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Review on Effect of Varying Natural Fiber Reinforcement on the Mechanical Properties of Epoxy Composites

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ABSTRACT: The increasing need of sustainable and environmental benign engineering materials has enhanced the exploration of natural fiber reinforced polymer composites as a possible alternative engineering materials to synthetic fibers composites. Epoxy resins are commonly used as a polymer base because they have high mechanical strength, dimensional stability and chemical resistance. This is a critical review of how the different natural fiber enhancement affect the mechanical properties of the epoxy composites with special attention to tensile, flexural, impact, and hardness properties. The effects of major parameters of reinforcement such as type of fibers, content of fibers (weight and volume fraction), length of fibers, orientation and surface treatment are analyzed systematically on the basis of the published experimental research. The review notes that in most cases, mechanical performance tends to increase with a rise in fiber content to a level where it starts to decline after an optimum point because of poor dispersion of the fibers, increase in content of the voids, and poor bonding between the fibers and the matrix. It also addresses the role of the chemical treatments to increase the interfacial adhesion and stress transfer efficiency. Also, how processing conditions and fabrication methods affect the quality of composite and failure behavior are discussed. The comparative experiences of natural fiber and synthetic fiber epoxy composites are provided as a setting to understand the performance trade-offs and sustainability gains. The review defines some of the main issues like sensitivity to moisture, fiber property variability, and long-term durability, and the direction of future research along with hybridization, enhanced surface modification, and predictive modeling. In general, the paper highlights the high promise of optimized natural fiber reinforced epoxy composite with regard to structural and semi-structural application.

KEYWORDS: Natural fiber reinforced composites; Epoxy matrix composites; Fiber reinforcement content; Mechanical properties; Tensile behavior; Flexural behavior; Impact strength; Fiber–matrix interface; Sustainable composite materials

I. INTRODUCTION

The high rate of industrialization and technological improvement has resulted in the wide utilization of composite materials of polymer type in a wide range of engineering uses such as in the aerospace, automotive, marine, construction and consumer products industries. Compared to traditional metallic materials, polymer matrix composites (PMCs) are mostly preferred because they have high capacities of strength per weight, they are not corrosive and can be easily designed and created. Historically, glass, carbon and aramid, are examples of synthetic fibers that have been widely used as reinforcements in polymer composites to attain better mechanical performance. Nevertheless, growing environmental issues, the exhaustion of non-renewable resources, and strict sustainability standards have led the scientists and the industry to investigate the solutions with environmentally friendly properties to synthetic fiber strengthening (Faruk et al., 2012; Pickering et al., 2016). Under this, the natural fiber reinforced polymer composites have become a potential group of sustainable material. Jute, sisal, flax, hemp, coir, banana and kenaf are examples of natural fibers which are renewable, biodegradable, economical, and easily accessible especially in the developing economies. The benefits of these fibers are

low density, reasonable specific mechanical properties, decreasing the tool wear when processing, and a smaller environmental impact throughout their life cycle (Satyanarayana et al., 2009; Mohammed et al., 2015).

