# Kenaf/Synthetic and Kevlar®/Cellulosic Fiber-Reinforced Hybrid Composites: A Review

Suhad D. Salman,[a,c,]* Zulkiflle Leman,[a] Mohamed T. H. Sultan, Mohamad R. Ishak,[b,d] and Francisco Cardona [b]

This paper reviews the published and ongoing research work on kenaf/synthetic and Kevlar®/cellulosic fiber-reinforced composite materials. The combination of natural fibers with synthetic fibers in hybrid composites has become increasingly applied in several different fields of technology and engineering. As a result, a better balance between performance and cost is expected to be achieved by 2015, through appropriate material design. This review is intended to provide an outline of the essential outcomes of those hybrid composite materials currently utilized, focusing on processing and mechanical and structural properties.

*Keywords: Hybrid composites; Kenaf fibers; Kevlar® fabric; Mechanical properties; Ballistic properties*

*Contact information: a: Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia; b: Aerospace Manufacturing Research Centre (AMRC), Level 7, Tower Block, Faculty of Engineering, 43400 UPM Serdang, Selangor, Malaysia; c: Materials Engineering Department, Faculty of Engineering, The University of Mustansiriyah, Baghdad, Iraq; d: Laboratory of Bio-Composites Technology, Institute of Tropical Forestry and Forest Products (INTROP), Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia;*
** Corresponding author: suhaddawood2007@yahoo.com*

## INTRODUCTION

The demand for raw materials for structural reinforcement to satisfy the requirements of the world market has been exponentially increasing in recent years (Herrera-Franco and Valadez-González 2005; Fifield and Simmons 2010; Hill and Hughes 2010). In the last decade, the attention of researchers has focused on a comparatively new classification of hybrid composite materials using natural and synthetic fibers (Ashori 2010; Sayer *et al.* 2010), which are considered to be more environmentally friendly. These new hybrid materials are being developed and utilized for structural engineering applications and can offer equal or better properties than their predecessors, as well as being overall cheaper to process and manufacture (Cheung *et al.* 2009; Pandey *et al.* 2010). The use of naturally available materials will help contribute to the local economy, generating increased income and widening availability of the products to ordinary people because of the low production costs (Begum and Islam 2013). Combining synthetic and natural fibers with the same resin results in hybrid composites with excellent physical properties. A good example of natural fibers being used in hybrid composites is kenaf fibers (Hou *et al.* 2000; Saheb and Jog 1999; Dipa and Jogeswari 2005). The properties of kenaf fibers have been investigated by various researchers and have demonstrated high performance (Mathur 2006; Milanese *et al.* 2011). Although synthetic fibers have excellent strength, there is a growing preference for the use of natural fibers in composite materials (Murali Mohan Rao *et al.* 2010). In spite of all the advantages of synthetic fibers (Bledzki and Gassan 1999), the associated health hazards and high price have actually motivated the exploration of natural fibers (Nishino *et al.* 2003). The advantages of natural fibers, combined with new environmental regulations, have boosted the demand for natural fiber composites. This demand has led scientists and technologists to work to improve many of their inherent drawbacks and provide new natural alternatives to reduce the use of synthetic composites (Santulli 2007; Faruk *et al.* 2012). In general, natural fiber-reinforced polymer composites do not match synthetic fiber-reinforced polymer composites with respect to mechanical strength. However, as a lighter material, they can more easily meet the standards required for other applications (Corbière-Nicollier *et al.* 2001; Mueller and Krobjilowski 2004). As a result, hybrid composites reinforced by natural/synthetic fibers in a single matrix have been studied, and enhanced mechanical strength has been obtained (Al-Mosawi Ali 2012). These composites are currently widely used because of their advantages, including low weight, abundance, low cost, and high specific mechanical properties (Herrera-Franco and Valadez-González 2004). Other properties of hybrid composites, such as acceptable specific strength properties, good thermal properties, low embodied energy, reduced tool wear, and reduced irritation to the skin and respiratory system, have also all been proven more than acceptable. The low energy requirements for processing of the natural fiber component of the hybrid system (as well as its biodegradability) have led to a sustainable increase in the market value of the composites (Wambua *et al.* 2003; Mohanty and Misra 2005). Kenaf fiber-reinforced composites with thermoset matrices have successfully proven their value and quality for use in various fields of engineering applications (Hancox 2000; Sharifah *et al.* 2005). Nevertheless, most research has primarily focused on kenaf fibers in random orientation or in compressed mats (Agbo 2009).

Natural fiber-reinforced polymer composites (NFRPCs) have been shown to be viable alternatives to synthetic fibers in many industrial applications. The general aims of this review are as follows: summarizing reports in the literature regarding the improvement of the properties of the polymer composites consisting of various types of resin matrices and natural fibers, and examining the reproducibility and long-term preservation of the material properties, presenting a brief comparative analysis of the mechanical strength of the hybrid composites and throwing some light on the environmental aspects and the economic impact of the substitution of synthetic fibers by natural ones in polymer composites.

## HYBRID COMPOSITES

One of the rising fields in composite science research is that of hybrid composite materials, one that is gaining attention in many different industrial sections. Researchers have begun developing hybrid polymer composites, where the natural fiber is combined with synthetic fiber using the same resin (Rao *et al.* 2011). The concept of hybridization provides flexibility and allows the designer to tailor the material properties according to particular requirements. Furthermore, the hybridization technique allows for a balance of performance and cost, thus pushing the prospect of hybrid polymer composites to be utilized in higher load-bearing structural applications (Al-Harbi 2001).

For over 3,000 years, the uses of natural fibers to reinforce materials in different fields of life have been reported (Bledzki and Gassan 1997; Richardson *et al.* 1998). In modern times, natural fibers have often been utilized in combination with synthetic fiber-based polymer composites. The bio-degradability of natural fibers, combined with new environmental regulations, has boosted demand for natural fiber composites and has led scientists and technologists to improve many of the inherent drawbacks of NFRP (Kline and Company Inc. 2000; Mohanty *et al.* 2002). A study on the hybridization of natural/synthetic fibers as reinforcement in hybrid composites has shown promising effects on the improvement of mechanical properties for the replacement of expensive and non-renewable synthetic fibers (Da Silva *et al.* 2008). The average maximum loading of natural fibers in hybrid composite materials is 50% (Mohanty *et al.* 2001). Burgueno *et al.* (2005) suggested that the mechanical properties NFRPCs (such as stiffness and strength) are improved because of the direct contribution of the stiffer and stronger synthetic fibers, as well as simultaneously gaining higher dimensional stability with respect to moisture absorption because of the barrier provided by the more impermeable synthetic fibers. Among the natural fibers used for composites, bast fibers, which are extracted from the stem of plants, *e.g.*, kenaf, and flax, generally provide excellent mechanical properties compared with natural fibers extracted from the leaf or from the seed (Akil *et al.* 2011).

The hybridization of the kenaf fiber has been used as reinforcement in both thermoplastic and thermoset polymer-based composites and has been extensively applied in many industrial fields worldwide (Mohanty *et al.* 2000; Gross and Kalra 2002; Mohanty *et al.* 2002). A common way to produce hybrid composites is by joining together laminas reinforced by different fibers (Varma *et al.* 1989). The reduction of matrix content at the expense of increasing the plant fiber in the composites enhances the environmental performance of NFRPCs in comparison to neat polymer and synthetic fiber-reinforced polymer composites (SFRPCs) (Joshi *et al.* 2004; Venkateshwaran *et al.* 2012). The stacking pattern of the various constituents in hybrid laminated composites plays a significant role in the mechanical properties of the hybrid composites, especially the tensile strength and modulus of the hybrid composites (Park and Jang 1998; Khalil *et al.* 2008).

## PROPERTIES OF HYBRID KENAF/SYNTHETIC FIBER COMPOSITES

It is important to understand the behavior of natural fibers under tensile, flexural, impact, and dynamic mechanical load to maximize their potential. As previously reported, hybrid composites that consist of cellulose fibers have shown acceptable mechanical behavior (Hariharan and Khalil 2005; De Rosa *et al.* 2009; Kong *et al.* 2009). Many potential natural fiber resources can be used in polymer composites. Kenaf fibers are amongst the most promising and have recently received greater attention as the top national commodity crop under the supervision of the Malaysian National Kenaf and Tobacco Board (Ling and Ismail 2012). There are many benefits to using kenaf fibers, such as their minimal abrasive wear to machinery, low density, low production costs, high specific strength, good damage resistance (Ishak *et al.* 2010; Ratna Prasad and Mohana Rao 2011), and extensive availability compared to *other* natural fibers. Added to this is the fact that there are no direct carbon dioxide outputs, and it is biodegradable and recyclable (Wambua *et al.* 2003).

With such benefits, kenaf fibers have attracted the attention of many investigators and scientists. Several researchers have proposed combining kenaf fibers with synthetic fibers to form hybridized composites. The applications of thermoset and thermoplastic matrices reinforced with cellulosic fiber-based products are supported by a number of publications and reviews (Wambua *et al.* 2003; Yahaya *et al.* 2014a). These highlight the fact that kenaf fiber-reinforced composites are an emerging substitute for synthetic fibers as reinforcement in composite materials (Mohanty *et al.* 2001). Despite this growing interest, limited attention has been devoted to the low- and high-velocity impact behavior of those natural fiber-based composites (Taj *et al.* 2007; El-Tayeb 2009). Descriptions of the various aspects of hybridization of natural and synthetic fibers have appeared in a number of review papers. Jawaid and Abdul Khalil (2011) reviewed studies performed on NFRPCs with special reference to the type of fibers, matrix polymers, treatment of fibers, and fiber-matrix interfaces in various aspects of the applications, outlining the use of hybrid composites fabricated by combining natural and synthetic reinforcements. A comprehensive review conducted by Nunna *et al.* (2012) discussed the potential for using NFRPCs for structural and infrastructural applications. It would appear that extensive work is being conducted, with some crossover of thought and focus, on the physical and mechanical properties of these types of hybrid composites. However, as of yet, the results of the investigation of the dynamic mechanical properties of the composites have not been reported. To improve the fiber/matrix interface in these hybrid composites, several researchers have developed hybrid composites by either chemical modification of fibers or using coupling agents to improve interface adhesion.

