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INFLUENCE OF THE FIBER LAYER STACKING SEQUENCE ON THE PROPERTIES OF HYBRID COMPOSITES: A REVIEW

Laura Setti de Sousa
``Instituto Militar de Engenharia``– IME
Rio de Janeiro – RJ
http://lattes.cnpq.br/5169541767210044

Lucio Fabio Cassiano Nascimento
``Instituto Militar de Engenharia``– IME
Rio de Janeiro – RJ
http://lattes.cnpq.br/7186497849886649

Fabio da Costa Garcia Filho
``Instituto Militar de Engenharia``– IME
Rio de Janeiro – RJ
http://lattes.cnpq.br/4940436394133128

Sergio Neves Monteiro
``Instituto Militar de Engenharia``– IME
Rio de Janeiro – RJ
http://lattes.cnpq.br/2962183322412029

Abstract: The hybridization of different types of fibers in the same matrix aims to combine the advantages of each material that constitutes it, through the balance between its mechanical properties and the economic requirements for its production and application. This phenomenon is especially observed when using natural fibers together with synthetic fibers, therefore, the partial replacement of synthetic fibers by natural fibers in polymer matrix composites results in a balance between low production cost/environmental impact and excellent mechanical properties. However, the mechanical performance of hybrid composites is subject to several variables, such as the specific properties of the fibers used, the type of material used as matrix and, mainly, the sequential arrangement of the reinforcement layers. Therefore, this article presents the most recent works that aim to investigate the influence of different stacking sequences of natural and/or synthetic fiber layers on the mechanical and ballistic behavior of hybrid polymer matrix composites.
Keywords: Hybrid composite. Synthetic fiber. Natural fiber. Sustainability.

INTRODUCTION

Currently, several researchers are focused on creating ecological materials that play a crucial role in promoting sustainable development, whose objective is to minimize the impact of human actions on the environment (ELFALEH et al., 2023). To achieve this objective, there is an increase in the creation and use of environmentally friendly materials to replace conventional materials, often coming from non-renewable sources (BLEDZKI; GASSAN, 1999). Due to this, the use of composites reinforced with natural lignocellulosic fibers (FNLs) emerges as a promising alternative for replacing synthetic fibers in engineering materials (MOHAMMED et al., 2015).

Although composite materials reinforced with natural fibers have numerous advantages over synthetic fibers, their heterogeneous microstructure results in composites with heterogeneous properties, which represents a challenge for their use in engineering (MOHAMMED et al., 2015). In view of this, it is unlikely that a single material made up of natural fibers will be able to satisfy all the requirements necessary for the manufacture of high-performance composites. To overcome this limitation, one approach that has shown promise is the introduction of innovative material combinations. This implies the use of lightweight materials in conjunction with other materials with superior mechanical performance, such as hybrid composites of natural fibers and synthetic fibers. This combination of materials allows the creation of structures that take advantage of the individual advantages of each component, resulting in more efficient materials, as well as being sustainable and cost-effective (PATHAK et al., 2023; KUMAR, S. et al., 2022; KUMAR, T. S. M.; et al., 2022).

In this context, hybrid composites consisting of two or more types of fibers in a single matrix tend to exhibit intermediate or even superior properties compared to composites reinforced with just one type of fiber, especially when natural fibers are combined with synthetic fibers, generating a balance between low production cost and environmental impact and excellent mechanical properties (MELIANDE et al., 2022a). The properties and performance of fiber-reinforced composite materials depend on several factors inherent to their constituent phases, that is, the reinforcement phase and the matrix phase. The type of fiber (natural or synthetic), its chemical composition, microstructure, volume fraction, orientation and arrangement of these fibers in the matrix are some of the variables that directly influence the properties of hybrid composites. Furthermore, several recent studies have indicated that the stacking sequence of layers of different fibers also influences the mechanical and ballistic properties of these materials (MOHAMMED et al., 2015).

NATURAL LIGNOCELLULOSIC FIBERS

FNLs can be considered as a solution, that is, as an alternative material to traditional materials used in reinforced composites, due to a series of advantages, such as their low cost, low density, high specific resistance, they are the result of renewable sources, biodegradable, in addition to representing a source of income for developing regions in Brazil and the world (MONTEIRO et al., 2011). Therefore, many studies are focused on investigating and exploring these materials as reinforcing elements in polymer matrix composites for various applications (NAYAK et al., 2022). Due to their advantages, natural fibers have gained increasing attention and application in industries, mainly in the civil construction, automotive and aerospace sectors, as shown in the graph in Figure 1.

Natural vegetable fibers are also called lignocellulosic natural fibers (NLFs), as they are basically composed of semi-crystalline cellulose microfibrils incorporated in a matrix of hemicellulose and lignin (JOHN; THOMAS, 2008). Furthermore, FNLs can be classified according to their location within the plant, that is, according to the part of the plant from which they are extracted. Although there is variation in the classifications proposed by different authors, a more comprehensive approach, based on John and Thomas (2008) and Meliande (2022b), suggests six subdivisions. Therefore, natural vegetable fibers come from the fruit (such as coconut), the seed (cotton), the leaves (curauá, sisal, banana), the stem (ramie, jute, linen), straw (corn, wheat, rice) or grasses (bamboo).

Another classification into which natural fibers can be divided is in terms of their use, as being primary, that is, cultivated as an agricultural activity (jute, hemp, sisal, among others) or secondary, when they are residues or by-products of the agro-industry (such as coconut and pineapple) (GHOLAMPOUR; OZBAKKALOGLU, 2020). This classification is extremely relevant in the context of sustainability, since the use of secondary fibers in engineering materials means giving a new destination to waste that would otherwise be discarded in the environment, thus promoting the principles of the circular economy.

The chemical composition and microstructure of FNLs, such as cellulose content, microfibrillar angle, crystallinity, degree of polymerization, density and diameter vary between different types of natural fibers and are directly associated with their mechanical properties. Furthermore, these structural parameters, as well as other characteristics, can vary between the same fiber species, interfering with their properties. This variation is influenced by where the plant is grown, whether the fiber is taken from the stem or leaves, the age of the plant and its pre-conditioning. Unlike synthetic fibers that have homogeneous microstructural characteristics and, consequently, uniform properties, natural fibers have a heterogeneous microstructure. The variation in these parameters is what determines the different properties between FNLs (MONTEIRO et al., 2011; JOHN; THOMAS, 2008; MOHANTY; MISRA; HINRICHSEN, 2000).

SYNTHETIC FIBERS

Synthetic fibers are manufactured exclusively in laboratories from polymers that are not found in nature, generally derived from petroleum by-products or from ceramic materials (CALLISTER; RETHWISCH, 2016;

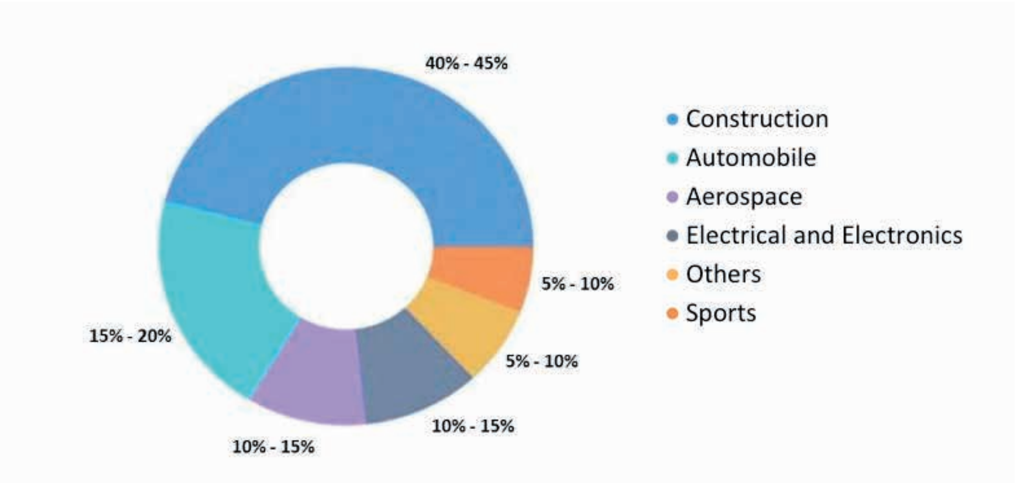

Figure 1 – Use of composites reinforced by natural fibers for the year 2021 by industrial segments. Adapted from (SABER; ABDELNABY, 2022)