II. NATURAL FIBERS USED IN EPOXY COMPOSITES

The natural fiber is the main reinforcing step in bio-based polymer composite and dictates the factors of mechanical performance, durability, and sustainability. The nature, chemical make-up, micro-structure, and inherent mechanical characteristics of epoxy based composites are very strong determiners of their behavior. This paragraph addresses the classification of natural fibers, types of fiber that are commonly used in epoxy composites and their underlying physical and mechanical properties with a special focus on the applicability of these properties with respect to the efficiency of reinforcement. There are broad classifications of natural fibers according to their source as plant fibers, animal fibers, and mineral fibers. Out of these groups, plant fibers have been the most widely used in epoxy composites because they are renewable, biodegradable, inexpensive, and possess moderately good specific mechanical characteristics. Plant fibers can also be distinguished by what part of the plant they are extracted, i.e. bast fibers (jute, flax, and hemp), leaf fibers (sisal and pineapple), seed fibers (cotton), and fruit fibers (coir). All types of plant fiber have unique physical and mechanical properties due to variations in cellulose proportion, microfibril angle and internal structure. Bast fibers tend to be more tensile and more rigid because they are higher in cellulose, and leaf and fruit fibers tend to be tougher and more impact resistant. These differences also play a major role in the choice of fibers in any particular epoxy composite application and dictate the degree to which mechanical properties will enhance with The strengthening property of natural fibers has been directly related to chemical structure and microstructure composition. The cellulose, hemicellulose, lignin, pectin, and traces of waxes and ash are the main components of plant fibers. Cellulose is the primary load bearing component, tensile strength, and stiffness are mostly due to cellulose. Hemicellulose and lignin are slow moving, however, they are also moister hydrophilic and give structure and rigidity. Natural fibers have a hierarchical organization, whereby cellulose microfibrils are incorporated within a hemicellulose amorphous matrix of lignin. Different fibers have varying levels of cellulose and the angle of the microfibrils which cause great differences in mechanical performance. The ones containing a greater amount of cellulose and a lower angle of microfibrils tend to have better tensile characteristics and thus are better tensile reinforcements in epoxy matrices. Numerous varieties of natural fibers have been explored as being used as reinforcement in epoxy composites, with the most commonly reported ones being jute, sisal, flax, hemp, banana, and coir. One of the most common bast fibers is the jute fiber because it has a high availability, cheap, and reasonably good mechanical properties. Strength reinforcements by use of epoxy composites with jute have shown significant improvements in tensile and flexural strength as the content of fibers increases to a certain ideal level after which the strengths start to deteriorate as a result of poor fiber dispersion and low interfacial bonding. The Agave plant makes sisal fiber that is extracted using the leaves of the plant and is very tough and has a good abrasion resistance. Sisal-epoxy composite has demonstrated significant increase in impact strength and flexural behavior, especially where correct fiber surface treatment is utilized to increase interfacial adhesion.

III. EPOXY–NATURAL FIBER INTERFACIAL CHARACTERISTICS

The effectiveness of natural fiber reinforced epoxy composite materials can be basically controlled by the quality of the fiber-matrix interface that determines the effectiveness of stress transfer between the epoxy matrix and the reinforcing fibers. In contrast to synthetic fibers, natural fibers have hydrophilic surfaces that have high concentrations of hydroxyl groups, but epoxy resins are relatively hydrophobic. The incompatibility of this nature usually leads to a lack of interfacial adhesion, limiting the reinforcing properties of natural fibers, especially when using larger fiber loadings. As a result, interfacial processes and modification protocols should be comprehended to decipher the impact of different reinforcement in natural fibers to mechanical traits. The mechanical interlocking, physical attraction, and chemical interactions join epoxy-natural fiber composites to give results on interfacial bonding. Mechanical interlocking takes place when the epoxy resin seeps into the surface disruptions and the fibers empty spaces in the fabrication binding the matrix to the fiber. The forces between polar groups on the fiber surface and functional groups in epoxy network are van der Waals forces and hydrogen bonding based on the physical interaction between the functional groups and the hydrogen bonding between the polar groups and the functional groups. Nevertheless, such interactions are not usually effective in providing effective stress

transfer especially when subjected to tensile and flexural loads (Bledzki and Gassan, 1999). The bonding is chemical and determines the occurrence of high interfacial adhesion. In natural fibers without treatment the presence of waxes, lignin and hemicellulose on the surface of the fibers prevent direct communication with the epoxy matrix. Consequently, the debonding at the interface is normally experienced during mechanical loading and hence premature failure by fiber pull-out instead of fiber fracture. This observation is further enhanced by the high proportion of fiber content/grade, in the sense that when the reinforcement level is high, then poor bonding and low wetting are more pronounced (Xie et al., 2010).