Data on the use of kenaf fiber with different synthetic fibers introduced into polymer compositions, along with the reinforcement data of some hybrid materials, have been collected from the literature and are summarized below. Kenaf fiber has been utilized in hybrid composites, with the aim to reduce the material cost and at the same time yield high strength-to-weight ratios. Those new hybrid composite materials have great potential in applications in many industrial areas. Table 1 shows how several researchers have combined kenaf fibers with various kinds of synthetic fibers and matrices (numbered according to the year the studies were reported). In most of the published results, a challenge still exists in the suitable analytical modeling work, and solving it will help in interpreting the experimental results and optimizing specific applications of the composites in many sectors.

The hybridization of thermoplastic natural rubber with carbon fiber (CF) and kenaf fiber (KF) was investigated to determine its mechanical properties by Anuar *et al.* (2008). Samples with various fiber contents were subjected to flexural testing, and samples with up to 30% fiber content were subjected to impact testing. The flexural strength and flexural modulus increased up to 15 vol% and then decreased for samples with 20 vol% and above because of a poor fiber-to-matrix interface bonding. Nevertheless, the impact testing results indicated that higher fiber content led to an increase in impact strength in treated and untreated fibers. Generally, the properties of the untreated hybrid materials were not only more consistent but also better than those of the treated hybrid composites.

**Table 1.** Reported Research Work on Kenaf/Synthetic Fiber Hybrid Composites

| Authors | Materials ( kenaf + synthetic ) fiber | Tests |
|---|---|---|
| (Anuar *et al.* 2008) | Hybrid kenaf + short carbon fiber composite | flexural test<br>impact test |
| (Cicala *et al.* 2009) | Hybrid kenaf mat + woven glass-reinforced epoxy vinyl ester resin for applications in the piping industry | tensile test<br>flexural test |
| (Akil *et al.* 2010) | Hybrid kenaf mat + glass-reinforced polyester composites | tensile test<br>flexural test |
| (Davoodi *et al.* 2010)<br>(Davoodi *et al.* 2011)<br>(Davoodi *et al.* 2012) | Hybrid kenaf + glass-reinforced epoxy composite for passenger car bumper beam | tensile test<br>flexural test<br>low-velocity impact test<br>high-velocity impact test |
| (Wan Busu *et al.* 2010) | Hybrid kenaf + short glass fiber-reinforced thermoplastic | tensile test<br>flexural test<br>impact test |
| (Ismail *et al.* 2011) | Hybrid kenaf + waste tire dust | tensile test |
| (Elsaid *et al.* 2011) | Hybrid kenaf fiber-reinforced concrete | tensile test<br>flexural test<br>low-velocity impact test |
| (Fulton 2011) | Hybrid kenaf mat + fiberglass-reinforced polyester composite | tensile test<br>flexural test |
| (Maleque *et al.* 2012) | Hybrid kenaf + glass-reinforced unsaturated polyester composite for structural applications | flexural test<br>low-velocity impact test |
| (Salleh *et al.* 2012a)<br>(Salleh *et al.* 2012b)<br>(Salleh *et al.* 2013) | Hybrid kenaf (powder, short and long) + fiberglass-reinforced composite<br>Hybrid long kenaf + woven glass fiber-reinforced with unsaturated polyester composites | tensile test<br>low-velocity impact test |
| (Ghani *et al.* 2012) | Hybrid kenaf + fiberglass polyester-reinforced composites. | tensile test |
| (Jeyanthi and Rani 2012) | Hybrid long kenaf + glass fiber-reinforced composite for automotive structures materials | tensile test<br>flexural test<br>impact test |
| (Munusamy 2012) | Hybrid kenaf mat + E-glass fiber-reinforced vinyl ester composites | tensile test<br>flexural test |
| (Osman *et al.* 2013) | Hybrid kenaf + glass fiber composite | flexural test |
| (Mansor *et al.* 2013) | Hybrid kenaf + glass fiber-reinforced polypropylene resin | tensile test<br>flexural test |
| (Bakar *et al.* 2013) | Hybrid kenaf + carbon fiber-reinforced epoxy composites | low-velocity impact test |
| (Afdzaluddin *et al.* 2013)<br>(Atiqah *et al.* 2014) | Hybrid kenaf + glass mat-reinforced unsaturated polyester composite for structural applications | tensile test<br>flexural test |

The tensile and flexural properties of laminated hybrid glass woven fabric and kenaf fiber mat-reinforced epoxy composites, designed for application in the piping industry, were determined by Cicala *et al.* (2009). A cost reduction of 20% and a weight savings of 23% compared to the actual commercial pipe could be achieved by improved designs that fulfilled the requirements of mechanical resistance. The data for the single layer revealed that kenaf fiber use led to lower properties when compared to one layer of glass fabric. However, a proper design of the laminate sequence allowed the design to maintain the desired resistance, even when kenaf fiber mat was used. A prototype fitting was produced and tested by an experimental simulation of the real working conditions. The test confirmed that the proposed fitting can withstand the specific working conditions and helped establish composition parameters, such as the volume fraction of the constituent materials (fibers plus resin), as well as other factors, such as the number of plies that affect the total thickness of the piping.

The flexural and indentation behavior of pultruded kenaf fiber mat/glass hybrid polyester composites has been monitored using acoustic emission and compared with that of kenaf fiber composites by Akil *et al.* (2010). It was concluded that pultrusion is an appropriate process for fabrication of kenaf with glass fiber composites and their hybrids. However, its successful implementation for large volume production still requires optimization, in view of the problems of insufficient impregnation and less effective control of fiber orientation, both of which were observed to affect the flexural (initial and residual) and indentation performance of the laminates, especially for the kenaf fiber laminates. It was noticed that hybridization can positively affect both the flexural strength and the modulus of the composites.

Davoodi *et al.* (2010) focused on the mechanical characteristics of a hybrid kenaf/glass-based epoxy composite material used in a passenger car bumper beam. This hybrid material, fabricated by a modified sheet molding compound method, displayed good mechanical properties, yielding a strong bond between the hybrid-reinforced fibers. The comparison charts in Fig. 1 show improved mechanical properties in comparison with the common bumper beam material glass-mat thermoplastic (GMT).

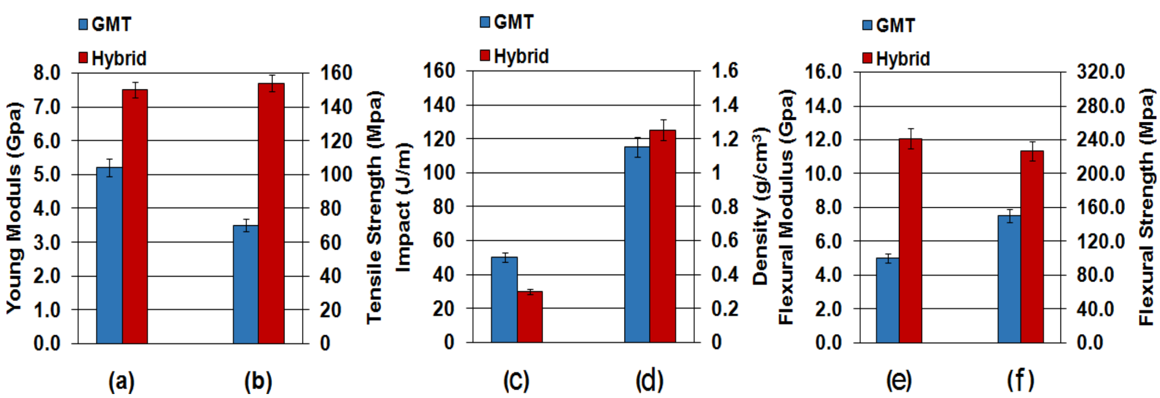


**Fig. 1.** (a) Tensile modulus, (b) tensile strength, (c) impact strength, (d) density, (e) flexural modulus, and (f) flexural strength (Davoodi *et al.* 2010, replotted)

The results indicate that for the hybrid material, some mechanical properties such as tensile strength, Young's modulus, flexural strength, and flexural modulus are slightly higher than the corresponding values for GMT, but impact strength is still low. In general, the results show the potential for utilization of hybrid natural fibers in some car structural components, such as bumper beams. Moreover, impact properties could be improved by optimizing the structural design parameters (thickness, beam curvature, and strengthening ribs), or through material improvement such as epoxy toughening, to modify the ductility behavior to improve energy absorption. There is a relatively small effect in the mechanical properties of the materials associated with its hybrid composition.

Wan Busu *et al.* (2010) examined thermoplastic natural rubber hybrid composites reinforced with kenaf and short glass fibers, compounded by the melt blending method. Hybrid composites were prepared with different levels of fiber content; the optimum composition for the hybrid composite is at the ratio of 30% kenaf fiber and 70% glass fiber. Thermoplastic natural rubbers (TPNR) were prepared from polypropylene (PP), natural rubber (NR), and liquid natural rubber (TPNR) with a ratio of 70:20:10. Tensile, flexural, impact, and scanning electron microscope tests of the hybrid composites were carried out. It was concluded that the combination of the kenaf fiber into TPNR increased the flexural modulus and impact strength by approximately 100%, in comparison to TPNR matrix. However, the maximum strain decreased with increasing fiber content. This work represents a significant step toward obtaining higher performance in natural hybrid composites for many different applications.

