A Review on Application of Natural fibre in Structural Reinforcement: Challenges of Properties Adaptation

ADEKOMAYA, O; ADAMA, K

1Department of Mechanical Engineering, Faculty of Engineering, College of Engineering and Environmental Studies, Olabisi Onabanjo University, Nigeria
2Department of Agricultural Engineering, Faculty of Engineering, College of Engineering and Environmental Studies, Olabisi Onabanjo University, Ibojan Campus, Ifo, Ogun State, Nigeria

ABSTRACT: The foray of natural fibre reinforced composite in structural application is not new and researchers are currently considering different approaches of maximizing its performance. In many published works, natural fibres have enjoyed reasonable patronage in cooling applications and in cementitious structural materials. The moisture affinity of these fibres is another challenge that have dominated literature for ages. Moreover, modification of natural fibre in structural application is a herculean tasks that have not been established in many published works. In this work, properties and characteristics variation of natural fibre in structural reinforcement are discussed. Substantial part of this work is also dedicated to main properties inherent in natural fibre, cellulose is considered the major framework embedded in the fibre structure.

Keywords: Natural fibre, reinforcement, structural application, chemical composition.

The application of natural fibres in reinforcement of composite have been reported in many past works (Adekomaya et al., 2017b, Santamouris, 2016) with improvement and shortcomings depending on the application of the resulting composites. Environmental concerns and sustainability of convectional materials are stimulating research into natural fibres. Natural fibres seem to be applicable in all facet of life in view of their availability and recyclability (Novais et al., 2016). Natural fibres have been a popular reinforcement in furniture, polymer matrix, and automotive industries. Part of their attractive tendencies in automotive component formations is their lightness and energy efficiency in these vehicles (Vigneault et al., 2009). Natural fibre are majorly sourced from plant-based derivatives and they are lignocellulosic in nature with components usually of cellulose, hemicelluloses, lignin, pectin and waxy substances. It is also noted in many published works that the embedded structural composition and chemical composition of these fibres made them suitable for variety of application as depicted in Figure 1 and Table 1. The different cross-sectional shapes of natural fibres are shown in Figure 2 confirms irregular and varying shape of natural fiber. Figure 3 is a reflection of schematic structure of a natural fibre and in the work of Kabir et al., 2012, cellulose is considered the major framework embedded in the fibre structure.

Part of the advantages of lignocellulosic content in the natural fibres over synthetic materials are their mechanical properties, low thermal conductivities values, non-abrasivity, enhanced energy recovery and biodegradability( Abdellaoui et al., 2015). The main disadvantages of natural fibres in the reinforcing of matrix is their moisture affinity, which brings about dimensional instability in the lignocellulosic based fibres. Abiola and his co-workers discussed in their work that for a natural fibre to effectively perform optimally in a matrix based composite, the interfacial structure and stress transferability of resulting composite and natural fibre must be sustainable. The stress transferability plays a key role in sustaining the mechanical properties of the resulting composite (Dong et al., 2014). The moisture affinity of natural fibre is a major drawback in the reinforced composite(Kabir et al., 2012, Szolnoki et al., 2015). Although, natural fibres have been treated in many experimental works and the resulting composites have shown reasonable improvement in their adhesion to matrix materials(Ramesh, 2016). In other
woks(Mechraoui et al., 2007, Nayak et al., 2012), most natural fibres have shown low degradation temperatures (~200 °C), which make them highly vulnerable to structural application compared with thermosets with high curing temperatures. This tendency tends to limit the scope of exploration of natural fibre composites to relatively low temperature applications. There are numerous other challenges as reported in the large variability of their mechanical properties, lower tensile strength as compared with synthetic fibre, and variation in mechanical properties when exposed to moisture(Ramamoorthy et al., 2015).