The role of the variation in fiber reinforcement on interfacial behavior has a strong connection with the fiber volume or weight fraction. When the fiber contents are low, the epoxy resin will be able to wet the fiber surfaces sufficiently to achieve relatively homogeneous stress distribution and mechanical properties. On the one hand, the resin availability is more competitive with the increasing fiber content which usually results in the incomplete wetting, formation of voids and agglomeration of fibers. These flaws serve to undermine the fiber-matrix interface and serve as a concentration of stress, and tensile and flexural strength declines as fiber loading is exceeded (Jawaid and Abdul Khalil, 2011). Thus, the presence of an optimum fiber content published by many studies can be partially explained by interfacial restrictions and not only fiber strength. A proper interface design is more important at the high-reinforcement levels to maintain mechanical operational ability. In order to eliminate interfacial incompatibility, chemical and physical surface treatment methods have been extensively used. One of the most widely used processes is alkali treatment (mercerization), which is the removal of hemicellulose, lignin, and surface impurities with sodium hydroxide solutions. This treatment makes the surfaces rough, uncovered cellulose fibrils and improved mechanical interlocking with the epoxy matrix resulting in high interfacial adhesion and mechanical toughness (Li et al., 2007). Another good method of interface modification is by silane coupling agents. The Silanes are used as molecular bridges between the hydrophilic fiber surface and the hydrophobic epoxy matrix where covalent bonds are formed with both phases. Many studies have indicated that tensile and flexural strength of silane-treated natural fiber epoxy composites have greatly increased at moderate to high levels of fiber loadings (Kabir et al., 2012). Acetylation, benzylation and enzymatic treatment of surfaces have also been experimented in order to minimize moisture uptake and enhance fiber-matrix compatibility. Although these treatments improve interfacial bonding, their performance is subject to the conditions of processing, type of fibers and level of reinforcement. The mechanical properties of epoxy composites directly and quantitatively depends on the quality of the fiber-matrix interface. Well bonded interfaces allow good transfer of stress leading to increased tensile strength and modulus and weak interfaces allow fiber pull-out and interfacial debonding which in turn increases its deficiency in the load bearing capability. Bending and impact loading is known to produce complex stress states at the interface making flexural and impact properties especially sensitive to interfacial quality. A common finding of fractographic analysis by scanning electron microscopy of untreated fiber composites is that they fail mostly by fiber pull-out and matrix cracking which implies that there is no good interfacial adhesion. By contrast, fiber composites that have been treated tend to exhibit fracture of fibers, and the pull-out lengths are smaller, which indicate enhanced stress transfer and interface strength. These findings help us conclude that the reinforcing potential of natural fibers can be fully exploited through the interface alteration, particularly the higher the fiber content is.

IV. EFFECT OF NATURAL FIBER REINFORCEMENT CONTENT ON MECHANICAL PROPERTIES

Mechanical behavior of natural fiber reinforced epoxy composites are highly controlled by the degree of reinforcement by fibers and usually measured in the form of weight fraction or volume fraction. The fiber material affects the stress transfer efficiency, stiffness, damage tolerance, and prevailing failure modes. One of the common findings of the literature is that mechanical properties increase with fiber content to an optimum, above which additional reinforcement disrupts properties through processing and interfacial constraints (Bledzki and Gassan, 1999; Faruk et al., 2012; Pickering et al., 2016). This section is a critical review of the effects of different contents of natural fibers on important mechanical properties of epoxy composites.

The tensile strength and tensile modulus are some of the most commonly utilized tensile reinforcement efficiency indicators of epoxy-based natural fiber composite. In low fiber contents, the load bearing behaviour is controlled by the epoxy matrix and enhancement by fibers is minimal. Given that enough interfaces bonding is attained, tensile strength and modulus tend to improve as fiber content is increased as the material is able to transfer stress more effectively between the matrix and the

fibers (Jawaid and Abdul Khalil, 2011; Mohammed et al., 2015). Some experimental studies indicate that tensile strength increases with fiber content to a certain optimum range, usually 20 to 40 percent by weight, depending on the type of fiber, surface treatment, and fabrication technique (Li et al., 2007; Yan et al., 2014). In this range, the fibers are fairly uniformly dispersed and sufficiently moistened with the epoxy resin, and thus, it easily shares loads. In addition to the optimal fiber loading, tensile strength tends to reduce because of fiber agglomeration, inadequate resin wetting and high content of the void, which are all contributory factors to weakening of the fiber-matrix interface, and subsequent premature failure through fiber pull-out and interfacial debonding (Xie et al., 2010; Kabir et al., 2012).