Hybrid Composite	Type of Fibers	Year of Publication	References
Synthetic/Synthetic	Aramid/glass	2022	(ÜSTUN; TOKSOY; TANOGLU, 2022)
	Aramid/carbon	2021; 2023	(ALKHATIB; MAHDI; DEAN, 2021) ;(XU et al, 2023)
	Carbon/aramid/ UHMWPE	2023	LI et al., 2023
Natural/Natural	Mauve/jute	2017	(NASCIMENTO et al., 2017)
	Jute/sisal	2019	(CAVALCANTI et al., 2019)
	Jute/curauá	2019	(CAVALCANTI et al., 2019)
	Palm oil/kenaf	2020	(HANAN; JAWAID; TAHIR, 2020)
	Sisal/caryota	2021	(ATMAKURI et al., 2021)
Synthetic/Natural	Aramid/kenaf	2015; 2018	(YAHAYA et al., 2015); (SALMAN; LEMAN, 2018)
	Glass/bamboo	2019	(ALI et al., 2019)
	Aramid/coconut	2019	(NAVEEN et al., 2019)
	Glass/jute	2022	(GHANI et al., 2022)
	Aramid/curauá	2023	(MELIANDE et al., 2023)

Table 1 – Research with fiber-reinforced hybrid polymer composites.

Source: The author

RAJAK; WAGH; LINUL, 2022). These fibers can be classified into two main categories: organic and inorganic fibers, which can also be subclassified according to their origin (KUMAR et al., 2023). Organic fibers are formed through the synthesis of organic molecules, that is, hydrocarbons (hydrogen and carbon) with covalent intramolecular bonds. This group includes polyamide fibers (such as nylon and aramid), polyester (PET and PBT), polyvinyl (PVA and PVC), polyethylene, among others. Inorganic synthetic fibers are manufactured from inorganic materials such as glass, carbon, boron and silicon carbide (CALLISTER; RETHWISCH, 2016; RAJAK; WAGH; LINUL, 2022).

The production of organic synthetic fibers involves polymerization, spinning and filament processing techniques. The large macromolecules that make up polymers are synthesized through a process called polymerization, the objective of which is to join smaller molecules (monomers) to each other, generating long chains of repeated units. Fibers are formed from a polymeric material through the spinning process, where, in general, the material to be spun is heated, transforming into a viscous liquid. This polymer is extruded through a *spinneret*, which consists of a small beak-shaped plate with several small, round holes. Passing the polymer through each of these holes results in a filament, which will be solidified through rapid cooling. These filaments then undergo processing that will depend on their use, that is, if fibers with improved mechanical properties are desired, a post-formation process called stretching is carried out. This technique is based on the permanent mechanical stretching of the fiber in its longitudinal direction, producing a highly oriented structure and, consciously, with improved tensile strength, modulus of elasticity and tenacity. Furthermore, these countless thin and continuous filaments can go through the carding process and sold to the textile industry for the manufacture of fabrics or can be cut into smaller lengths to produce discontinuous fibers (CALLISTER; RETHWISCH, 2016; RAJAK; WAGH; LINUL, 2022).

Due to their industrialized manufacturing process, synthetic fibers have homogeneous microstructural characteristics, which results in uniform properties, unlike FNLs (MONTEIRO et al., 2011). However, synthetic fibers present some notable challenges, such as the high production cost, high energy consumption, the fact that they are a non-renewable material, density often greater than that of FNLs, in addition to being abrasive to the processing machines (MONTEIRO et al., 2015).

POLYMERIC MATERIALS

The term polymer has its origins in the Greek language poly (many) and mero (repeating unit), referring to compounds with tens of thousands of repeating units (meres), which are joined together through interatomic covalent bonds. Because of this, the molecules that make up a polymer are gigantic and because of their size, they are called macromolecules. The small molecule from which the polymer will be synthesized is called monomer, and is the primordial substance necessary for its manufacture (CALLISTER; RETHWISCH, 2016; CANEVAROLO, 2002).

Polymeric materials can be either synthetic, that is, produced by man, like those mentioned previously, or natural, like those derived from plants and animals (MANO; MENDES, 2004). Thus, polymers are classified into three main categories, according to the chemical structure of the monomer, the average number of mers in each chain and the type of covalent bond present in: plastics, rubbers (elastomers) and fibers (CANEVAROLO, 2002).

Plastics are known for their structural

rigidity and are widely used in various applications. Many polymeric materials fall into this category, such as polyethylene, polypropylene, poly (vinyl chloride), epoxies, phenolics, polyesters, among others. Some of these polymers are considered rigid and brittle, while others are more flexible and can withstand greater deformations before fracturing. Furthermore, these materials can exhibit different degrees of crystallinity, as well as different structures and molecular configurations (linear, branched, etc.). Plastics are subclassified into thermoplastics or thermosets based on their behavior at elevated temperatures. Thermoplastic polymers soften when heated and harden when cooled. This phenomenon occurs because thermoplastic polymers are, in general, formed by linear structures or some branched structures, which results in flexible chains when introducing an increase in temperature. This means that secondary bonding forces decrease, facilitating the movement of adjacent chains when tension is applied. Polyethylene, polystyrene and polyvinyl chloride are examples of thermoplastics. Thermosetting or thermosetting polymers become permanently rigid during their formation and do not soften upon heating. This occurs because its structure is networked, that is, most of the bonds are crossed and covalent between nearby molecular chains after the curing process. Therefore, when a high temperature is introduced, these bonds bind the chains to each other and prevent their movement, which results in their dimensional stability, as well as more rigid and resistant characteristics. Vulcanized rubbers, epoxies, phenolics and polyesters are some of these polymers with cross-links and networks, characterized as thermosetting (CALLISTER; RETHWISCH, 2016).

HYBRID COMPOSITE

The use of two or more types of fibers in the same matrix defines a new category of fiber-reinforced composite, the hybrid composite. The properties of hybrids tend to be better than the properties of composites reinforced with just one type of fiber, especially when natural fibers and synthetic fibers are used, generating a balance between low production cost and environmental impact and excellent mechanical properties (JOHN; THOMAS, 2008).

However, hybridization can be carried out not only by combining natural and synthetic fibers, but also by combining different natural fibers, or by a combination of different synthetic fibers (SAFRI et al., 2018). Therefore, many researchers are exploring the feasibility and performance of hybrid composites joining different fibers, as shown in Table 1.