The interface in the fibre–matrix composite is the reaction zone where the individual fibre and matrix are chemically and physically bonded. This on its own, already confer major disadvantages on composite as per hydrophilicity. In most cases where the resulting composite display poor adhesion across the phase boundary, this further propagate weak dispersion of force across the composite boundaries, resulting in poor performance of the composite. The threat of the moisture attack is mostly predominant at the interfacial boundaries as a result of the presence of hydrophilic hydroxyl groups on the fibre surface(Ayrilmis et al., 2011). Lately, the emergence of modifiers and coupling agents have largely reduced the interfacial bonding gap between the fibre and matrix(Pérez-Pacheco et al., 2013, Adekomaya et al., 2016). In most cases, the natural fibres are modified with different chemical additives and coupling agents. As a result of this intervention, significant improvements have been recorded in the mechanical properties of the natural fibre reinforced composites. Table 2 showcases the mechanical properties of natural fibres as an illustrative background for structural application. It can be observed in this Table that the tensile strength of these fibers appear to have been enhanced as a result of chemical modifiers used in the treatment of these fibres. This may not be the same for moisture contents level of these fibers as the level are still relatively high compare with the synthetic fibers.

**Table 1. Structural composition of specific natural fibres (Fakirov, 2007, Abiola et al., 2014)**

| Name of the fibres | Cellulose (wt.%) | Lignin (wt.%) | Hemicellulose (wt.%) | Pectin (wt.%) | Wax (wt.%) | Microfibrillar/spiral angle | Moisture content (wt.%) |
|--------------------|------------------|--------------|---------------------|--------------|-----------|--------------------------|------------------------|
| Bast fibres        |                  |              |                     |              |           |                          |                        |
| Jute               | 61–71.5          | 12–13        | 13.6–20.4           | 0.2          | 0.5       | 8.0                      | 12.6                   |
| Flax               | 71               | 2.2          | 18.6–20.6           | 2.3          | 1.7       | 10.0                     | 10.0                   |
| Hemp               | 70.2–74.4        | 3.7–5.7      | 17.9–22.4           | 0.9          | 0.8       | 6.2                      | 10.8                   |
| Ramie              | 68.6–76.2        | 0.6–0.7      | 13.1–16.7           | 1.9          | 0.3       | 7.5                      | 8.0                    |
| Leaf fibres        |                  |              |                     |              |           |                          |                        |
| Sisal              | 67–78            | 8.0–11.0     | 10.0–14.2           | 10.0         | 2.0       | 20.0                     | 11.0                   |
| Pineapple leaf fibre | 70–82           | 5–12        | –                   | –            | –         | 14.0                     | 11.8                   |
| Seed fibres        |                  |              |                     |              |           |                          |                        |
| Cotton             | 82.7             | 0.7–1.6      | 5.7                 | –            | 0.6       | –                        | 33–34                  |

The interface in the fibre–matrix composite is the reaction zone where the individual fibre and matrix are chemically and physically bonded. This on its own, already confer major disadvantages on composite as per hydrophilicity. In most cases where the resulting composite display poor adhesion across the phase boundary, this further propagate weak dispersion of force across the composite boundaries, resulting in poor performance of the composite. The threat of the moisture attack is mostly predominant at the interfacial boundaries as a result of the presence of hydrophilic hydroxyl groups on the fibre surface(Ayrilmis et al., 2011). Lately, the emergence of modifiers and coupling agents have largely reduced the interfacial bonding gap between the fibre and matrix(Pérez-Pacheco et al., 2013, Adekomaya et al., 2016). In most cases, the natural fibres are modified with different chemical additives and coupling agents. As a result of this intervention, significant improvements have been recorded in the mechanical properties of the natural fibre reinforced composites. Table 2 showcases the mechanical properties of natural fibres as an illustrative background for structural application. It can be observed in this Table that the tensile strength of these fibers appear to have been enhanced as a result of chemical modifiers used in the treatment of these fibres. This may not be the same for moisture contents level of these fibers as the level are still relatively high compare with the synthetic fibers.
Table 2: Natural fibre properties (Ramamoorthy et al., 2015, Väisänen et al., 2016)