The flexural properties give an insight into composite behavior of tensile, compressive, and shear stresses combined and would be relevant especially in structural and semi-structural application. Many studies have also indicated that the flexural strength and flexural modulus increase with the increase in the content of natural fibers up to optimum, which is due to the capacity of the fibers to limit the deformation of the matrix and slow the crack propagation during the presence of bending loads (Jawaid and Abdul Khalil, 2011; Faruk et al., 2012). Flexural strength often becomes lower at higher contents of fiber though. Such a decrease is connected to the inability to fill interstitial spaces between tightly packed fibres and introduce local stresses, especially on the tensile surface of the specimen in bending (Li et al., 2007; George et al., 2016). Conversely, flexural modulus usually keeps rising with fiber loading because the beneficial impact of the fibers on the stiffness of the material is greater than the negative impact of interfacial flaws (Mohammed et al., 2015). The impact behavior of fiber content is more complicated than tensile and flexural because the impact strength is affected by various energy absorption processes. Impact strength tends to rise at low to moderate fiber content levels, and the mechanisms that affect impact strength include fiber debonding, fiber pull-out, matrix cracking, and crack deflection all of which dissipate large quantities of energy during fracture (Satyanarayana et al., 2009; Pickering et al., 2016).

V. EFFECT OF FIBER LENGTH, ORIENTATION, AND ARCHITECTURE ON MECHANICAL PROPERTIES

In addition to fiber content, fiber length, fiber orientation and reinforcement architecture are also important in determining the mechanical performance of natural fiber reinforced epoxy composites. These parameters control the performance of stress transfer, crack arrest processes and anisotropy of mechanical reaction. The difference in fiber geometry and position can hence increase or decrease the reinforcing effect of natural fibers even when at the same fiber contents. This section summarizes the reported results on the influence of fiber length, orientation, and architecture on tensile, flexural, and impact properties of natural fiber composite made of epoxy. An important parameter of the load transfer efficiency between the natural fibers and epoxy matrix is the fiber length. Fibers shorter than a critical length cannot become fully tensile, because stress is not transmitted to the fibers to make them fracture before interfacial debonding can take place. This has led to composites that have very short fiber reinforcements usually having low tensile and flexural strength enhancement (Bledzki and Gassan, 1999; Li et al., 2007). There is generally an increase in the mechanical properties of fibers as their length exceeds the critical length of the fiber because of better stress transfer and higher chances of fracturing fibers instead of pulling out when loading occurs. A number of studies indicate that considerably high tensile and flexural strength is obtained with long or continuous natural fibers in epoxy matrices than short-fiber composites with the same fiber content (Jawaid and Abdul Khalil, 2011; Yan et al., 2014). Nonetheless, increased length of the fiber also comes with processing problems such as fiber alignment, resin impregnation, and minimization of voids, especially in high reinforcement levels. Although mechanically poorer than long-fiber systems, short-fiber epoxy composites have the benefits of isotropic behavior, ease of fabrication, and complexity of geometry. The choice of fiber length is, therefore, an option between mechanical performance and manufacturability, depending on the purpose of use. The orientation of the fibers has a determining effect on the directional mechanical characteristics of epoxy composites. Unidirectional fiber alignment permits the greatest amount of load transfer along the axis of the fiber leading to the birth of better tensile and flexural characteristics in the loading direction. Many experiments show that unidirectional natural fibre epoxy composite with a higher degree of strength and stiffness is observed than randomly oriented system especially when it comes to loading along the grain (Pickering et al., 2016; Faruk et al., 2012). Random fiber composites, however, have lower peak mechanical properties, but they have more homogeneous behavior in more than one direction. This isotropic response is beneficial in components which are exposed to multi-axial or random loading. The structural design of fibers, such as order of layering as well as order of stacking, also acts on the performance of the composite. Damage tolerance Multilayer laminates with

