pressure into 20 bar, 30 bar, 40 bar, and 50 bar. This gives a range of speed from 175m/s to 245m/s.

RESULTS AND DISCUSSION

Surface Treatment

The treatment of kenaf with the NaOH solution increased the unit break of the fibre bundle by removing impurities and making the fibre stronger, thus providing an easier surface to work with. The concentration of the solution, which was 6% NaOH, and the condition of the treatment, in which the fibres were immersed in a water bath at 95 °C, were decided based on the results as shown in Fig. 2 below. The 9% treated kenaf fibre showed significant decrease in the unit break of fibre bundle due to the chemical being too strong, whereby damaging the fibres and making them weaker.

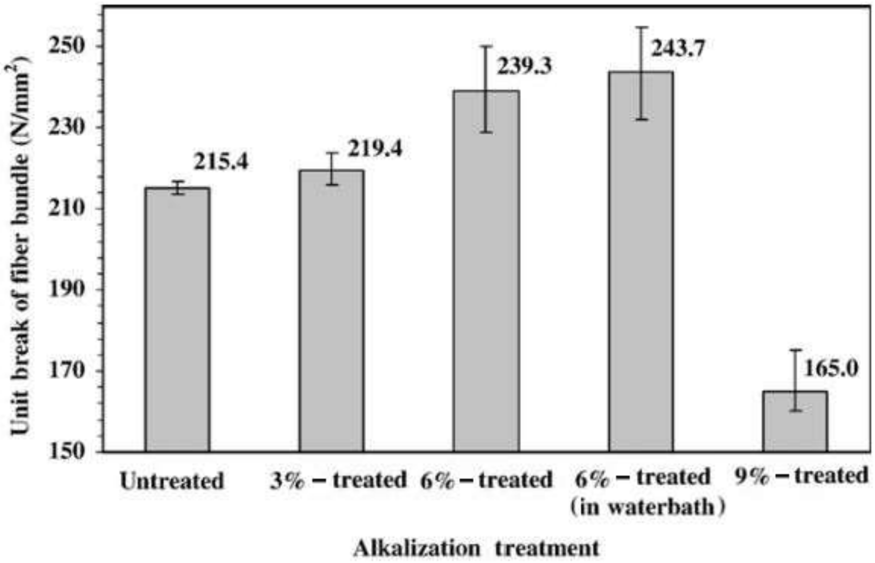


Fig. 2. Average unit break of kenaf fibre bundles (Edeerozey *et al*. 2007)

Mechanical Properties

The tests were conducted with five specimens for each configuration. Table 5 below shows the mean results, which were derived from the average value of these tests.

Table 5. Mean Test Results

Configuration	Ultimate Tensile Strength UTS (MPa)	Tensile Modulus (GPa)	Tensile Strain (%)	Flexural Modulus (GPa)	Maximum Flexural Stress (MPa)
1	310.0 ± 32.10	22.5	2.51	3.99 ± 0.12	10.76
2	342.4 ± 36.03	22.1	2.34	5.64 ± 0.05	61.00
3	276.0 ± 32.44	22.5	2.12	3.66 ± 0.11	10.89
4	277.6 ± 11.85	24.6	2.13	5.47 ± 0.18	27.45
5	470.3 ± 39.21 (B1)	24.9	4.07	8.83 ± 0.05 (B2)	90.59
6	170.8 ± 12.27	16.6	2.21	4.49 ± 0.16	22.03
7	396.9 ± 40.68 (C1)	26.6	2.89	6.24 ± 0.01 (C2)	32.08
8	222.3 ± 40.46	19.5	1.09	5.33 ± 0.02	74.10
9	592.4 ± 42.08 (A1)	26.6	5.20	1.21 ± 0.11 (A2)	34.89
10	269.6 ± 40.11	15.8	1.85	3.21 ± 0.66	15.15
11	277.1 ± 46.23	22.8	1.93	1.32 ± 0.22	24.41