Üstün, Toksoy and Tanoğlu (71) investigated the effect of hybridization on the mechanical and ballistic performance of epoxy resin composite structures reinforced with aramid fiber and glass fiber fabric. The hybrid composites were prepared with a proportion of 64% fiber weight, with two-layer thickness configurations, 50%:50% (H1) and 70%:30% (H2) for aramid and glass fibers, respectively. Figure 2 shows the cross section of the deformation cone/wedge generated by the impact of the projectile on the four different composites tested, where the arrows indicate the direction of the impact. Therefore, it can be seen that in the composite reinforced only by aramid fibers (a) the main deformation mechanism was fiber breakage, while in the composite reinforced with glass fibers (b) delamination predominated. Hybrid structures H1 (c) and H2 (d) suffered fiber breakage, delamination and bulging of the composite during projectile penetration.

In hybrid composites H1 and H2, due to the presence of a glass fiber fabric layer at the

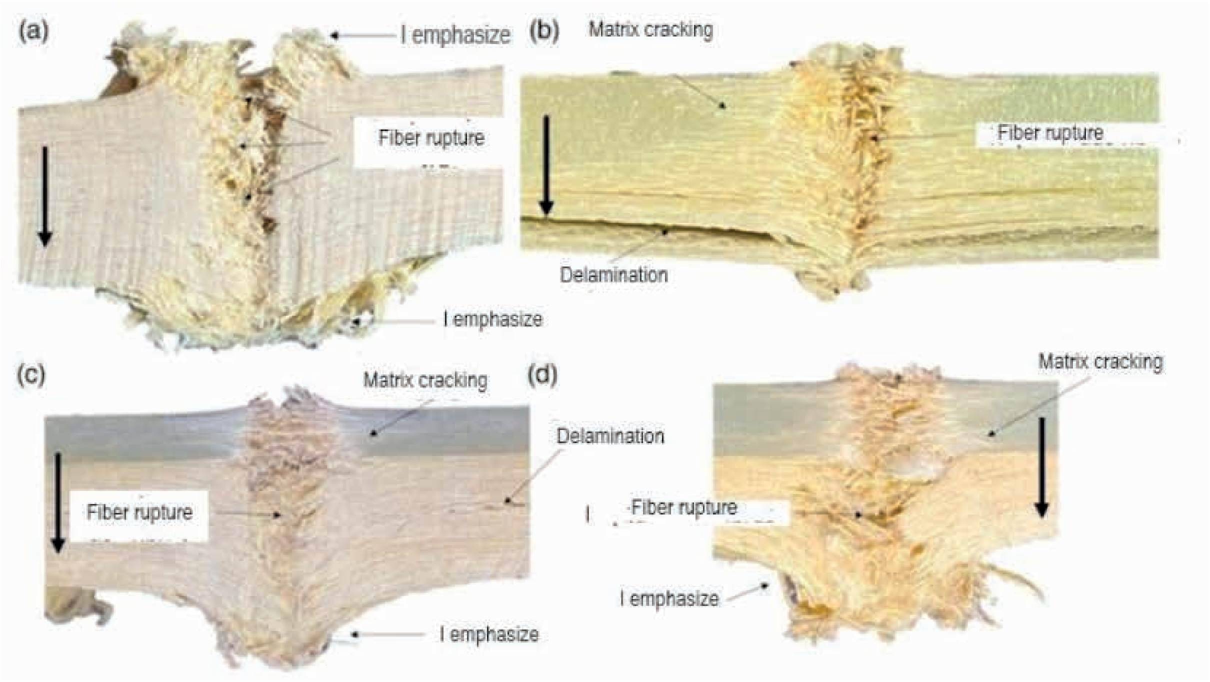

Figure 2 – Deformation mechanisms of composites (a) A, (b) E, (c) H1, (d) H2. Adapted from (ÜSTÜN; TOKSOY; TANOĞLU, 2022)

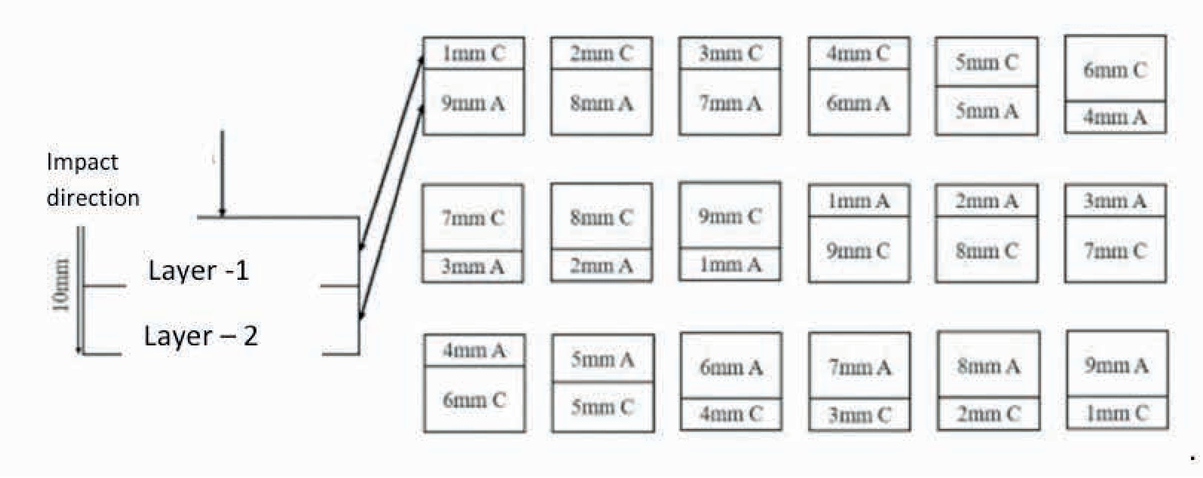

Figure 3 – Aramid/carbon hybrid composite stacking sequences. Adapted from (XU et al., 2023)

front, the aramid layers had sufficient time to delaminate and bulge. This resulted in greater energy absorption and improved ballistic performance for the hybrid structures. Therefore, it was found that the fiberglass fabric layers, combined with the aramid fabric layers, increased the energy absorption capacity of the hybrid composites, resulting in an improvement in ballistic performance.

Carbon and aramid fibers are widely used in industry as high-performance textile materials and, because of this, Xu et al. (2023) proposed a finite element method to investigate the effect of layer thickness and stacking sequence on the ballistic behavior of the composite. The epoxy matrix specimens were produced containing two layers of carbon fiber (C) and aramid (A), whose individual layers had variable thicknesses, but with a total thickness of 10mm, as illustrated in Figure 3, totaling 18 different configurations.

Therefore, based on the simulation of the impact caused by a 7.62mm caliber projectile, it was confirmed that the sample in which the impact occurs on the face of the aramid layer demonstrates superior performance in terms of resistance to ballistic impact compared to the sample where the impact hits the face of the carbon fiber. Furthermore, the hybrid composite with a thickness of 9 mm of aramid and 1 mm of carbon fiber presents the highest ballistic impact resistance with the lowest weight.

The ballistic behavior of hybrid laminated composite reinforced with carbon fiber fabric, Kevlar and UHMWPE was investigated by Li et al. (2023) through tests and compared to estimates obtained by the developed finite element model. The composite was manufactured by stacking five layers of carbon fiber on the impact surface, followed by twelve layers of Kevlar fabric and six layers of UHMWPE fabric on the back, called C5 K12 PE6. For comparison purposes, an epoxy matrix composite, reinforced only with Kevlar fabric and with a thickness similar to the hybrid composite, was prepared, resulting in a total of twenty-seven layers, called K27. Therefore, it was found that the energy absorption capacity of the hybrid composite can be improved by 16.4% compared to the epoxy matrix composite reinforced with Kevlar fabric alone. This result is associated with the fact that hybrid composites present greater transverse deformation and longer interaction time between the projectile and the intermediate (Kevlar) and posterior (UHMWPE) layers. Furthermore, in the first five layers, both composites (C5 K12 PE6 and K27) exhibit similar energy absorption capacity. This is because the front layers do not have enough time to respond to the impact load before failing, regardless of the type of material.