switching fiber orientations can enhance anisotropy in mechanical properties. Research of laminated natural fiber epoxy composites shows that the number of layers typically increases the stiffness and load-bearing capacity in case interlaminar bonding is sufficient (Yan et al., 2014). Mixed architectures using a combination of various natural fibers or using natural fibers with small quantities of synthetic fibers have also been considered to achieve the balance between the strength, toughness and sustainability. These types of hybrids are usually characterized by synergies like better impact resistance and longer crack propagation compared to single fibre systems (Pickering et al., 2016; Faruk et al., 2012). The length and the orientation of the fiber play a significant role in the impact resistance and fracture mechanism. Long and woven fibers support crack bridging, fiber pull-out and delamination that help in increasing the energy absorption during impact loading. Conversely, short and randomly oriented fibers are likely to enhance matrix-dominated brittle fracture hence less impact strength (Satyanarayana et al., 2009; Kabir et al., 2012). It is always found in fractographic tests that aligned and woven fiber composites have shorter fiber pull-out lengths and greater fiber breakage which is evidence of better stress transfer and higher interfacial performance. These processes gain in significance with increasing fiber contents and in these cases reinforcement efficiency is constrained otherwise by the interfacial constraints. It is quite clear as per the literature reviewed that in order to guarantee the desired mechanical performance, fiber length, orientation, and architecture need to be optimized along with the fiber content. Although adding fiber content will increase the stiffness and strength to the maximum level, improper geometry or orientation of fibers will eliminate the effects. Thus, rational composite design involves a combined solution that takes into account the reinforcement content, the geometry of fibers, and the architecture to achieve maximum mechanical potential of the natural fiber reinforced epoxy composites.

VI. INFLUENCE OF FABRICATION AND PROCESSING TECHNIQUES ON MECHANICAL PERFORMANCE

Mechanical characteristics of natural fiber reinforced epoxy composites do not only depend on the characteristics of the fibers and the parameters of reinforcement, they are significantly affected by fabrication and processing techniques. Processing controls fiber wetting, resin distribution, fiber alignment retention, interfacial integrity, and all of these have direct implications on tensile, flexural and impact performance. Since natural fibers are highly sensitive to humidity and thermal decomposition, the choice and regulation of processing strategies is especially essential in the realization of standardized and maximized mechanical performance (Faruk et al., 2012; Pickering et al., 2016). A number of fabrication methods have been utilized in the manufacture of the natural fiber reinforced epoxy composites with unique benefits and constraints. A hand lay-up technique is among the most common ones because of its simplicity, low cost of tools, and the possibility to use it to investigate the issue on the laboratory scale. Under this technique, the fibers are put manually into a mold and they are then impregnated with epoxy resin. Although hand lay-up is cost-effective and versatile, it can lead to uneven resin distribution, increased voids, and fiber volume fraction inconsistency, which can negatively impact the mechanical properties (Jawaid and Abdul Khalil, 2011; Mohammed et al., 2015). Compression molding provides a better control of the fiber content, laminate thickness and surface finish. The pressure used in the process of curing improves the wetting of the fiber and minimizes the creation of voids and this results in high tensile and flexural strengths as opposed to hand lay-up composites. But, natural fibers can be destroyed under too much pressure or displace the fibers, especially with high reinforcement (George et al., 2016). Another important factor that is of great importance in determining the efficiency of stress transfer in epoxy composites is fiber wetting. Poor wetting would result into low interfacial bonding and early failure during mechanical loading. Viscosity of resin used, the temperature and pressure used in curing and impregnation time are some of the processing parameters that have a strong impact on wetting behavior especially when the fibers content is high (Bledzki and Gassan, 1999; Xie et al., 2010). Another important factor of mechanical performance is the void content. Voids are stress concentrators and they ignite microcracks, which increase tensile strength and flexural strength, and seriously deteriorate fatigue and impact resistance. Composites made by hand lay-up represent natural fibers tend to have more void fractions, particularly when the fiber loading is high, and vacuum-based methods largely reduce the voids (Kabir et al., 2012; George et al., 2016). The factors of curing temperature, the length of time spent on curing and the post-curing treatments are significant in defining the end-result network structure of the epoxy matrix, as well as in defining the quality of the fiber-matrix interface. When properly cured, the epoxy resin will have full cross-linking, which leads to the enhancement of the stiffness, thermal stability, and load-bearing capacity. Poor curing, conversely, causes the decrease in the strength of the matrix and the poor interfacial adhesion (Petrie, 2006). The use of natural fibers also gives more

restrictions on the curing conditions since they are thermally unstable. High curing temperatures may lead to degradation of fibers, mechanical integrity, and moisture loss and thus may introduce porosity at the interface. In turn, to strike a balance between the cross-linking of the matrix and the maintenance of fibers, optimized low-temperature curing schedules are frequently favored in relation to natural fiber epoxy composites (Mohammed et al., 2015).