Ismail *et al.* (2011) prepared waste tire dust (WTD)/kenaf fiber hybrid filler filled natural rubber compounds with a constant 30 phr loading and increasing partial replacement of WTD by kenaf fiber. Not only the mechanical properties but also the rubber-fiber interactions of the hybrid compounds were investigated. They found that the value of tensile strength and elongation at break value were reduced with increasing kenaf fiber loading, and this conclusion was supported by the results obtained from the SEM micrographs of the fractured surface. The properties of the hybrid material depend on various factors, and the two most important are the thickness and the dispersion of the constituents relative to each other in the polymeric matrix.

An investigation was conducted by Elsaid *et al.* (2011) to determine the mechanical characteristics of natural fiber-reinforced concrete, which is made using the bast fibers of the kenaf plant. Kenaf fibers with different volume weights were used to reinforce concrete (KFRC) to produce appropriate mixture proportions according to established mixing procedures. A comparison between the tensile strength and modulus of rupture characteristics of KFRC samples and pure concrete samples was obtained. It was found that the mechanical properties of KFRC are similar to those of pure concrete samples. Furthermore, the KFRC showed more distributed cracking and higher toughness than pure concrete samples. A better bond between the kenaf fibers and the concrete was obtained, indicating that KFRC is a promising natural structural material that can be employed in a number of structural applications.

Fulton (2011) studied the effects of pressure and lay-up on a hybrid composite of randomly oriented kenaf fiber mat and fiberglass/polyester sheet molding compound (SMC) with 3 (g/k/g) and 4 (g/k/k/g) layers. The bending modulus of elasticity (MOE), the bending modulus of rupture (MOR), the tensile modulus, and the maximum tensile strength of the hybrid composites were all measured. Both ultimate tensile and flexural strength were, on average, higher in the single-layer kenaf samples. The double-layer kenaf samples were also, in general, more capable of bearing higher loads than the specimens with neat fiberglass reinforcement, which had lower ultimate tensile strength. The average of the maximum measured values was greater for the single-layer kenaf samples and smaller for the double-layer kenaf samples. The results showed that the hybrid composite properties were highly affected by the preparation, molding, and layering pattern. Ultimately, the best overall mechanical properties were obtained for samples consisting of a single layer of kenaf fibers.

The best geometrical bumper beam concept to fulfill the safety parameters of the bumper beam product design specification (PDS) was selected by Davoodi *et al.* (2011). Various bumper beam concepts with the same frontal curvature, thickness, and overall dimensions were considered in the designed hybrid composite material. In addition, the best concept was selected by the low-speed impact simulation of those hybrid composite materials. Mechanical properties such as deflection, strain energy, cost, and ease of manufacturing were investigated to shape a hybrid having improved value. It was concluded that hybridization with other reinforcement fibers or resins could improve the mechanical characteristics of natural fibers. It was found that geometric optimization plays a major role in structural strength amelioration; therefore, a double hat profile (DHP) could be utilized for the bumper beam of a small car. Furthermore, by adding reinforced ribs or increasing its thickness, the bumper beam could be strengthened to comply with the defined PDS. It was concluded that proper concept selection plays an important role in the ultimate structural strength, with material considered as a constant parameter. Moreover, the results showed that bio-based composite material has the potential to be used in automotive structural components to aid design optimization and that the toughened epoxy hybrid kenaf/glass fiber composite can be employed in small-sized car bumpers. The results indicated that the developed hybrid composite beam possesses similar mechanical properties to the typical synthetic bumper beam material and that it is possible to utilize it in manufacturing the structural components of a car.

In 2012, Davoodi *et al.* studied how to improve the impact strength of a hybrid kenaf/glass fiber epoxy composite using a modified sheet molding compound of glass mat thermoplastic (GMT). It was reported that most of the mechanical properties of the hybrid glass mat thermoplastic material were similar to those of the GMT. In addition, cross-section, thickness, and reinforcement ribs could be used to enhance structural impact resistance to comply with bumper beam product design standards (PDS). According to these results, the impact strength was improved by 54% over the impact strength of the non-toughened bio-composite, even though the produced material still could not out-perform the GMT. However, there were also some negative impacts on other mechanical properties of the developed hybrid composites.

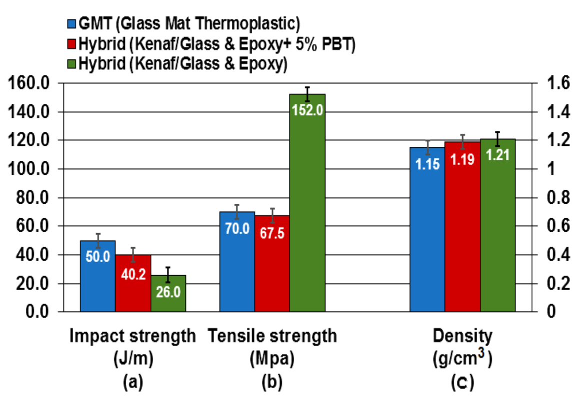


**Fig. 2.** Comparison chart of (a) impact strength, (b) tensile strength, and (c) density (Davoodi *et al.* 2012), replotted)

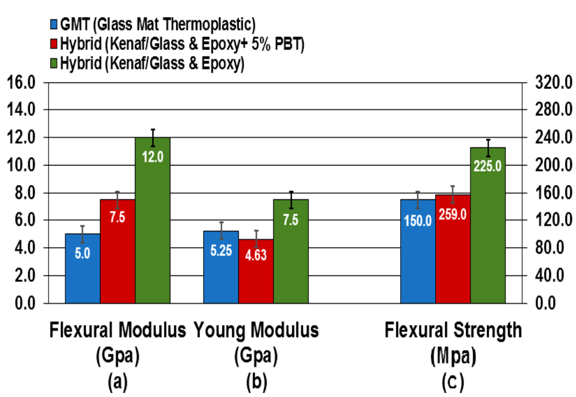


**Fig. 3.** Comparison chart of (a) flexural modulus, (b) Young's modulus, and (c) flexural strength (Davoodi *et al.* 2012), replotted)

The results, as shown in Figs. 2 and 3, highlight the potential for utilization of the toughened hybrid bio-composite in certain automotive structural components. When comparing the ratios of flexural properties to the equivalent tensile ones, it can be seen that, with only a few exceptions, the flexural strength is on the order of 60% of the tensile strength, while the modulus is almost doubled in flexural mode. However, the few exceptions that were encountered prevent generalization.

The flexural and impact properties of kenaf/glass fiber-reinforced unsaturated polyester (UPE) hybrids composite were investigated by Maleque *et al.* (2012). The 70% volume fraction of resin was kept constant as kenaf and glass fiber content was varied with various volume fractions. Hybrid composites were fabricated using a sheet molding compound (SMC) process, and kenaf fiber was treated with 6% sodium hydroxide for 3 h. The results indicated that the treated kenaf with 15/15 v/v fiber-reinforced hybrid composite showed higher flexural strength, while the untreated 15/15 v/v composite showed a higher value of impact strength than their treated counterpart. The study concluded that 15/15 v/v fiber-reinforced unsaturated polyester hybrid composite is the most appropriate hybrid composite formulation for use in many engineering structural applications, such as in the automotive, aerospace, and construction industries. It was observed that adding a comparatively small amount of glass fabric to the kenaf fiber-reinforced polyester resin enhanced the mechanical properties of the resulting hybrid composite.

The effect of various fiber types (powder, short, and long) on the tensile properties of composites was investigated by Salleh *et al.* (2012a). Kenaf composites with and without the addition of fiberglass were fabricated by a combination of hand lay-up method and cold-press method, then characterized by tensile testing and scanning electron microscopy. The results showed a large improvement in tensile strength and modulus with the introduction of long kenaf/woven fiberglass hybrid composites, while the opposite trends were observed for the kenaf-powder based composites. This study concluded that the properties of hybrid composites depend on several factors, including the interaction of fillers with the polymeric matrix, form and volume, and the orientation of the fillers. It also determined the effect of glass fiber loading on the properties of the composites with each type of kenaf fiber.

The effect of water absorption on the mechanical properties of long kenaf/woven glass hybrid composite was studied by Salleh *et al.* (2012b) at room temperature under three different environmental conditions, *i.e.*, distilled water, rain water, and sea water. The rates of moisture uptake by the composites increased with immersion time. The exposure of natural fiber composite materials to environmental conditions leads to a decrease in the fracture toughness. Furthermore, the specific decrease in the fracture toughness as a result of water absorption depends on many factors, such as the content of the fiber, fiber orientation, area of exposed surface, specific permeability of the fiber, void content, and the level of interface adhesion between the fiber and the matrix in the composites. It is extremely important that the composites have a useful and extensive working life for different outdoor applications. To meet this aim, it is fundamental to control and reduce the environmental degradation of cellulosic fiber properties to increase their service life.

The mechanical strength of kenaf fiber/glass-reinforced unsaturated polyester hybrid composites was examined by Ghani *et al.* (2012) when subjected to water absorption testing. They reported that the mechanical characteristics of kenaf fiber decreased after the moisture penetrated into the composite, while the strain to failure increased during the test from the 1st day until the 3rd week, followed by a drop at the 4th week. The formation of hydrogen bonding between the water molecules and cellulose fiber strongly affected the mechanical properties of hybrid composites and caused deterioration in tensile modulus. Another parameter that affects the strength of the hybrid composites is the failure strain of individual fibers, so maximum results are obtained when the fibers have similar strain values.