Therefore, the front layers are subjected to high shear stresses during the initial phase of the penetration process. As the impact speed decreases, stretching of the fabric fibers and delamination of the composite are observed. The projectile speed reduces considerably, culminating in the final perforation of the composite. The intensity of delamination becomes more pronounced at the interfaces between carbon fiber and Kevlar fabrics and between Kevlar and UHMWPE fabrics, due to the incompatibility between the different fabric layers. Delamination results in a large transverse deformation in the Kevlar and UHMWPE layers, which leads to greater strength thanks to the increased interaction time between the projectile and the hybrid composite. Therefore, more impact energy can be absorbed and, consequently, greater resistance to penetration than that observed in the K27 composite.

The mechanical tensile and flexural properties of hybrid composites reinforced exclusively with natural fibers such as jute/sisal and jute/curauá were studied by Cavalcanti et al. (2019) and compared with the properties of the pure jute fiber-based composite. The composites were manufactured with a reinforcement volumetric fraction of 30% fibers and 70% epoxy resin. The proportion of natural fibers used in the hybrid composites was 60% jute and 40% other fibers (sisal or curauá). The results obtained demonstrated that the hybridization process improved the tensile properties of all types of hybrid composites. The tensile strength of untreated jute/curauá and jute/sisal composites increased by approximately 77% and 68%, respectively, compared to pure untreated jute composites. Furthermore, the flexural strength of hybrid composites increased with the incorporation of fibers, however, the tests showed that the alkaline treatment had a positive effect on the flexural properties of the jute/sisal composite, when compared to the untreated condition, while the mixed alkalization and silanization treatment had a positive impact on the jute/curauá composite. Therefore, just like the hybridization of natural fibers in the epoxy matrix, the treatments applied to the fibers also had different effects on the mechanical properties of the hybrid composites.

Hanan, Jawaid, and Tahir (2020) conducted a series of experiments with the aim of investigating the effect of hybridization of kenaf fiber and palm fiber on the mechanical properties of epoxy matrix composites. The hybrid composites were manufactured maintaining different weight proportions of palm and kenaf fibers as 4:1, 1:1 and 1:4, respectively, totaling 50% by weight of reinforcement phase. The results demonstrated a significant improvement in tensile and flexural properties as kenaf fiber content increased. This was because kenaf fibers have the ability to withstand a higher load during force transfer, resulting in an improvement in the mechanical properties of the epoxy matrix hybrid composite.

Atmakuri et al. (2021) investigated the influence of hybridization of sisal (S) and caryota (C) fibers on the tensile and flexural properties of the polymer matrix composite compared to composites reinforced with only the individual fibers. The hybrid composites were developed with a 40% volumetric fraction of reinforcement (fibers), with a total of five different samples, each with fiber proportions varying between 40% (for composites reinforced with only one type of fiber) and 15%., 20%, 25% (40C/0S, 25C/15S, 20C/20S, 15C/25S, 0C/40S). Figure 4 shows the results of the tensile test of the five composites and it can be seen that the hybrids presented higher tensile strength than the 40C/0S and 0C/40S composites. Notably, the 15C/25S composite achieved the most significant performance at 38.2 MPa. This behavior can be attributed to the better properties of sisal fiber compared to caryote fiber, in addition to the fact that the increase in the content of individual sisal fibers results in the agglomeration of these fibers and, consequently, in the loss of strength.

With regard to flexural properties, a similar trend was observed to those observed in tensile properties. Consequently, the hybrid composites demonstrated better performance, with the 15C/25S configuration achieving the highest flexural strength, at 89.16 MPa, while the composite reinforced only with caryote fiber showed the lowest strength, reaching 64.09 MPa, as illustrated. in the graph in Figure 5.

INFLUENCE OF STACKING SEQUENCE

The mechanical properties of hybrid composites depend on several factors, such as the characteristics of the fibers that constitute them, the type of material used as matrix, the architecture of the fabric weave, the orientation of the fibers and the layer stacking sequence.

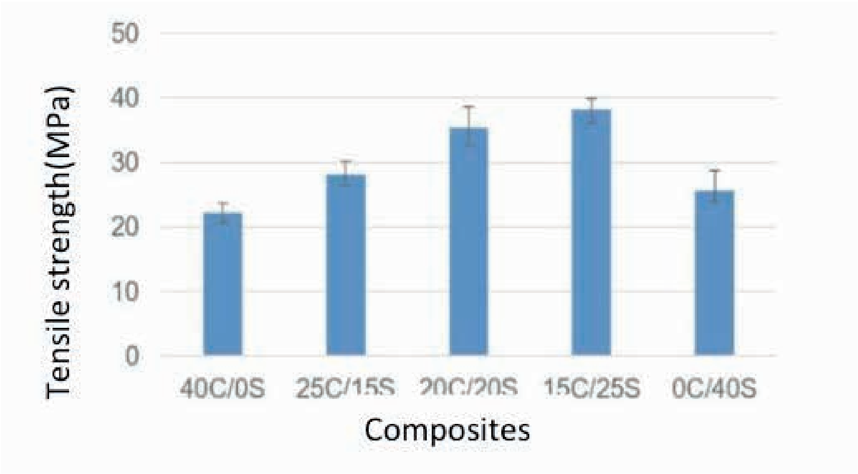

Figure 4 – Tensile strength of the five different composites. Adapted from (ATMAKURI et al., 2021)

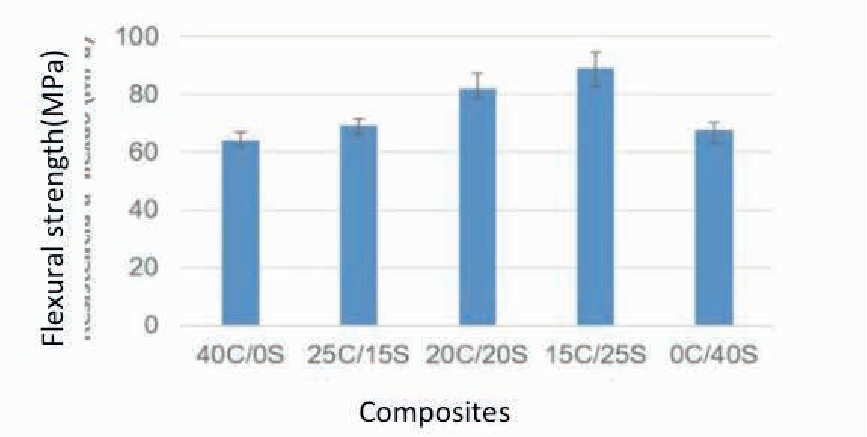

Figure 5 – Flexural strength of the five different composites. Adapted from (ATMAKURI et al., 2021)

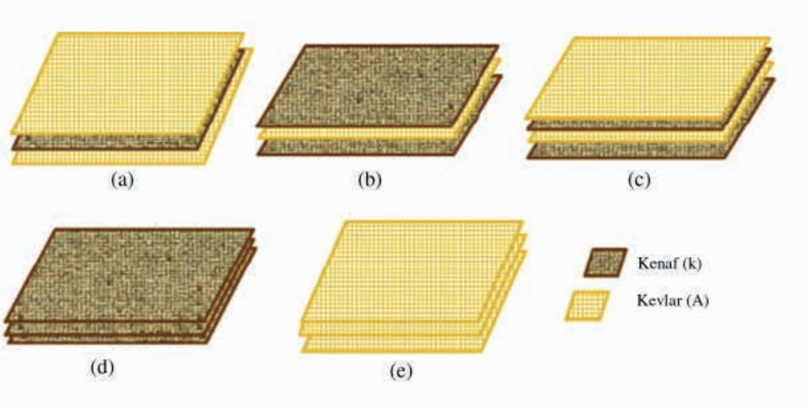

Figure 6 – Illustration of the configuration of the composites (a) A/k/A (b) k/A/k (c) A/k/A/k (d) k/E and (e) Kevlar/epoxy. (YAHAYA et al., 2015)

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This way, a lot of research is being developed with the aim of analyzing and understanding the influence of different ways of stacking layers of different fibers (DEWANGAN; PANIGRAHI, 2021).