VII. FAILURE MECHANISMS AND FRACTURE BEHAVIOR OF NATURAL FIBER REINFORCED EPOXY COMPOSITES

The knowledge of the failure mechanisms will be critical when analyzing the results of the mechanical tests, and in designing natural fiber reinforced epoxy composites. Type of the fracture and damage evolution is highly dependent on the fiber type, fiber material, surface quality, geometry of reinforcement and processing conditions. Natural fiber epoxy systems in comparison to synthetic fiber composites tend to have complex and mixed-mode failure because of the variability of fiber properties and a relatively weak fiber-matrix interfaces. This part provides the review of the majority of failure modes that could be observed in various loading conditions and the manner in which these mechanisms change depending on the natural reinforcement with fibers. In tensile loading, failure of natural fiber epoxy composite usually starts at the weakest phase which can be the epoxy matrix, the fiber-matrix interface or fiber. Tensile failure at low fiber contents is mainly matrix dominated which is associated with matrix cracks and little fiber pull-out. When this happens, there is minimal contribution of fibers in load bearing, and fracture surfaces are also characterised by smooth regions of matrix with little fibers involvement (Bledzki & Gassan, 1999; Faruk et al., 2012). With optimum fiber contents effective stress transfer occurs where a transition occurs between matrix-dominated failure to fiber-dominated or mixed-mode failure. Fracture surfaces have the tendency to exhibit fiber breakage, less pull-out lengths, high fiber-matrix adhesion and this implies that it is efficiently reinforced. At too high levels of fiber loading, however, tensile failure is often controlled by interfaces debonding and fiber agglomeration. Lack of good resin wetting and high level of void content facilitates crack formation at the interface, which causes untimely failure and low tensile strength (Xie et al., 2010; Kabir et al., 2012). Flexural loading presents a mixture of tensile stress and compressive stress with shear stress leading to more complicated failure mechanisms. The most frequently used initiation mechanisms on the tensile side of a flexural specimen are matrix cracking and interfacial debonding, and compressive failure on the other side may be through fiber buckling and localized crushing of the matrix (Jawaid & Abdul Khalil, 2011). As the fiber content increases, flexural failure usually changes to a matrix cracking to interlaminar delamination and fiber pull-out, especially in laminated and woven composites. At high reinforcement content, interlaminar bonding is weakened because of insufficient resin between layers of fibers, thus delamination is a failure mode dominant. The flexural strength and stiffness are heavily decreased by such delamination regardless of higher fiber content (George et al., 2016; Yan et al., 2014). Natural fiber epoxy composite impact failure has various energy dissipation processes occurring which are; matrix cracking, fiber-matrix debonding, fiber pull-out, fiber fracture, and delamination. Fibers pull-out and crack deflection provide a great contribution to energy absorption and leads to better impact resistance at low to moderate fiber contents (Satyanarayana et al., 2009; Pickering et al., 2016). Impact behavior is also usually brittle at increased fiber contents. The limitation of matrix deformation, augmented fiber-fiber contacts and low grade interfacial bondage restrict energy loss processes, culminating in quick crack propagation and diminished impact toughness. The impact performance of woven and long-fiber architectures is often favorable to that of short-fiber systems because of a high rate of crack bridging and delamination resistance (Yan et al., 2014; Mohammed et al., 2015). SEM has seen a lot of application in the correlation of mechanical performance and fracture morphology in natural fiber epoxy composites. The typical SEM images of untreated fiber composites reveal that the fibers have large pull-outs, smooth fiber surfaces and that there are interfacial gaps, which demonstrate poor bonding. Contrastingly, surface-treated fiber composites display jagged fiber surfaces, shredded fibers and shorter pull-out lengths which confirm enhanced interfacial adhesion and stress transfer (Li et al., 2007; Kabir et al., 2012). Microstructural examination also shows the negative contribution of voids and agglomerates, which serve as the place of crack origin. Such defects are more common with fiber contents and improper processing and this is the reason why mechanical properties begin to decrease after optimal reinforcement levels (Xie et al., 2010). The development of mechanisms of failure at different natural fiber reinforcement levels highlights the need to have balanced composite design. Although incorporation of fiber content increases stiffness and load carrying capacity, high levels of reinforcement cause failure to occur towards interfacial debonding and delamination, which compromises mechanical reliability. Hence, failure measurement can give vital