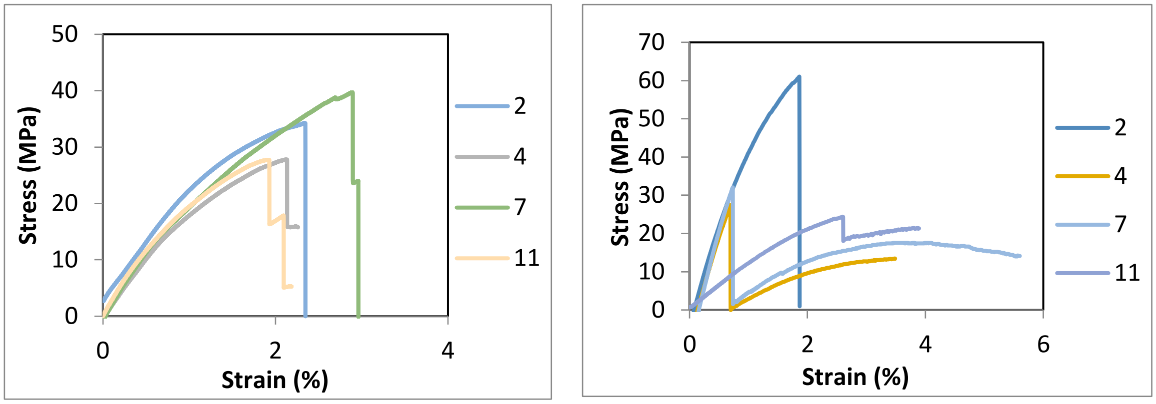
A1 in the table shows that Configuration 9 (fully untreated x-ray film layers) had the highest tensile strength, followed by Configuration 5 (B1) (fully treated kenaf layers) and Configuration 7 (C1) (three layers of surface-treated x-ray films sandwiched in-between two layers of kenaf fiber treated with NaOH solution on the top and bottom of the layers). The reason for Configuration 9's high strength was its plastic-based nature, and both Configurations 9 and 5 had no interfacial bond issues, in contrast to the other configurations that consisted of two different materials. Therefore, with the aim of producing a specimen with hybrid composite properties, Configuration 7 was chosen.

A2 in the table shows Configuration 9 with the lowest flexural modulus and Configuration 5 (B2) with the highest. However, for bulletproof armour application, materials that are not too soft, thereby making it weak, and not too hard, thereby making it uncomfortable for the wearer, are desired. Hence, Configuration 7 (C2) was again chosen for its moderate flexural modulus.

Table 6. Mechanical Properties of Natural Fibre Composites (Pickering *et. al.* 2016)

Fibre	Ultimate Tensile Strength UTS (MPa)	Tensile Modulus (GPa)	Flexural Strength (MPa)	Flexural Modulus (GPa)
Sisal	330.0	10.0	290.0	22.0
Flax	160.0	15.0	190.0	15.0.
Harakeke	223.0	17.0	223.0	14.0
Hemp	165.0	17.0	180.0	9.0

Based on Table 6, the mechanical properties of other natural fibre reinforced polymeric composite have quite similar tensile strength to kenaf fibre. However, they were still not as strong as Configuration 7. On the other hand, their flexural modulus was higher than kenaf fibre, meaning that they are rigid and not suitable for ballistic application.