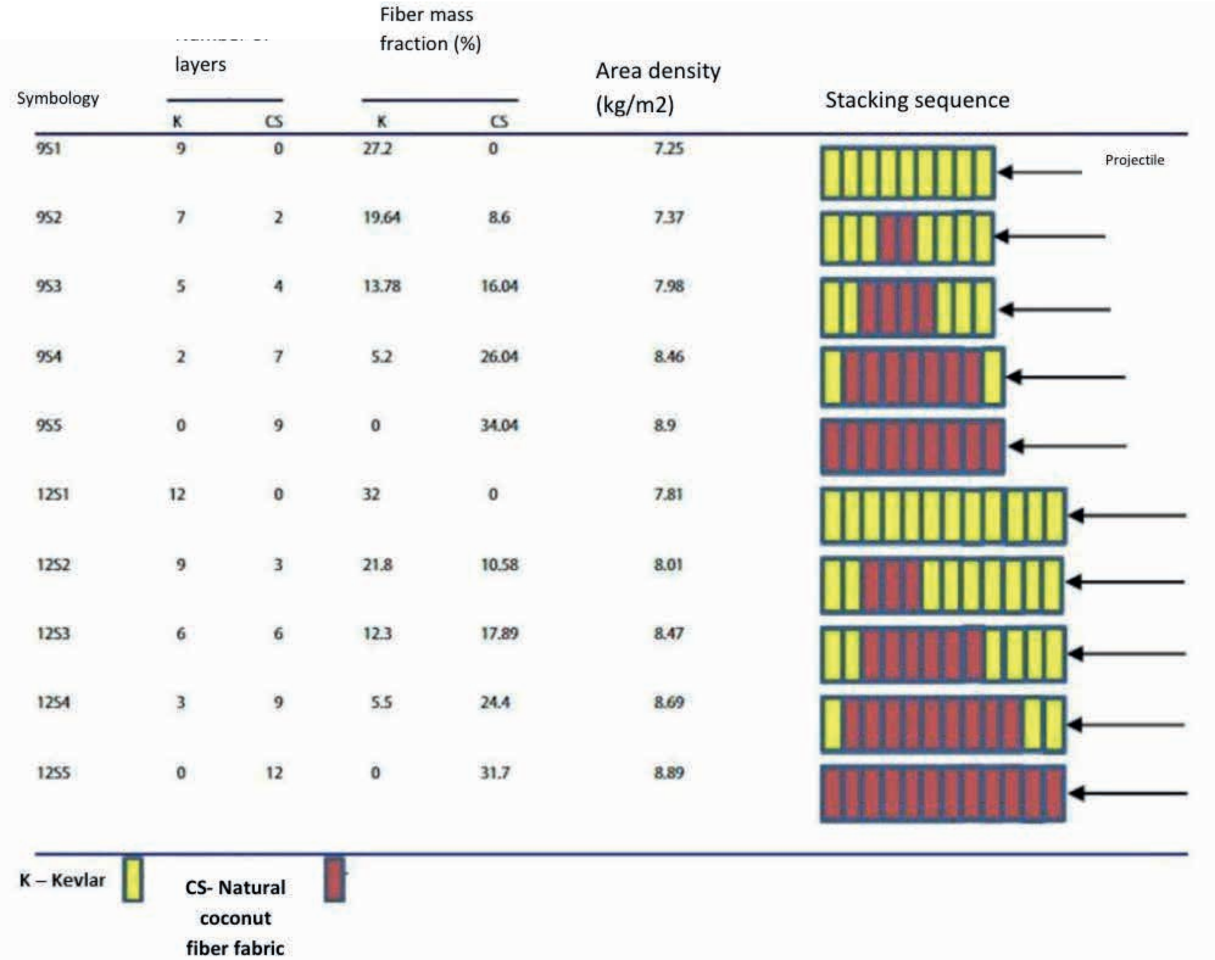
Yahaya et al. (2015), in their work, sought to verify the effect of the stacking sequence of layers of kenaf (k) and Kevlar (A) fabric in epoxy matrix composites on the mechanical properties of traction, flexion and impact. Three different configurations of hybrid composites were produced, two of them consisting of three layers of fabric and the other consisting of four layers. Pure samples of kenaf/epoxy and Kevlar/epoxy were also manufactured for comparison with the hybrid composites. Figure 6 illustrates the five different samples that were subjected to the tests.

The tensile test results indicated that the A/k/A composite (Kevlar/kenaf/Kevlar) exhibits a slightly higher tensile strength (8%) compared to the k/A/k composite (kenaf/Kevlar/kenaf). Furthermore, the final deformation of the A/k/A composite is higher than that of the k/A/k and A/k/A/k composites, which indicates that the arrangement of high-strength aramid fabric in the outer layer and layers of kenaf fabric of Lower resistance internally improves the tensile properties of the composite. The three-layer hybrid sample had an average tensile strength of 99.4 MPa, while the average tensile strength of the 4-layer hybrid laminates was 123 MPa. Therefore, the increase in tensile strength of the four-layer hybrid composite is attributed to the addition of one more layer of Kevlar. Regarding the flexural results, it was observed that the kenaf/epoxy composites presented the lowest flexural resistance among the tested samples, the Kevlar/epoxy composites presented the highest results and, as expected, the hybrid composites exhibited intermediate properties. The different stacking sequences influenced the results, as the four-layer hybrid composite, whose kenaf layer (A/k/A/k*) received the loading, showed slightly better flexural properties compared to Kevlar (A/ k/A/k) as the layer subjected to load. The Charpy impact test showed that hybrid composites, whose impact layer was composed of kenaf fabric, obtained the best results.

The study carried out by Ali et al. (2019) involved testing to determine the ballistic limit of fiberglass-bamboo hybrid composites. Samples with a total of 22 layers were used, with two different stacking sequences. One of them consisted of 9 layers of fiberglass fabric, followed by 4 layers of bamboo fiber fabric, and finally another 9 layers of fiberglass fabric (configuration 9:4:9 WEG: WB:WEG). The other configuration consisted of 18 layers of bamboo fiber fabric and a further 4 layers of fiberglass fabric (18:4 WB: WEG configuration). The 18:4 WB: WEG composite was capable of supporting the projectile at a velocity of up to 482 m/s (ballistic limit), exceeding the minimum velocity required to meet National Institute of Justice (NIJ) Level IIIA standards. While the 9:4:9 WEG: WB:WEG composite achieved level II according to the international NIJ standard.

Naveen et al. (2019) conducted a study in which they developed hybrid composites by combining epoxy resin reinforced with Kevlar fibers and coconut fibers (CSs). The laminated composites were manufactured with 9 and 12 layers of Kevlar® and CSs following five different stacking sequences (S1-S5), as illustrated in Figure 7.