Hybrid long fiber glass-reinforced thermoplastics with twisted kenaf fiber (KLFRT) were investigated by Jeyanthi and Rani (2012) to improve the desired mechanical properties for car bumper beams as automotive structural components. As shown in the reported comparison charts, there are some mechanical advantages of twisted kenaf hybrid materials, fabricated by a hot impregnation method (TKLFRT), as they presented better mechanical properties in comparison to the typical bumper beam material (LFRT, Fig. 4). This means that a hybrid kenaf/glass-reinforced material can be employed in automotive structural components, such as bumper beams and front end modules. Moreover, the impact characteristics can be enhanced by optimizing the structural parameters. The reported results indicated that tensile strength, Young's modulus, flexural strength, and flexural modulus are better than the typical bumper beam material because of the ability of the hybrid materials to absorb more impact load and offer more protection to the front car component. When comparing the ratios of flexural properties to the equivalent tensile ones, it can be seen that, with only a few exceptions, flexural strength is on the order of 20% of the tensile strength, while the tensile and flexural moduli are almost equal. However, the few exceptions that were encountered prevent generalization.

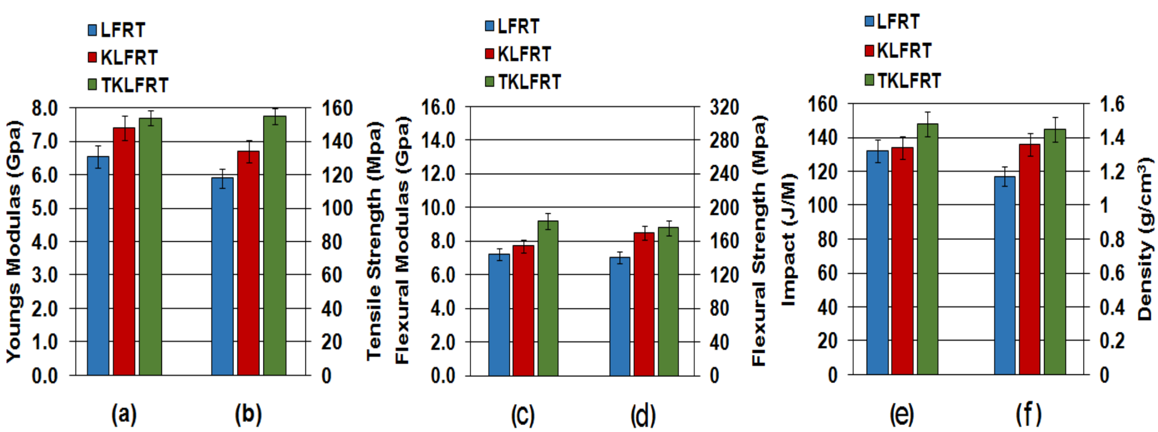


**Fig. 4.** (a) Tensile modulus, (b) Tensile strength, (c) Flexural modulus, (d) Flexural strength, (e) Impact strength, and (f) Density (Jeyanthi and Rani 2012), replotted

Munusamy (2012) evaluated the use of soy oil-based polyurethane foam as a core material in sandwich constructions, with face sheets of hybridized kenaf and E-glass fibers in a vinyl ester matrix. The composites were designed to replace plywood sheeting on steel frame for mass transit bus flooring. The bio-based sandwich composites showed promise as candidates for the replacement of plywood for bus flooring by displaying an increase of 130% of flexural strength and 135% of flexural modulus plus better indentation values, in comparison with their plywood counterparts. The use of natural fiber webbing in place of glass fiber webbing in the foam core would also increase the bio-based content without decreasing the mechanical properties. There were a few promising steps that could be explored in the fabrication of the sandwich composites, such as increasing the bio-based content of the PU foams, increasing the number of natural fiber lay-ups, and by using a bio-based matrix as an alternative for the vinyl ester resin system. It was found that hybridization of the fibers provides high flexural strength and high modulus, making the materials an excellent alternative to plywood on mass transit bus flooring.

Pultruded kenaf/glass fiber hybrid reinforced composites (PKGRC) were studied by Osman *et al.* (2013), investigating the effect of water absorption on the mechanical properties of the composites. In this study, the composite samples were immersed in distilled water at 65 °C for a period of six weeks. To compare the hybrid composite and conventional composites, pultruded kenaf fiber reinforced composites (PKRC) and pultruded glass fiber-reinforced composites (PGRC), specimens were prepared and underwent the same water absorption test. The study reported that the flexural and compressive characteristics of the composites decreased with increasing water uptake. Further variables were introduced by the hybridization process; therefore the flexural modulus and strength are not enough to fully characterize the effect of water absorption on the materials. Additional evaluation tests should establish the failure mechanism because of the water absorption, which should explain the progressive drop in the mechanical properties of the materials during the test.

The analytical hierarchy process (AHP) method was applied by Mansor *et al.* (2013) in the selection of the most appropriate natural fiber for the hybridization of glass fiber-reinforced polymer composites in the design of center lever parking brake components for passenger vehicles. For the hybridization process, 13 candidate natural fiber-based materials were chosen and investigated to calculate their overall scores in three main performance indices, according to established component product design standards. It was concluded that the kenaf bast fiber yielded the highest score, so it was selected as the best candidate material to produce hybrid polymer composites for the automotive components. The experimental tests confirmed the suitability of the proposed fiber hybrid system to withstand real working conditions.

The tensile strength and low-velocity impact of kenaf/fiberglass composites were investigated by Salleh *et al.* (2013). The findings of this study revealed that the tensile properties of the composites were impaired even when low impact energy was used. As for the hybrid composites, the tensile properties were hardly affected when tested with impact energy below 6 J. However, the tensile properties were reduced after the impact energy during the test increased above 6 J. Therefore, the impact damage of the composites can be predicted from measurements taken from the residual tensile strength of impacted specimen, and from the damage zones of the composites. A positive effect (increases in the properties) of hybridization was observed for the elongation at break while a negative hybridization effect (reduction in properties) was noted for both tensile strength and Young modulus of the hybrid composites, in comparison with the glass-fiber counterparts.

The reinforcing effects of the combination of alkali-treated and untreated kenaf hybridized with carbon fiber in epoxy composites, followed by high-energy gamma radiation, were investigated by Bakar *et al.* (2013). This study was undertaken at different fiber loadings with an overall fiber content of 20 wt%. The results showed that the impact strength of the alkali-treated and gamma-irradiated hybrid composites were increased by

26% in comparison to the untreated and irradiated hybrid composites. Generally, the hybrid composites with carbon fiber substituted by kenaf fiber were both stronger and cheaper than the plain CFRP laminate.

Afdzaluddin *et al.* (2013) studied the synergistic effect on flexural properties of treated kenaf-glass mat reinforced unsaturated polyester hybrid composites. The prepared laminates had a constant matrix volume fraction of 70% and 30% of kenaf and glass fiber, respectively. The results showed that the composition with equal content percentage of fibers gave optimum flexural properties in comparison to other fibers proportion. It was concluded that the hybrid composites could be utilized for many engineering structural applications, mainly as automotive panels, specifically bottom structure and bumper beams. It was also observed that in the hybrid composites the flexural tests require special attention because of the many possible failure modes, and therefore this flexural test is not enough to properly characterize the structural performance of the hybrid material.

The unsaturated polyester-resin-based hybrid composites with a resin:fiber ratio equal to 70:30 (v/v) with treated and untreated kenaf mat with 6% sodium hydroxide (NaOH) and glass fiber in mat form were developed and characterized by Atiqah *et al.* (2014). The hybrid composites were tested for flexural, tensile, and Izod impact strength using ASTM standards. The percentage 15/15% v/v (K/G) of treated kenaf with glass fiber-reinforced unsaturated polyester hybrid composite showed the highest flexural, tensile and impact strength values. The strength of the hybrid composites depends not only on the hybrid composition but also on the orientation of each fiber layer. When stiffer plies are placed away from the neutral axis, the flexural modulus is increased, so laminates of sandwich construction should be preferred.

## PROPERTIES OF HYBRID KEVLAR®/CELLULOSIC FIBERS COMPOSITES

Here, a survey is presented on the main aspects on reported studies of the Kevlar®/cellulosic fiber hybrid laminates used in structural components. The performance of the hybrid panels when subjected to mechanical testing, including the effect of laminate configuration and manufacturing procedure on the impact properties of the hybrid composite, was investigated (Isaac and Ishai 2006).

Kevlar® is a synthetic fiber and a well-known component of military items such as warfare helmets, face masks, and vests. Kevlar® exhibits high strength, high flexibility, high modulus, little elongation, low density, non-conductivity, and corrosion impedance and is capable of absorbing significant amounts of energy. Kevlar® is DuPont's name for aramid fibers.

The advantage of Kevlar® fiber is its elevated impedance to impact failure; hence, it is commonly utilized in the field to reduce impact damage. Kevlar® is obtainable as fabric materials (Callister and Rethwisch 2011; Sultan *et al.* 2012a; Sultan *et al.* 2012b).

There are a few studies focused on the properties of hybrid Kevlar®/cellulosic fibers reinforced composites. The reported research work on Kevlar®/cellulosic fibers hybrid composites is presented in Table 2.