information on why ideal fiber content does exist and why better interfacial bonding and processing is needed to take advantage of increased levels of reinforcement.

VIII. COMPARATIVE ANALYSIS OF NATURAL FIBER–EPOXY COMPOSITES WITH SYNTHETIC FIBER COMPOSITES

To have a significant assessment of natural fiber reinforced epoxy composites, it is necessary to compare these types of composite with the typical synthetic fiber systems, and specifically glass fiber reinforced epoxy composite systems that are commonly used in structural and semi-structural applications. These comparisons aid in providing some context to the mechanical performance, durability, cost and sustainability trade-offs inherent in replacing the use of synthetic fibers with the use of natural fibers. This part summarizes comparative reports made on the literature on the same topic and focus has been given to mechanical properties, density-specific performance, environmental impact, and suitability of application. Glass and carbon synthetic fibers have very high absolute tensile strength, modulus, and fatigue resistance as compared to the natural fibers. Glass fiber reinforced epoxy composite is therefore found to be superior to natural fiber composites in tensile and flexural strength over a broad fiber content (Bledzki and Gassan, 1999; Faruk et al., 2012). As an illustration, glass fiber epoxy composite products typically feature tensile strengths that are more than 300 MPa, compared to most natural fiber epoxy products coming in between 50-150 MPa, which varies with the type of fiber, surface treatment and degree of reinforcement (Pickering et al., 2016). The difference in performance is however reduced significantly when mechanical properties are divided by density. The natural fibers have very low densities (1.2-1.5 g/cm³), relative to glass fibers (around 2.5 g/cm³), and, as a result, natural fibers exhibit competitive specific strength and specific modulus values (Jawaid and Abdul Khalil, 2011). Some of the studies state that flax-epoxy and hemp-epoxy composites can decide the specific stiffness of glass fiber epoxy composites, specifically with the optimal fiber contents and proper surface treatment (Yan et al., 2014). One area in which natural fiber composites can be beneficial as compared to synthetic fiber systems is impact behavior. Glass fiber epoxy composites are prone to brittle fracture when impact loaded, and little energy is absorbed once the crack has started. Conversely, natural fiber epoxy composites tend to exhibit a more progressive failure because of the fiber pull-out, debonding, and deflection mechanisms of crack, which increase the dissipation of energy (Satyanarayana et al., 2009; Pickering et al., 2016). Consequently, natural fiber epoxy composites often have similar or better impact resistance with intermediate fiber contents, even though their tensile and flexural strength is less. This property makes them desirable in the case when maximum load-bearing capacity is not as important as the damage tolerance and energy absorption e.g. in automotive interior panels and protective structures (Mohammed et al., 2015). The environmental performance of natural fiber reinforced epoxy composites is one of the greatest strengths of such alloys. Natural fibers are renewable and biodegradable and linked with much less energy use and carbon output in the process of production as compared to synthetic fibers. According to the life cycle assessment studies, it is always true that natural fibers instead of glass fibers lead to the minimization of greenhouse emissions, embodied energy, and end-of-life environmental burden (Faruk et al., 2012; Pickering et al., 2016). Synthetic fibers on the other hand are energy consuming to manufacture, non-biodegradable and difficult to recycle and dispose. Such sustainability concerns are increasingly becoming important in the choice of materials used by industries that are regulated by environmental conditions and corporate sustainability goals. Economically, the natural fibers tend to be cheaper compared to the synthetic fibers especially in areas where agricultural residues are easily accessible. There are more economic advantages such as lower material cost and less wear of tools in the processing (Jawaid and Abdul Khalil, 2011). Natural fiber composites, however, may need extra processing, e.g. fiber treatment, drying, and controlled curing to address the problem of moisture, which partially neutralizes cost benefits. Glass fiber epoxy composites are less cheap in the cost of raw materials, but with high-level consistency, ease of process with high fiber volume, and established design standards. These considerations are still in support of synthetic fibers in the high-performance structural use where reliability and predictability are very important (Bledzki and Gassan, 1999). In order to achieve any performance improvement between natural and synthetic fiber composite, hybrid reinforcement strategies have received some significant focus. Dual composites with natural fibers and sparse quantities of glass fibers in an epoxy framework tend to be synergistic and gain a higher degree of strength and stiffness without decreasing the benefits of impact resistance and sustainability (Faruk et al., 2012; Yan et al., 2014). This kind of hybrid system has shown that partial replacements with natural fibers of synthetic fibers can provide balanced