To evaluate the ballistic performance of the composites, a compressed air pistol and 8mm caliber ammunition were used, capable of reaching the target at a speed of around 300 to 320 m/s. The results of the residual velocity tests revealed that the 9S1 laminate presented the lowest energy absorption,



Symbology	layers K	layers CS	Fiber mass fraction (%) K	Fiber mass fraction (%) CS	Area density (kg/m2)	Stacking sequence
9S1	9	0	27.2	0	7.25	
9S2	7	2	19.64	8.6	7.37	
9S3	5	4	13.78	16.04	7.98	
9S4	2	7	5.2	26.04	8.46	
9S5	0	9	0	34.04	8.9	
12S1	12	0	32	0	7.81	
12S2	9	3	21.8	10.58	8.01	
12S3	6	6	12.3	17.89	8.47	
12S4	3	9	5.5	24.4	8.69	
12S5	0	12	0	31.7	8.89	

Figure 7 – Symbol of laminates and their corresponding weight fraction and stacking sequence. Adapted from (NAVEEN et al., 2019)

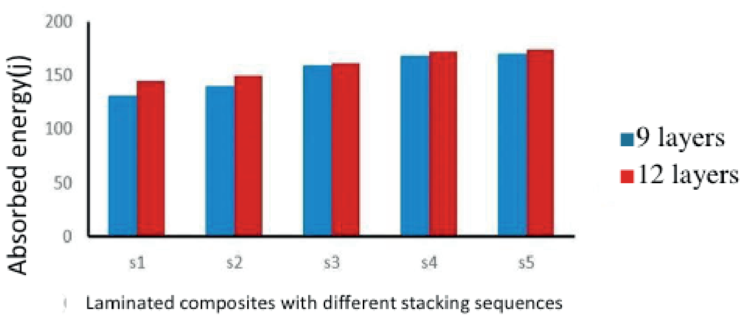


Figure 8 - Energy absorption of laminated composites. Adapted from (NAVEEN et al., 2019)

despite all of its nine layers being composed of Kevlar® fabric. 9S2 hybrid laminates exhibited 6.9% higher energy absorption than 9S1 composite laminates due to replacing 2 layers of Kevlar® with CS. Likewise, 9S3 and 9S4 hybrid laminates have 21.7% and 28% greater energy absorption than pure Kevlar®/epox composites (9S1). Epoxy matrix composites reinforced only with natural coconut fabric (9S5) exhibited the highest energy absorption among 9-layer laminated composites, with a 30% increase over epoxy composites reinforced only with Kevlar® fabric (9S1). Such behavior was similarly observed in 12-layer composites, where the 12S1 composite had the lowest energy absorption. The 12S2, 12S3, 12S4 and 12S5 hybrid composites showed energy absorption 3.2%, 11.2%, 18.6% and 20% greater than the 12S1 laminates, respectively. Figure 8 illustrates this relationship, through the graph, for each type of composite.

Furthermore, it is clear that by increasing the number of layers, laminated composites have the ability to absorb more energy. This is evidenced by the fact that the energy absorption of the 12S1 laminate, consisting of 12 layers exclusively of Kevlar®, is 11.3% higher than that of the 9S1 laminated composites, which contain only 9 layers of Kevlar®. Likewise, the 12S5 laminated composites, with 12 layers of coconut fiber fabric, showed 2.53% greater energy absorption than the 9S5 laminates.

In the study developed by Alkhatib, Mahdi and Dean (2021), hybrid composite plates intended for ballistic protection were investigated by analyzing the indentation depth generated by the impact of a projectile. The composites were manufactured from two types of synthetic fiber fabric: carbon and aramid (Kevlar). To analyze the effect of hybridization and stacking sequences, two different configurations were analyzed with composite reinforced only by Kevlar fabric (KFRP40), all consisting of 40 layers of fabric in total. Thus, one of the hybrid composites was formed by four layers of carbon fiber, followed by six more layers of Kevlar fabric, repeating this sequence four times, totaling 40 layers ([CFRP4/KFRP6]4). The second configuration of the hybrid composite consisted of ten layers of carbon fiber, followed by another thirty layers of Kevlar fabric ([CFRP10/KFRP30]). Ballistic test results revealed that the [CFRP4/KFRP6]4 hybrid composite was not able to prevent complete penetration of the projectile, indicating that the introduction of carbon fiber layers between the Kevlar layers reduced the ballistic properties of the composite. However, the hybrid composite with thirty layers of Kevlar ([CFRP10/KFRP30]) managed to fully absorb the projectile's energy and the indentation value was below the limit established by the NIJ international standard (44mm). Thus, the researchers concluded that the material stacking sequence has a significant impact on the energy dissipation mechanism of hybrid composite plates and, consequently, on their energy absorption capacity.

Ghani et al. (2022) investigated the effect of six different fabric layer stacking sequences, using jute (J) and glass (G) fibers, on the mechanical properties of hybrid composites based on poly(butylene succinate), a biodegradable polyester known as PBS. Figure 9 illustrates the arrangement of the layers of the six hybrid composites and the two composites manufactured from pure glass fiber and pure jute. The composites were all produced with five layers of fabric in total.

To evaluate some of the mechanical properties of these composites, tensile, flexural and impact tests were carried out. In Figure 10, the results regarding the tensile strength and elastic modulus for the composites of pure jute (PJ), pure glass fiber (PG) and the six hybrid composites are presented, each with a distinct stacking sequence.

It can be seen that as the number of glass fiber layers increases, the tensile properties of the composites improve further, indicating a direct correlation between the tensile strength and the number of glass fiber layers in the composites.

Therefore, when comparing hybrid composites with the same number of layers of jute and glass fiber, but different stacking sequences, it was observed that the composite with three layers of jute and two layers of glass GJJJG presented a 12% increase in resistance to traction and 20% in the elastic modulus in relation to the JGJGJ hybrid composite. Similarly, the GJGJG composite, with two jute and three glass fiber layers, exhibits 28% and 20% higher tensile strength and modulus of elasticity, respectively, compared to the JGGGJ hybrid composite. Furthermore, it is noted that both the tensile strength and the modulus of elasticity are higher in composites in which glass fibers are used as external layers.

The three-point bending test performed by Ghani et al. (2022) showed a similar trend to the tensile test, as evidenced in Figure 11, which presents the results of flexural strength and modulus. The addition of a glass fiber layer to the pure jute composite resulted in improvements of 10.62% in flexural strength and 22.96% in modulus. When comparing hybrid composites with the same number of layers of each fiber type, it was observed that the GJJJG composite exhibited 16% and 32% higher flexural strength and modulus, respectively, compared to the JGJGJ composite. The GJGJG composite presented flexural strength and modulus 17% and 24% higher, respectively, in relation to the JGGGJ composite. This improvement is associated with the use of high-strength and performance fibers, such as fiberglass, in the outer layers of the composite, improving its mechanical properties. This is because the high strength and modulus of the fiberglass fabric in the upper and lower layers supports the applied load, while the interior (jute fibers) absorbs and evenly distributes the loads.

Finally, the Izod impact test showed that the percentage increase in impact resistance of the GJJJG and GJGJG composites was 15% and 14% greater than JGJGJ and JGGGJ, respectively. Proving that the fiberglass layers must be positioned on the surface of the composite to ensure the best results, an effect even more significant than the increase in the number of fiberglass layers, as verified by the comparison of the JGGGJ and GJJJG specimens.