**Table 2.** Reported Research Work on Kevlar®/ Cellulosic Fiber Hybrid Composites

| Authors name | Materials ( Kevlar® + natural) fiber | Tests |
|---|---|---|
| (Radif 2009) | Hybrid ramie + Kevlar® polyester resin | High-velocity impact test |
| (Ou *et al.* 2010) | Hybrid Kevlar® + wood fiber composites. | Tensile test<br>Flexural test<br>Low-velocity impact test |
| (Zhong *et al.* 2011) | Hybrid Kevlar® + sisal fiber composites. | Tensile test |
| (Azrin Hani Abdul *et al.* 2011) | Hybrid woven coir + Kevlar®-reinforced epoxy composites | Flexural test<br>High-velocity impact test |
| (Sarasini *et al.* 2013) | Hybrid woven Kevlar® + basalt fabrics reinforced epoxy composites | Flexural test<br>Low-velocity impact test |

Radif (2009) studied different types of laminated composite material of ramie/Kevlar®/polyester resin, which were subjected to high impact testing and intended for application in body armor. The target structures consist of three types of hybrid, as shown in Fig. 5. It was concluded that the target's geometry plays a main role in increasing impact response, because the test results presented high resistant impact for pairs from panels with total thickness of 15 mm. The need to design an economical form of body armor involving common materials has resulted in the reduction of the Kevlar® content and the total material cost. High velocity impact testing was performed with the aim of estimating the ballistic limit, the upmost energy absorption, the composite failure mechanism, the life time rupture, the target geometry, and the environmental influence on the armor composite materials. The results indicated that the maximum ballistic limit able to support the impact has a speed between 250 m/s and 656.8 m/s for the second safeguard standard according to the National Institute of Justice standard (NIJ) of USA. The author recommended an increase of the number of Kevlar® layer from (8 Kevlar® - 8 ramie) to (10 Kevlar®-10 ramie) for the armor to comply with the second level of the National Institute of Justice (NIJ) and (13 Kevlar®-13 ramie) to (15 Kevlar®-15 ramie) for the third protection level. The last level of protection can be achieved by increasing the armor thickness to 30 mm.

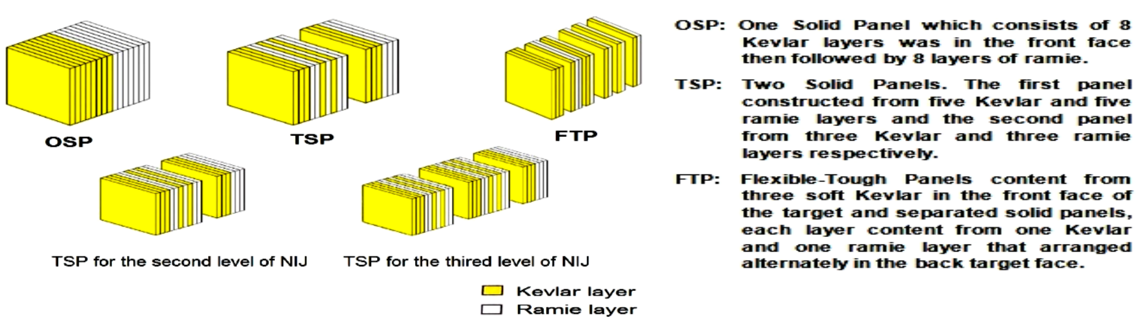


**Fig. 5.** The configurations of the hybrid Kevlar®/ramie composites (Radif 2009)

Kevlar® fiber was used as reinforcement for wood-flour/high-density-polyethylene composites (WF/HDPE) by Ou *et al.* (2010) to enhance its mechanical properties. The addition of a small amount (2 to 3%) of Kevlar® fibers resulted in an improvement in the tensile, flexural, and impact properties. It can be concluded that the grafted Kevlar® fibers can be used as a reinforcement to improve the strength and toughness of WF/HDPE composites. It was found that hybridization with Kevlar® fibers improved the mechanical properties of those thermoplastic materials.

Zhong *et al.* (2011) examined the influence of the surface micro-fibrillation on the mechanical properties of the hybrid composites produced with sisal and aramid fibers. Surface micro-fibrillation of cellulose fibers was chosen as a suitable technique for composites of sisal/Kevlar® fiber with phenolic resin to enhance the interfacial adhesion to the matrix. The development of micro fibrils on the fiber surface vastly enhanced the interfacial adhesion between the sisal fiber and the resin by providing a large contact area and by inhibiting the formation of spontaneous cracks in the composites. As a consequence, the compression, tensile, internal bonding strengths, and wear resistance of the hybrid composite materials was significantly improved.

Properties such as the high velocity impact and flexural strength of textile coir yarn/Kevlar® yarn reinforced epoxy composites materials were examined by Azrin Hani Abdul *et al.* (2011). Samples were prepared from coir yarn/Kevlar® yarn, interlaced of coir and Kevlar® with various warp/weft direction and epoxy reinforced composites materials, as shown in Fig. 6.

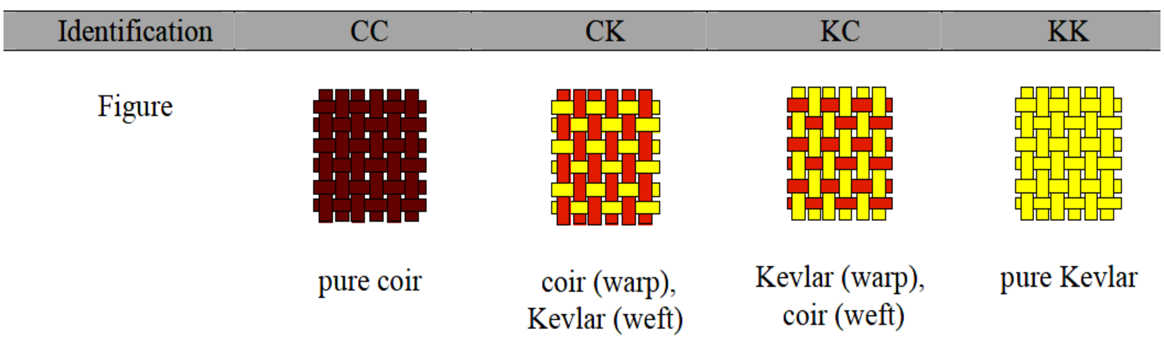


**Fig. 6.** Specification of woven fabric produced (Azrin Hani Abdul *et al.* 2011)

The results indicated that the composites containing Kevlar® fiber displayed high impact properties along with low flexural performance. The results also indicated that the composite plate with woven coir yarn (warp) and Kevlar® yarn (weft), with flexural strength and impact strength of 17 MPa and 67 kJ/m², respectively, displayed the closest property values to neat woven Kevlar® composite, as shown in Figs. 7 (a) and (b).

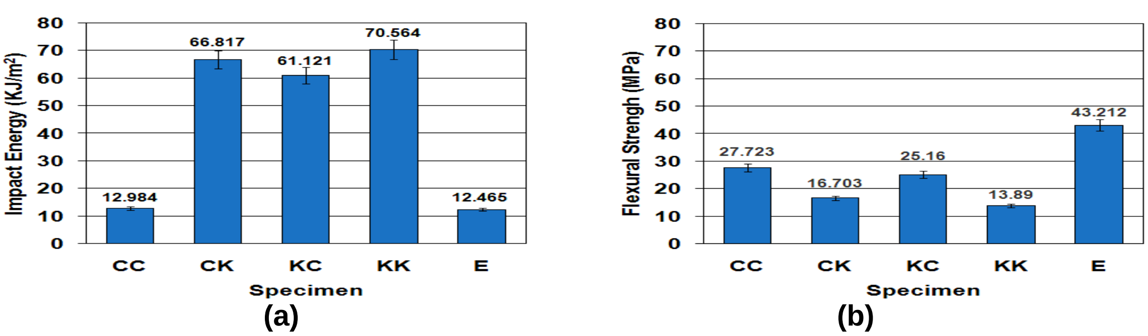


**Fig. 7.** (a) Impact strength of specimens, (b) Flexural strength of specimens (Azrin Hani Abdul *et al.* 2011), replotted)

It was concluded in this study that coir fibers could be used as a potential reinforcing material for high velocity impact impedance, such as body armor, in order to decrease the use of synthetic fibers while taking advantage of natural resources. Accordingly, the cost of the material will decrease as coir fibers are normally cheap and disposed as an undesirable waste. It was also found that altering the interlacing of coir and Kevlar® with various warp/weft directions (but keeping the same lay-up) influences the results for hybrid properties without changing the percentage of fiber content in the hybrid formulation.

The low velocity impact behavior of hybrid laminates reinforced with woven Kevlar® and basalt fabrics and produced by resin transfer molding with different stacking sequences was investigated by Sarasini *et al.* (2013). Residual post-impact properties of the different configurations of aramid/basalt hybrid laminates were characterized by quasi-static four-point bending tests. From the results, the hybrid laminates with arrangement of alternating gradation of basalt and aramid fabrics had the best impact energy absorption ability and improved damage tolerance with regard to the all Kevlar® laminates. At the same time basalt and hybrid laminates with a sandwich design of seven basalt fabric layers at the centre of the laminate as core and three Kevlar® fabric layers for each side of the composite as skins, presented the most compatible flexural behavior. The Kevlar®-skin/basalt-core type (BT-HS) outperformed the other lay-up sequences in quasi-static testing at all impact energies, thus suggesting a positive effect played by the hybridization design. The results indicated that it is possible to achieve impact absorption and damage tolerance similar to those of aramid laminates through the appropriate design of hybrid composites employing the cheaper basalt fibers for partial substitution of aramid fibers. It should be noted that the stacking sequence of the fiber layers has great effect on the properties of hybrid composites.

## PROPERTIES OF HYBRID KENAF/KEVLAR® FIBER COMPOSITES

The interest and evaluation of high performance materials, manufactured from kenaf fiber, is growing in recent years. Not only price savings, but also lowering in density is achieved by using kenaf fibers in comparison to Kevlar® fibers. The following researchers investigated the use of Kevlar® fibers in kenaf composites as a method to improve their properties, as shown in Table 4.