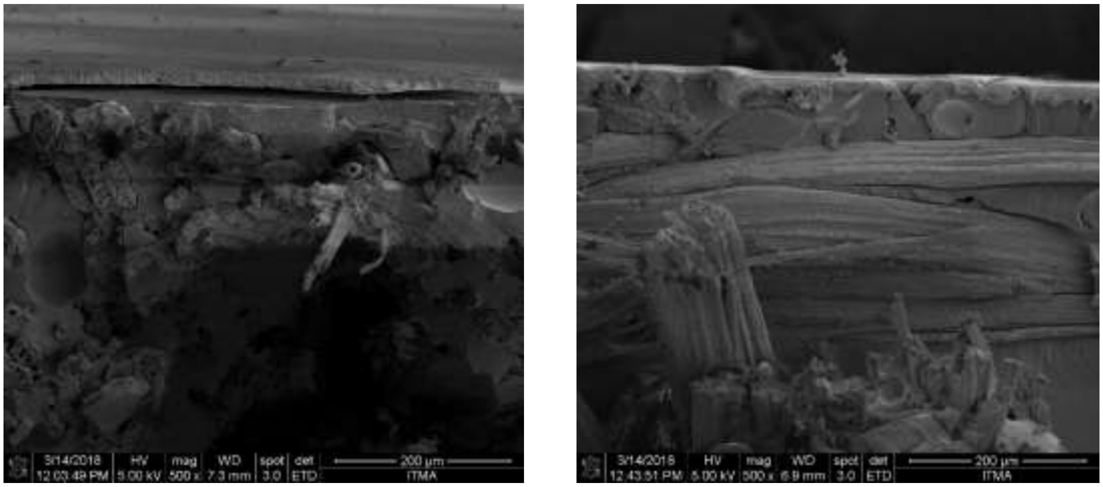
a b

Fig. 3. Stress against strain curve for: a) tensile test; b) flexural test.

Based on Fig. 3, when Configuration 7 was compared with the other sandwich-based configurations (namely Configuration 2 that uses only treated x-ray films, Configuration 4 that uses only treated fibre, and Configuration 11 that uses non-treated layers), the maximum tensile stress of Configuration 7 considerably exceeded that of the other configurations. It can also be observed that even though the maximum flexural stress of Configuration 7 was lower than that of Configuration 2, the curve was steeper than the other configurations, which made it the most flexible. This quality favors manufacturers because they can produce more flexible equipment that fits its wearers more comfortably.

Morphological Observations

Through field emission scanning electron microscopy (FESEM), the failure mode of the specimen after tensile test can be observed as in Fig. 4.



a b

Fig. 4. Post-tensile test FESEM image for: a) specimen with untreated materials; b) specimen with fully treated materials

The specimen with untreated materials displayed obvious delamination at the top part of the image, which is between the kenaf fiber and x-ray films. In contrast, the specimen fabricated with treated materials as shown in the picture on the right hand side had not delaminated after tensile test was conducted. This shows that treatment process did improve the interfacial bonding between the two distinct materials.

High Velocity Impact Properties

Table 7 below shows the mean high-velocity impact test results, which include the data of its respective pressure setting, the corresponding bullet speed, absorbed energy and maximum force exerted.

Table 7. Mean High-velocity Impact Test Results

Pressure (bar)	20	30	40	50
Bullet speed (m/s)	179.21	214.43	232.55	242.78
Absorbed energy (J)	111.07	133.15	138.36	127.29
Maximum force (N)	680.37	805.16	838.56	771.46

Based on Table 7, it can be seen that the design was able to absorb up to 138 J of impact energy. The reading at 50 bar pressure dropped due to the specimen being fully penetrated by the impact, hence showing the limit of the specimen’s impact resistance characteristic. However, the specimen showed promising characteristic, being able to withstand up to 838 N of impact force. This shows that the design does have ballistic impact resistance qualities.

CONCLUSIONS

1. Even though treating the kenaf fibre with sodium hydroxide solution and the x-ray films with a surface treatment substantially improved the interfacial bond between the two materials, the interfacial bond was still lacking.
2. Configurations with full kenaf fibre layers gave a high tensile strength. However, they were very rigid, and this would make them very uncomfortable for the human body.
3. The chemical and surface treatments performed on the specimen only improved the interfacial adhesion between the two different materials; they did not improve in any way the interfacial adhesion between the same materials.
4. Even though the chemical treatment improved the bonding strength for kenaf to the x-ray film, it unfortunately weakened the strength of the fibre itself. This effect may be due to either the chemical thinning out of the fibres, or just an error in the treatment process.
5. Impact testing showed that the design is qualified as a high-velocity impact resistant material due to its ability to withstand high impact force and absorb significant impact energy.

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