CONCLUSION

As highlighted in the literature, the appropriate selection of the fiber layer stacking sequence in the manufacture of hybrid composites is extremely important. The mechanical and ballistic properties of these materials are strongly influenced by the arrangement of the fibers, showing that different structural arrangements result in different performances. Research on hybrid composites with different fibers, such as Kevlar, kenaf, coconut fiber, glass fiber and jute, among others, highlights the complexity of this area, where factors such as tensile strength, flexion and energy absorption are affected by the architecture of the weave, fiber orientation and stacking sequence.

Therefore, the work suggests that specific strategies, such as positioning high-strength fibers, such as synthetic ones, on external surfaces, can optimize the mechanical properties of composites. Furthermore, the analysis of different configurations revealed that variation in the number and order of layers significantly influences the mechanical, ballistic performance and energy absorption of these materials. This way, these studies provide valuable information for the design and manufacture of hybrid composites with

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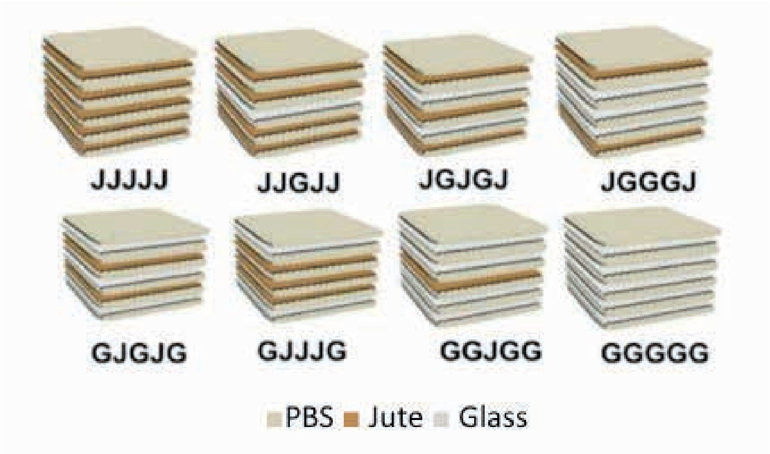

Figure 9 - Jute/glass fiber stacking sequence. Adapted from (GHANI et al., 2022)

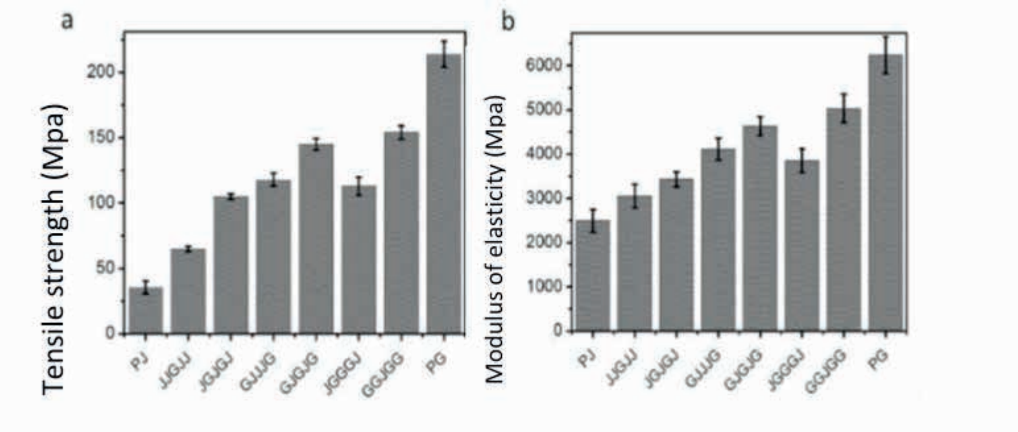

Figure 10 – Tensile strength (a) and Modulus of elasticity (b) of hybrid composites reinforced with jute and glass fiber. Adapted from (GHANI et al., 2022)

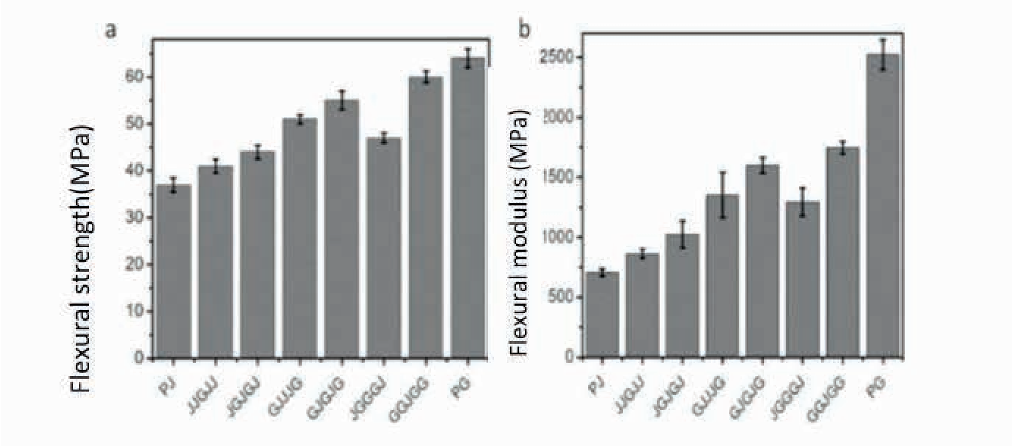

Figure 11 – Flexural strength (a) and flexural modulus (b) of hybrid composites reinforced with jute and glass fiber. Adapted from (GHANI et al., 2022)

improved mechanical properties for various applications.

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REFERENCES

ALI, A.; ADAWIYAH, R.; RASSIAH, K.; NG, W. K.; ARIFIN, F.; OTHMAN, F.; HAZIN, M. S.; FAIDZI, M.; ABDULLAH, M.; AHMAD, M. M. **Ballistic impact properties of woven bamboo- woven e-glass- unsaturated polyester hybrid composites**. Defence Technology, v. 15, p. 282–294, 2019.

ALKHATIB, F.; MAHDI, E.; DEAN, A. **Design and evaluation of hybrid composite plates for ballistic protection: Experimental and numerical investigations**. Polymers, v. 13, 2021.

ATMAKURI, A.; PALEVICIUS, A.; KOLLI, L.; VILKAUSKAS, A.; JANUSAS, G. **Development and analysis of mechanical properties of caryota and sisal natural fibers reinforced epoxy hybrid composites**. Polymers, v. 13, 2021.

BLEDZKI, A. K.; GASSAN, J. **Composites reinforced with cellulose based fibres**. Progress in Polymer Science, v. 24, p. 221–274, 1999.

CALLISTER, W. D.; RETHWISCH, D. G. **Ciência e engenharia de materiais: uma introdução**. 9. ed. Rio de Janeiro: LTC, 2016.

CANEVAROLO JR, S. V. **Ciência dos polímeros: um texto básico para tecnólogos e engenheiros**. 2. ed. São Paulo: Artliber, 2002.

CAVALCANTI, D.; BANEA, M.; NETO, J.; LIMA, R.; SILVA, L. da; CARBAS, R. **Mechanical characterization of intralaminar natural fibre-reinforced hybrid composites**. Composites Part B: Engineering, v. 175, 2019.

DEWANGAN, M. K.; PANIGRAHI, S. K. **Factors influencing the ballistic impact mechanisms of textile composite materials: a review**. Polymers for advanced technologies, v. 32, p. 1901–1923, 2021.

ELFALEH, I.; ABBASSI, F.; HABIBI, M.; AHMAD, F.; GUEDRI, M.; NASRI, M.; GARNIER, C. **A comprehensive review of natural fibers and their composites: An eco-friendly alternative to conventional materials**. Results in Engineering, v. 19, 2023.