**Table 4.** Reported Research Work on Kenaf/Kevlar® Fiber Hybrid Composites

| Authors | Materials ( kenaf + Kevlar® ) fiber | Tests |
|---|---|---|
| (Kamardin *et al.* 2013) | Hybrid kenaf powder + Kevlar® fiber reinforced polypropylene resin. | Tensile test<br>Low velocity impact test. |
| (Bakar *et al.* 2014) | Hybrid long kenaf + Kevlar® fibers reinforced epoxy composites. | Tensile test<br>Low velocity impact test. |
| (Yahaya *et al.* 2014a)<br>(Yahaya *et al.* 2014b) | Hybrid non-woven kenaf + Kevlar® fibers reinforced epoxy composites. | Tensile test<br>Flexural test<br>High velocity impact test. |

Impact and tensile tests were carried out by Kamardin *et al.* (2013) in a 20 to 40% weight ratio of kenaf powder (K) polypropylene (PP), reinforced with Kevlar® (KV) composites, prepared using a hot-press technique. This hybridization was designated as KPP/KV and then tested using Izod impact and drop weight tests. The effect of the addition of kenaf powders on the impact toughness was also evaluated, and the optimum weight ratio of KPP sample was selected, followed by the drop weight impact test. It was concluded that the impact toughness of KPP reinforced with KV was almost 4 to 6 times higher than the samples without KV. It was observed that hybridization effects provided improved impact and tensile properties for this hybrid structure.

The effect of different weight percentage of Kevlar® incorporated into kenaf/epoxy composites was investigated by Bakar *et al*. (2014). The impact properties of Kevlar®, in different weight percentages, is shown in Table 5, reinforced with long kenaf fiber composites and studied using a DYNATUP 9250 drop weight machine. The impact energy absorbed and hardness increased with the increasing weight fraction of Kevlar® in the composite panels. The result showed that a 20 wt% of Kevlar® with long kenaf composites exhibited the maximum value of energy absorption, (12.76 J) for a hybrid composite in a design of 2Kevlar®/kenaf/2Kevlar®. It was demonstrated that the incorporation of Kevlar® fiber into the kenaf composites enhances the impact properties and hardness of the kenaf-based composites.

**Table 5.** Impact Parameters for Hybrid Composites; Bakar *et al.* (2014)

| Laminate | Weight percentage (Wt %) | Peak load (KN) | Energy absorbed (J) | Energy to maximum load (J) |
|---|---|---|---|---|
| 5Kevlar® | 25 | 2.13 | 14.37 | 5.07 |
| 2Kevlar®/Kenaf/2Kevlar® | 20 | 2.09 | 12.76 | 5.41 |
| 2Kevlar®/Kenaf/Kevlar® | 15 | 1.93 | 12.25 | 4.61 |
| Kevlar®/Kenaf/Kevlar® | 10 | 1.63 | 9.56 | 4.15 |

More recently, tensile testing, quasi-static penetration, and ballistic properties of non-woven kenaf fiber/Kevlar® epoxy hybrid laminates have been experimentally investigated by Yahaya *et al.* (2014a,b). Three layers with thicknesses ranging from 3.1 mm to 10.8 mm by hard projectile at normal incidence have been experimentally investigated for ballistic armor spall-liner application. Not only the effect of hybridization but also the effects of layering sequence of non-woven kenaf–Kevlar® in an epoxy matrix in three different layering sequences based on the locations of the kenaf layers were investigated. The results showed hybrid composites with kenaf at the innermost layers (Kevlar® at the outer layers) gave maximum penetration force and energy absorption. In addition, maximum force to initiate penetration was higher in hybrid composites compared to kenaf/epoxy and Kevlar®/epoxy composites. Hybridization of kenaf–Kevlar® resulted in a positive effect in terms of energy absorbed (penetration) and maximum load.

## CONCLUSIONS

This review paper offers an overview of the studies involving the physical, mechanical, thermal, and dynamic mechanical properties of kenaf/synthetic and Kevlar®/cellulosic hybrid composites. The findings of this research could be summarized as below:

1. Natural fiber hybrid composites are cost effective and possess impressive mechanical and thermal stability, and might partially replace and reduce the utilization of synthetic fibers as reinforcements of polymeric composites.
2. The use of natural fibers in various applications provides researchers with the challenge of developing suitable techniques to obtain high properties of the fibers that are up to the required standard, in order to use them to reinforce polymer composites. The basic structural components of cellulosic fibers and their effect on the physical, mechanical, and thermal properties of hybrid composites should therefore continue to be fully investigated.
4. It was shown that there is a high potential for the use of hybridization of kenaf/synthetic and Kevlar®/cellulosic fiber reinforced composites to form hybrid composites with extensive potential applications in many industrial fields.
5. It was also concluded that by using relatively simple equipment it is possible to manufacture composite materials with significantly improved environmental and mechanical performance.

Future research on hybrid composites requires exploring their potential application in other areas such as aircraft components, armor industry, rural areas, and biomedical devices. There is a need for extended analysis of the different properties of hybrid composites by modern equipment, such as X-ray photoelectron spectroscopy (XPS), atomic force microscopy (AFM), and stress relaxation in most of the areas covered in this review. This will help not only in better interpreting the experimental results but also in optimizing specific applications of the hybrid composite materials in many sectors.

## ACKNOWLEDGEMENTS

This work is supported by UPM under GP-IPS/2014/9438714 and GP-IPB grant, 9415402. The authors would like to express their gratitude and sincere appreciation to the Mechanical and Manufacturing Engineering Department and Aerospace Manufacturing Research Centre of the Universiti Putra Malaysia. Our appreciation and gratitude also extend to the Ministry of Higher Education & Scientific Research of Iraq and to the Material Engineering Department, College of Engineering, at the University of Mustansiriyah for their scientific assistance and financial support.

## REFERENCES CITED

Afdzaluddin, A., Maleque, M. A., and Iqbal, M. (2013). "Synergistic effect on flexural properties of kenaf-glass hybrid composite," *Advanced Materials Research* 626, 989-992. DOI: 10.4028/www.scientific.net/AMR.626.989

Agbo, S. (2009). *Modelling of Mechanical Properties of a Natural and Synthetic Fiber-Reinforced Cashew Nut Shell Resin Composites,* M.Sc. thesis, University of Nigeria, Nsukka, Nigeria.

Akil, H. M., De Rosa, I. M., Santulli, C., and Sarasini, F. (2010). "Flexural behaviour of pultruded jute/glass and kenaf/glass hybrid composites monitored using acoustic emission," *Materials Science and Engineering: A* 527(12), 2942-2950. DOI: 10.1016/j.msea.2010.01.028

Akil, H. M., Omar, M. F., Mazuki, A. A. M., Safiee, S., Ishak, Z. A. M., and Abu Bakar, A. (2011). "Kenaf fiber reinforced composites: A review," *Materials & Design* 32(8-9), 4107-4121. DOI: 10.1016/j.matdes.2011.04.008

Al-Harbi, K. M. A.-S. (2001). "Application of the AHP in project management," *International Journal of Project Management* 19(1), 19-27. DOI: 10.1016/S0263-7863(99)00038-1

Al-Mosawi Ali, I. (2012). "Mechanical properties of plants-synthetic hybrid fibers composites," *Research Journal of Engineering Sciences* 1(3), 22-25.

Anuar, H., Ahmad, S., Rasid, R., Ahmad, A., and Busu, W. (2008). "Mechanical properties and dynamic mechanical analysis of thermoplastic-natural-rubber-reinforced short carbon fiber and kenaf fiber hybrid composites," *Journal of Applied Polymer Science* 107(6), 4043-4052. DOI: 10.1002/app.27441/

Ashori, A. (2010). "Hybrid composites from waste materials," *Journal of Polymers and the Environment* 18(1), 65-70. DOI: 10.1007/s10924-009-0155-6

Atiqah, A., Maleque, M. A., Jawaid, M., and Iqbal, M. (2014). "Development of kenaf-glass reinforced unsaturated polyester hybrid composite for structural applications," *Composites Part B: Engineering* 56, 68-73. DOI: 10.1016/j.compositesb.2013.08.019

Azrin Hani Abdul, R., Roslan, A., Jaafar, M., Roslan, M. N., and Ariffin, S. (2011). "Mechanical properties evaluation of woven coir and kevlar reinforced epoxy composites," *Advanced Materials Research* 277, 36-42. DOI: 10.4028/www.scientific.net/AMR.277.36

Bakar, M. A. A., Ahmad, S., Kuntjoro,W., and Kasolang, S. (2013). "Effect of carbon fibre ratio to the impact properties of hybrid kenaf/carbon fibre reinforced epoxy composites," *Applied Mechanics and Materials* 393, 136-139. DOI: 10.1177/0021998305047267

Bakar, N. H., Mei Hyie, K., Ramlan, A. S., Hassan, M. K., and Jumahat, A. (2014). "Mechanical properties of kevlar reinforcement in kenaf composites," *Applied Mechanics and Materials* 465, 847-851. DOI: 10.4028/www.scientific.net/AMM.465-466.847

Begum, K., and Islam, M. A. (2013). "Natural fiber as a substitute to synthetic fiber in polymer composites: A review," *Research Journal of Engineering Sciences* 2(3), 46-53.

Bledzki, A. K., and Gassan, J. (1997). "Fiber reinforced plastics," in: *Handbook of Engineering Polymeric Materials*, S. Kalia, B. S. Kaith, and I. Kaur (eds.), Marcel Dekker Inc., New York, NY, pp. 787-810.