mechanical performance and lower environmental impact, and thus are promising candidates to semi structural applications.

IX. CONCLUSION

The review has critically assessed the influence of different natural fiber reinforcement on the mechanical properties of the epoxy composites through synthesizing, and analyzing a wide range of experimental literature. As it is very evident in the discussion, the natural fiber reinforced epoxy composites are a potential class of sustainable material able to provide acceptable mechanical performance in a broad array of engineering and semi-structural applications should reinforcement parameters be optimized well. The pattern that is common to a variety of natural fiber types is that tensile, flexural, impact, and hardness can be improved as a result of adding fiber content to a certain optimal level of reinforcement. It is due to this improvement in the transfer of load that the epoxy matrix has on the fibers and the contribution of the stiffness by the reinforcement. However, outside this optimum, mechanical properties are usually compromised by poor resin wetting, fiber agglomeration, high percentage of voids, as well as, poor bonds at the interfaces between fibers and the matrix. The presence of such optimum fiber content emphasizes the fact that the more reinforcement there is, the less performance can be expected and emphasizes the need to have balanced composite design. The review continues to prove that fiber content alone does not determine mechanical behavior. The length of the fibers, their orientation and the arrangement of the structure are all greatly important in reinforcing the structure and the manner in which it fails. Natural fiber reinforcements are always long, aligned, and woven which makes them better than short and random fibers in strength, stiffness, and even in impact resistance due to better energy absorption mechanisms. Simultaneously, the consequences of processing limitations of more fiber contents and intricate structures demand a cautious management of fabrication parameters. The interfacial properties are discovered to be a decisive parameter that determines performance of the composite, especially at the high reinforcement levels. The alkali and silane modification are chemical surface treatments that determine the enhancement of fiber-matrix adhesion, minimization of moisture sensitivity, and enhancing ease-of transfer of stress. By analogy, fabrication and processing modalities have a profound influence on the void content, wetting of the fibers, and inter-face integrity, and vacuum-assisted and pressure-based systems tend to create better mechanical performance than open-mould-based systems. Relative analysis and comparison with synthetic fiber epoxy composites indicate that the natural fiber structures though not comparable to the absolute strength and stiffness of glass or carbon fiber composites, still provide competitive specific properties, greater impact strength, decreased density, less cost, and high environmental benefits. These properties render natural fiber reinforced epoxy reinforced composites especially appealing concerning uses where sustainability, light weight, and sustainable damage tolerance are more essential than optimal load carrying capability. Mechanical performance of the natural fiber reinforced epoxy composites has a complex interaction between the types of the fibers, the content of the reinforcement, the quality of the interfaces, the geometry of the fiber, and the method of processing. The best usage of natural fibers is achieved when there is an integrated design approach, and not through the independent optimization of parameters. The summary of results in this review gives a consistent approach of reinforcement actions and can be an important source of information to researchers and engineers whose objective is to design high-performance and sustainable epoxy-based composite materials.

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