GHANI, M. U.; SIDDIQUE, A.; ABRAHA, K. G.; YAO, L.; LI, W.; KHAN, M. Q.; KIM, I.-S. **Performance evaluation of jute/glass-fiber-reinforced polybutylene succinate (pbs) hybrid composites with different layering configurations**. Materials, v. 15, 2022.

GHOLAMPOUR, A.; OZBAKKALOGLU, T. **A review of natural fiber composites: properties, modification and processing techniques, characterization, applications**. Journal of Materials Science, v. 55, 2020

HANAN, F.; JAWAID, M.; TAHIR, P. M. **Mechanical performance of oil palm/kenaf fiber-reinforced epoxy-based bilayer hybrid composites**. Journal of Natural Fibers, v. 17, 2020.

JOHN, M. J.; THOMAS, S. **Biofibres and biocomposites**. Carbohydrate Polymers, v. 71, p. 343–364, 2008.

KUMAR, S.; DAS, E. K.; AHUJA, P.; BABU, R. G. **Ballistic efficiency of corchorus fiber and aramid reinforced epoxy composite for armor material application**. Materials Today: Proceedings, v. 57, p. 65–71, 2022.

KUMAR, S. D.; SAMVEL, R.; ARAVINDH, M.; VIBIN, R.; POOVARASU, E.; PRASAD, M. S. **Ballistic studies on synthetic fibre reinforced polymer composites and it's applications – a brief review**. Materials Today: Proceedings, 2023.

KUMAR, T. S. M.; JOLADARASHI, S.; KULKARNI, S. M.; DODDAMANI, S. **Optimization of process parameters for ballistic impact response of hybrid sandwich composites**. International Journal on Interactive Design and Manufacturing (IJIDeM), v. 17, p. 1099–1111, 2022.

LI, Z.; XUE, Y.; SUN, B.; GU, B. **Ballistic penetration damage for hybrid carbon/kevlar/uhmwpe fiber laminated composites: Experimental and numerical techniques**. Composite Structures, v. 316, 2023.

MANO, E. B.; MENDES, L. S. **Introdução a polímeros**. 2. ed. São Paulo: Editora Edgard Blucher, 2004. 207 p.

MELIANDE, N. M.; OLIVEIRA, M. S.; PEREIRA, A. C.; BALBINO, F. D. P.; FIGUEIREDO, A. B.-H. da S.; MONTEIRO, S. N.; NASCIMENTO, L. F. C. **Ballistic properties of curaua-aramid laminated hybrid composites for military helmet**. Journal of Materials Research and Technology, v. 25, p. 3943–3956, 2023.

MELIANDE, N. M.; OLIVEIRA, M. S.; SILVEIRA, P. H. P. M. da; DIAS, R. R.; MARÇAL, R. L. S. B.; MONTEIRO, S. N.; NASCIMENTO, L. F. C. **Curaua–aramida hybrid laminated composites for impact applications: Flexural, charpy impact and elastic properties**. Polymers, v. 14, 2022a.

MELIANDE, N. M. **Caracterização de Compósitos Híbridos de Epóxi com Tecido de Aramida e Manta de Curauá para Capacete Balístico**. Mestrado em Ciência dos Materiais — Instituto Militar de Engenharia, Rio de Janeiro, 2022b.

MOHAMMED, L.; ANSARI, M. N. M.; PUA, G.; JAWAID, M.; ISLAM, M. S. A. **A review on natural fiber reinforced polymer composite and its applications**. Journal of Polymer Science, 2015.

MOHANTY, A. K.; MISRA, M.; HINRICHSEN, G. **Biofibres, biodegradable polymers and bio-composites: An overview**. Macromolecular Materials and Engineering, v. 276/277, 2000.

MONTEIRO, S. N.; LOPES, F. P. D.; BARBOSA, A. P.; BEVITORI, A. B.; SILVA, I. L. A. D.; COSTA, L. L. D. **Natural lignocelullosic fibers as engineering materials – an overview**. Metallurgical and Materials Transactions A, v. 42, p. 2963–2974, 2011.

MONTEIRO, S. N.; LOURO, L. H. L.; TRINDADE, W.; ELIAS, C. N.; FERREIRA, C. L.; LIMA, E. de S.; WEBER, R. P.; SUÁREZ, J. C. M.; FIGUEIREDO, A. B.-H. da S.; PINHEIRO, W. A.; SILVA, L. C. da; JR Édio P. L. **Natural curaua fiber-reinforced composites in multilayered ballistic armor**. Metallurgical and Materials Transactions A volume, v. 46, 2015.

NASCIMENTO, L. F. C.; LOURO, L. H. L.; MONTEIRO, S. N.; GOMES, A. V.; MARçAL, R. L. S. B.; JúNIOR Édio P. L.; MARGEM, J. I. **Ballistic performance of mallow and jute natural fabrics reinforced epoxy composites in multilayered armor**. Materials Research, v. 20, 2017

NAVEEN, J.; JAWAID, M.; ZAINUDIN, E. S.; SULTAN, M. T. H.; YAHAYA, R. **Evaluation of ballistic performance of hybrid kevlar®/cocos nucifera sheath reinforced epoxy composites**. The Journal of The Textile Institute, v. 110, p. 1179–1189, 2019.

NAYAK, S. Y.; SULTAN, M. T. H.; SHENOY, S. B.; KINI, C. R.; SAMANT, R.; SHAH, A. U. M.; AMUTHAKKANNAN, P. **Potential of natural fibers in composites for ballistic applications – a review**. Journal of Natural Fibers, v. 19, p. 1648–1658, 2022.

PATHAK, R. K.; PATEL, S.; GUPTA, V. K.; BANDARU, A. K. **A computational analysis of the high-velocity impact performance of lightweight 3d hybrid composite armors**. Applied Composite Materials, v. 30, p. 727–751, 2023.

RAJAK, D. K.; WAGH, P. H.; LINUL, E. **A review on synthetic fibers for polymer matrix composites:performance, failure modes and applications**. Materials, v. 15, 2022.

SABRE, D.; ABDELNABY, A. H. **Recent developments in natural fiber as reinforcement in polymeric composites: A review.** Asian Journal of Applied Science and Technology (AJAST), v. 6, 2022.

SAFRI, S. N. A.; SULTAN, M. T. H.; JAWAID, M.; JAYAKRISHNA, K. **Impact behaviour of hybrid composites for structural applications: A review**. Composites Part B: Engineering, v. 133, p. 112–121, 2018.

SALMAN, S. D.; LEMAN, Z. B. **Physical, mechanical and ballistic properties of kenaf fiber reinforced poly vinyl butyral and its hybrid composites**. Natural Fibre Reinforced Vinyl Ester and Vinyl Polymer Composites. Development, Characterization and Applications, p. 249–263, 2018.

ÜSTüN, H. S.; TOKSOY, A. K.; TANOğLU, M. **Investigation of hybridization effect on ballistic performance of multi-layered fiber reinforced composite structures**. Journal of Composite Materials, v. 56, 2022.

XU, J.; TANG, L.; LIU, Y.; ZHOU, L.; CHEN, J.; JIANG, Z.; LIU, Z.; YANG, B. **Hybridization effects on ballistic impact behavior of carbon/ aramid fiber reinforced hybrid composite**. International Journal of Impact Engineering, v. 181, 2023.

YAHAYA, R.; SAPUAN, S.; JAWAID, M.; LEMAN, Z.; ZAINUDIN, E. **Effect of layering sequence and chemical treatment on the mechanical properties of woven kenaf–aramida hybrid laminated composites**. Materials & Design, v. 67, p. 173–179, 2015.