Bledzki, A. K., and Gassan, J. (1999). "Composites reinforced with cellulose based fibres," *Progress in Polymer Science* 24(2), 221-274. DOI: 10.1016/S0079-6700(98)00018-5

Burgueño, R., Quagliata, M. J., Mohanty, A. K., Mehta, G., Drzal, L. T., and Misra, M. (2005). "Hybrid biofiber-based composites for structural cellular plates," *Composites*

*Part A: Applied Science and Manufacturing* 36(5), 581-593. DOI: 10.1016/j.compositesa.2004.08.004
Callister, W. D., and Rethwisch, D. G. (2011). *Materials Science and Engineering*, 8th Ed., John Wiley & Sons, Asia.
Cheung, H.-Y., Ho, M.-P., Lau, K.-T., Cardona, F., and Hui, D. (2009). "Natural fibre-reinforced composites for bioengineering and environmental engineering applications," *Composites Part B: Engineering* 40(7), 655-663. DOI: 10.1016/j.compositesb.2009.04.014
Cicala, G., Cristaldi, G., Recca, G., Ziegmann, G., El-Sabbagh, A., and Dickert, M. (2009). "Properties and performances of various hybrid glass/natural fibre composites for curved pipes," *Materials & Design* 30(7), 2538-2542. DOI: 10.1016/j.matdes.2008.09.044
Corbière-Nicollier, T., Gfeller Laban, B., Lundquist, L., Leterrier, Y., Månson, J. A. E., and Jolliet, O. (2001). "Life cycle assessment of biofibres replacing glass fibres as reinforcement in plastics," *Resources, Conservation and Recycling* 33(4), 267-287. DOI: 10.1016/S0921-3449(01)00089-1
Da Silva, R. V., Aquino, E. M. F., Rodrigues, L. P. S., and Barros, A. R. F. (2008). "Development of a hybrid composite with synthetic and natural fibers," *Matéria (Rio de Janeiro)* 13(1), 154-161. DOI: 10.1590/S1517-70762008000100019
Davoodi, M. M., Sapuan, S. M., Ahmad, D., Ali, A., Khalina, A., and Jonoobi, M. (2010). "Mechanical properties of hybrid kenaf/glass reinforced epoxy composite for passenger car bumper beam," *Materials & Design* 31(10), 4927-4932. DOI: 10.1016/j.matdes.2010.05.021
Davoodi, M. M., Sapuan, S. M., Ahmad, D., Aidy, A., Khalina, A., and Jonoobi, M. (2011). "Concept selection of car bumper beam with developed hybrid bio-composite material," *Materials & Design* 32(10), 4857-4865. DOI: 10.1016/j.matdes.2011.06.011
Davoodi, M. M., Sapuan, S. M., Ahmad, D., Aidy, A., Khalina, A., and Jonoobi, M. (2012). "Effect of polybutylene terephthalate (PBT) on impact property improvement of hybrid kenaf/glass epoxy composite," *Materials Letters* 67(1), 5-7. DOI: 10.1016/j.matlet.2011.08.101
De Rosa, I. M., Santulli, C., Sarasini, F., and Valente, M. (2009). "Post-impact damage characterization of hybrid configurations of jute/glass polyester laminates using acoustic emission and IR thermography," *Composites Science and Technology* 69(7-8), 1142-1150. DOI: 10.1016/j.compscitech.2009.02.011
Dipa, R., and Jogeswari, R. (2005). "Thermoset biocomposites," in: *Natural Fibers, Biopolymers, and Biocomposites*, A. K. Mohanty, M. Misra, and L. T. Drzal (eds.), CRC Press, Boca Raton, FL. DOI: 10.1201/9780203508206.ch9
El-Tayeb, N. S. M. (2009). "Development and characterisation of low-cost polymeric composite materials," *Materials & Design* 30(4), 1151-1160. DOI: 10.1016/j.matdes.2008.06.024
Elsaid, A., Dawood, M., Seracino, R., and Bobko, C. (2011). "Mechanical properties of kenaf fiber reinforced concrete," *Construction and Building Materials* 25(4), 1991-2001. DOI: 10.1016/j.conbuildmat.2010.11.052
Faruk, O., Bledzki, A. K., Fink, H.-P., and Sain, M. (2012). "Biocomposites reinforced with natural fibers: 2000–2010," *Progress in Polymer Science* 37(11), 1552-1596. DOI: 10.1016/j.progpolymsci.2012.04.003

Fifield, L. S., and Simmons, K. L. (2010). "Compression molded, bio-fiber reinforced, high performance thermoset composites for structural and semi-structural applications," *10th Annual Automotive Composites Conference & Exhibition*, Sep. 15-16, Troy, MI.

Fulton, I. T. (2011). *The Effect of Layup and Pressure on Mechanical Properties of Fiberglass and Kenaf Fiber Composites*, M.Sc. thesis, Mississippi State University, Starkville, MS.

Ghani, M. A. A., Salleh, Z., Hyie, K. M., Berhan, M. N., Taib, Y. M. D., and Bakri, M. A. I. (2012). "Mechanical properties of kenaf/fiberglass polyester hybrid composite," *Procedia Engineering* 41, 1654-1659. DOI: 10.1016/j.proeng.2012.07.364

Gross, R. A., and Kalra, B. (2002). "Biodegradable polymers for the environment," *Science* 297(5582), 803-807. DOI: 10.1126/science.297.5582.803

Hancox, N. L. (2000). "1 - An overview of the impact behaviour of fibre-reinforced composites," in: *Impact Behaviour of Fibre-Reinforced Composite Materials and Structures*, S. R. Reid and G. Zhou (eds.),Woodhead Publishing, Cambridge, UK, pp. 1-32. DOI: 10.1533/9781855738904.1

Hariharan, A. B. A., and Khalil, H. P. S. A. (2005). "Lignocellulose-based hybrid bilayer laminate composite: Part I - Studies on tensile and impact behavior of oil palm fiber-glass fiber-reinforced epoxy resin," *Journal of Composite Materials* 39(8), 663-684. DOI: 10.1177/0021998305047267

Herrera-Franco, P. J., and Valadez-González, A. (2004). "Mechanical properties of continuous natural fibre-reinforced polymer composites," *Composites Part A: Applied Science and Manufacturing* 35(3), 339-345. DOI: 10.1016/j.compositesa.2003.09.012

Herrera-Franco, P. J., and Valadez-González, A. (2005). "A study of the mechanical properties of short natural-fiber reinforced composites," *Composites Part B: Engineering* 36(8), 597-608. DOI: 10.1016/j.compositesb.2005.04.001

Hill, C., and Hughes, M. (2010). "Natural fibre reinforced composites opportunities and challenges," *Journal of Biobased Materials and Bioenergy* 4(2), 148-158. DOI: 10.1166/jbmb.2010.1079

Hou, J. P., Petrinic, N., Ruiz, C., and Hallett, S. R. (2000). "Prediction of impact damage in composite plates," *Composites Science and Technology* 60(2), 273-281. DOI: 10.1016/S0266-3538(99)00126-8

Isaac, M., and Ishai, D. O. (2006). *Engineering Mechanics of Composite Materials*, Oxford University Press, New York, NY.

Ishak, M. R., Leman, Z., Sapuan, S., Edeerozey, A., and Othman, I. S. (2010). "Mechanical properties of kenaf bast and core fibre reinforced unsaturated polyester composites," *9th National Symposium on Polymeric Materials (NSPM 2009)* 012006. DOI: 10.1088/1757-899X/11/1/012006

Ismail, H., Omar, N. F., and Othman, N. (2011). "The effect of kenaf fibre loading on curing characteristics and mechanical properties of waste tyre dust/kenaf fibre hybrid filler filled natural rubber compounds," *BioResources* 6(4), 3742-3756. DOI: 10.15376/biores.6.4.3742-3756

Jawaid, M., and Abdul Khalil, H. P. S. (2011). "Cellulosic/synthetic fibre reinforced polymer hybrid composites: A review," *Carbohydrate Polymers* 86(1), 1-18. DOI: 10.1016/j.carbpol.2011.04.043

Jeyanthi, S., and Rani, J. J. (2012). "Improving mechanical properties by kenaf natural long fiber reinforced composite for automotive structures," *Journal of Applied Science and Engineering* 15(3), 275-280.
Joshi, S. V., Drzal, L. T., Mohanty, A. K., and Arora, S. (2004). "Are natural fiber composites environmentally superior to glass fiber reinforced composites?" *Composites Part A: Applied Science and Manufacturing* 35(3), 371-376. DOI: 10.1016/j.compositesa.2003.09.016
Kamardin, N. K., Taib, Y. M., and Kalam, A. (2013). "Impact toughness of kenaf powder, polypropylene and kevlar," *Applied Mechanics and Materials* 393, 152-155. DOI: 10.1016/S0266-3538(03)00096-4
Khalil, H. A., Kang, C., and Adawi, T. (2008). "The effect of different laminations on mechanical and physical properties of hybrid composites," *Journal of Reinforced Plastics and Composites* 28(9), 1123-1137. DOI: 10.1177/0731684407087755
Kline and Company, Inc. (2000). *Opportunities for Natural Fibers In Plastic Composites*, Little Falls, New Jersey, http://www.klinegroup.com/reports/brochures/y463/brochure.pdf.
Kong, K., Hejda, M., Young, R. J., and Eichhorn, S. J. (2009). "Deformation micromechanics of a model cellulose/glass fibre hybrid composite," *Composites Science and Technology* 69(13), 2218-2224. DOI: 10.1016/j.compscitech.2009.06.006
Ling, P. A., and Ismail, H. (2012). "Tensile properties, water uptake, and thermal properties of polypropylene/waste pulverized tire/kenaf (PP/WPT/KNF) composites," *BioResources* 8(1), 806-817. DOI: 10.15376/biores.8.1.806-817
Maleque, M. A., Afdzaluddin, A., and Iqbal, M. (2012). "Flexural and impact properties of kenaf-glass hybrid composite," *Advanced Materials Research* 576, 471-474. DOI: 10.1016/j.proeng.2011.04.335
Mansor, M. R., Sapuan, S. M., Zainudin, E. S., Nuraini, A. A., and Hambali, A. (2013). "Hybrid natural and glass fibers reinforced polymer composites material selection using Analytical hierarchy process for automotive brake lever design," *Materials & Design* 51, 484-492. DOI:10.1016/j.matdes.2013.04.072
Mathur, V. K. (2006). "Composite materials from local resources." *Construction and Building Materials* 20(7), 470-477. DOI: 10.1016/j.conbuildmat.2005.01.031
Milanese, A. C., Cioffi, M. O. H., and Voorwald, H. J. C. (2011). "Mechanical behavior of natural fiber composites," *Procedia Engineering* 10, 2022-2027. DOI: 10.1016/j.proeng.2011.04.335
Mohanty, A. K., and Misra, M. (2005). *Natural Fibers, Biopolymers, and Biocomposites*, Taylor & Francis, Boca Raton, FL.
Mohanty, A., Misra, M., and Hinrichsen, G. (2000). "Biofibres, biodegradable polymers and biocomposites: An overview," *Macromolecular Materials and Engineering* 276-277, 1-24. DOI: 10.1002/(SICI)1439-2054(20000301)276:1%3C1::AID-MAME1%3E3.0.CO;2-W
Mohanty, A. K., Misra, M., and Drzal, L. T. (2001). "Surface modifications of natural fibers and performance of the resulting biocomposites: An overview," *Composite Interfaces* 8(5), 313-343. DOI: 10.1163/156855401753255422
Mohanty, A. K., Misra, M., and Drzal, L. T. (2002). "Sustainable bio-composites from renewable resources: Opportunities and challenges in the green materials world,"

*Journal of Polymers and the Environment* 10(1-2), 19-26. DOI: 10.1023/A%3A1021013921916

Mueller, D. H., and Krobjilowski, A. (2004). "Improving the impact strength of natural fiber reinforced composites by specifically designed material and process parameters," *INJ* Winter, 31-38.

Munusamy, S. R. (2012). *Development of Biobased Sandwich Structures for Mass Transit Application*, M.Sc. thesis, North Dakota State University, Fargo, ND.

Murali Mohan Rao, K., Mohana Rao, K., and Ratna Prasad, A. V. (2010). "Fabrication and testing of natural fibre composites: Vakka, sisal, bamboo and banana," *Materials & Design* 31(1), 508-513. DOI: 10.1016/j.matdes.2009.06.023

Nishino, T., Hirao, K., Kotera, M., Nakamae, K., and Inagaki, H. (2003). "Kenaf reinforced biodegradable composite," *Composites Science and Technology* 63(9), 1281-1286. DOI: 10.1016/S0266-3538(03)00099-X

Nunna, S., Chandra, P. R., Shrivastava, S., and Jalan, A. K. (2012). "A review on mechanical behavior of natural fiber based hybrid composites," *Journal of Reinforced Plastics and Composites* 31(11), 759-769. DOI: 10.1177/0731684412444325

Osman, M. R., Akil, H. M., and Mohd Ishak, Z. A. (2013). "Effect of hybridization on the water absorption behaviour of pultruded kenaf fibre-reinforced polyester composites," *Composite Interfaces* 20(7), 517-528. DOI: 10.1080/15685543.2013.811182

Ou, R., Zhao, H., Sui, S., Song, Y., and Wang, Q. (2010). "Reinforcing effects of Kevlar fiber on the mechanical properties of wood-flour/high-density-polyethylene composites," *Composites Part A: Applied Science and Manufacturing* 41(9), 1272-1278. DOI: 10.1016/j.compositesa.2010.05.011

Pandey, J. K., Ahn, S. H., Lee, C. S., Mohanty, A. K., and Misra, M. (2010). "Recent advances in the application of natural fiber based composites," *Macromolecular Materials and Engineering* 295(11), 975-989. DOI: 10.1002/mame.201000095

Park, R., and Jang, J. (1998). "Stacking sequence effect of aramid–UHMPE hybrid composites by flexural test method: Material properties," *Polymer Testing* 16(6), 549-562. DOI: 10.1016/S0142-9418(97)00018-4

Radif, Z. S. (2009). *Development of a Green Combat Armour from Rame-Kevlar-Polyester Composite*, M.Sc. thesis, Universiti Putra Malaysia, Serdang, Malaysia.

Rao, H. R., Kumar, M. A., and Reddy, G. R. (2011). "Hybrid composites: Effect of fibers on mechanical properties," *International Journal of Macromolecular Science* 1(1), 9-14.

Ratna Prasad, A. V., and Mohana Rao, K. (2011). "Mechanical properties of natural fibre reinforced polyester composites: Jowar, sisal and bamboo," *Materials & Design* 32(8-9), 4658-4663. DOI: 10.1016/j.matdes.2011.03.015

Richardson, M. O., Madera-Santana, T. J., and Hague, J. (1998). "Natural fibre composites. The potential for the Asian markets," *Progress in Rubber and Plastics Technology* 14(3), 174-188.

Saheb, D. N., and Jog, J. P. (1999). "Natural fiber polymer composites: A review," *Advances in Polymer Technology* 18(4), 351-363. DOI: 10.1002/(SICI)1098-2329(199924)18:4<351::AID-ADV6>3.0.CO;2-X

Salleh, Z., Berhan, M. N., Hyie, K. M., and Isaac, D. H. (2012a). "Cold-pressed kenaf and fibreglass hybrid composites laminates: Effect of fibre types," *World Academy of*

*Science, Engineering and Technology, International Science Index 71* 6(11), 740 - 744.
Salleh, Z., Taib, Y. M., Hyie, K. M., Mihat, M., Berhan, M. N., and Ghani, M. A. A. (2012b). "Fracture toughness investigation on long kenaf/woven glass hybrid composite due to water absorption effect," *Procedia Engineering* 41, 1667-1673. DOI: 10.1016/j.proeng.2012.07.366
Salleh, Z., Hyie, K. M., Berhan, M. N., Taib, Y. M., Hassan, M., and Isaac, D. (2013). "Effect of low impact energy on kenaf composite and kenaf/fiberglass hybrid composite laminates," *Applied Mechanics and Materials* 393, 228-233. DOI: 10.4028/www.scientific.net/AMM.393.228
Santulli, C. (2007). "Impact properties of glass/plant fibre hybrid laminates," *Journal of Materials Science* 42(11), 3699-3707. DOI: 10.1007/s10853-006-0662-y
Sarasini, F., Tirillò, J., Valente, M., Ferrante, L., Cioffi, S., Iannace, S., and Sorrentino, L. (2013). "Hybrid composites based on aramid and basalt woven fabrics: Impact damage modes and residual flexural properties," *Materials & Design* 49, 290-302. DOI: 10.1016/j.matdes.2013.01.010
Sayer, M., Bektaş, N. B., and Çallioğlu, H. (2010). "Impact behavior of hybrid composite plates," *Journal of Applied Polymer Science* 118(1), 580-587. DOI: 10.1002/app.32437
Sharifah, H., Martin, P., Simon, T., and Simon, R. (2005). "Modified polyester resins for natural fiber composites," *Compos. Sci. Technol*. 65(3-4), 525-535. DOI: http://doi.org/10.1016/j.compscitech.08.005
Sultan, M. T. H., Basri, S., Rafie, A. S. M., Mustapha, F., Majid, D. L., and Ajir, M. R. (2012a). "High velocity impact damage analysis for glass epoxy-laminated plates," *Advanced Materials Research* 399, 2318-2328. DOI: 10.4028/www.scientific.net/AMR.399-401.2318
Sultan, M. T. H., Worden, K., Staszewski, W. J., and Hodzic, A. (2012b). "Impact damage characterisation of composite laminates using a statistical approach," *Composites Science and Technology* 72(10), 1108-1120. DOI: 10.1016/j.compscitech.2012.01.019
Taj, S., Munawar, M. A., and Khan, S. (2007). "Natural fiber-reinforced polymer composites," *Proceedings-Pakistan Academy of Sciences* 44(2), 129.
Varma, I. K., Anantha Krishnan, S. R., and Krishnamoorthy, S. (1989). "Composites of glass/modified jute fabric and unsaturated polyester resin," *Composites* 20(4), 383-388. DOI: 10.1016/0010-4361(89)90664-2
Venkateshwaran, N., Elayaperumal, A., and Sathiya, G. K. (2012). "Prediction of tensile properties of hybrid-natural fiber composites," *Composites Part B: Engineering* 43(2), 793-796. DOI: 10.1016/j.compositesb.2011.08.023
Wambua, P., Ivens, J., and Verpoest, I. (2003). "Natural fibres: Can they replace glass in fibre reinforced plastics?" *Composites Science and Technology* 63(9), 1259-1264. DOI: 10.1016/S0266-3538(03)00096-4
Wan Busu, W. N., Anuar, H., Ahmad, S. H., Rasid, R., and Jamal, N. A. (2010). "The mechanical and physical properties of thermoplastic natural rubber hybrid composites reinforced with *Hibiscus cannabinus* L and short glass fiber," *Polymer-Plastics Technology and Engineering* 49(13), 1315-1322. DOI: 10.1080/03602559.2010.496408

Yahaya, R., Sapuan, S., Jawaid, M., Leman, Z., and Zainudin, E. (2014a). "Effect of post curing, fibre content and resin-hardener mixing ratio on the properties of kenaf-aramid hybrid composites," *Applied Mechanics and Materials* 548, 7-11. DOI: 10.4028/www.scientific.net/AMM.548-549.7

Yahaya, R., Sapuan, S. M., Jawaid, M., Leman, Z., and Zainudin, E. S. (2014b). "Quasi-static penetration and ballistic properties of kenaf–aramid hybrid composites," *Materials & Design* 63, 775-782. DOI: 10.1016/j.matdes.2014.07.010

Zhong, L. X., Fu, S. Y., Zhou, X. S., and Zhan, H. Y. (2011). "Effect of surface microfibrillation of sisal fibre on the mechanical properties of sisal/aramid fibre hybrid composites," *Composites Part A: Applied Science and Manufacturing* 42(3), 244-252. DOI: 10.1016/j.compositesa.2010.11.010

Article submitted: April 6, 2015; Peer review completed: July 20, 2015; Revised version received: August 9, 2015; Accepted: August 10, 2015; Published: August 14, 2015.
DOI: 10.15376/biores.10.4.Salman