| Natural fibre | Tensile strength (MPa) | Young’s modulus (GPa) | Density (kg m$^{-3}$) | Moisture content (%) |
|---------------|------------------------|-----------------------|-----------------------|----------------------|
| Cotton        | 300–700                | 6–10                  | 1550                  | 8.5                  |
| Kapok         | 93.3                   | 4                     | 311–384               | 10.9                 |
| Bamboo        | 575                    | 27                    | 1500                  | –                    |
| Flax          | 500–900                | 50–70                 | 1400–1500             | 12                   |
| Hemp          | 310–750                | 30–60                 | 1400–1500             | 12                   |
| Jute          | 200–450                | 20–55                 | 1300–1500             | 12                   |
| Kenaf         | 295–221               | 22–60                 | 1220–1400             | 17                   |
| Ramie         | 110–1\*              | 23                    | 1550                  | 8.5                  |
| Abaca         | 12                    | 41                    | 1500                  | 14                   |
| Banana        | 529–914               | 27–32                 | 1300–1350             | –                    |
| Pineapple     | 413–600               | 60–82                 | 1440–1560             | –                    |
| Sisal         | 80–840                | 9–22                  | 1300–1500             | 11                   |
| Coir          | 106–175               | 6                     | 1150–1250             | 13                   |

Fig 4. Bamboo culm (a); Cross section of bamboo culm (Lau et al., 2018)

Part of the work of Lau et al. (2018), discussed the enormous prospect of bamboo fibre in structural application with other natural fibres. Although, the authors highlighted key of their advantages to include low density, low cost, high mechanical strength and high growth rate as part of their comparative advantages over other natural fibres. Some other published works (Yao and Li, 2003, Deshpande et al., 2000) also reported that bamboo fibre possess the ability of producing oxygen and absorbing carbon dioxide in about approximately three times when compared with other plants fibre, thereby reducing carbon emission and greenhouse gas effect to a limit. In another observation (Mitch et al., 2010), some tiny holes are cited on bamboo as revealed by SEM Micrograph (Fig. 4). In a similar paper (Zakikhani et al., 2014), bamboo fibre is reported to be porous in nature, with high moisture content, and sometimes difficult to extract fine and continuous fibre from their parent fibers. Their thermal degradation is also noted as a major setback especially during their manufacturing process. This further reduces the prospect of bamboo in structural reinforcement.

Properties Adaptation of Natural fibers: Exploring the properties of natural fibres in engineering applications is a great task that have not been resolved in many past works. Some of the issues raised is the high level of moisture absorption (5–10%), bonding tendency of fiber and matrix which appear to be the most pressing disadvantage of adapting natural fibre in real life. In automotive industry, natural fiber is gaining space and the global market has accorded natural fibre the much needed recognition it deserves. Cost and weight saving properties of natural fibers is a tool that have saved reasonable quantity of fossil fuel demand in cold chain (Adekomaya et al., 2017a). Car manufacturers are currently utilizing natural fibre composites as an alternative for glass fiber and aluminum sheet. In structural applications, it has been observed that cementitious based materials is formed from tension-susceptible materials, thereby propagate micro-cracks easily from the surface or at the interface between cement phase and aggregate after the hydration process. For concrete formations, cement is a basic material to bond all aggregates substances.
(sand, fine and small large stones) together to form resultant structures with reasonable compressive strength. Dispersion of this fiber in cementitious components is a recurrent issue in many past works. Some researchers (Ho et al., 2012; El-Sabbagh, 2014) have once concluded that if large quantity of natural fibres agglomerates together, it would largely reduce the ultimate strength of the structures (Fig. 5). This has further enhanced the treatment of natural fibre with NaOH or AlCl₃, H₂SO₄ or Ca(OH)₂ thereby making them to resist harsh weather and temperature. In light of the above, natural fibre reinforced cement composites are often used in residential housing for exterior applications only i.e. siding and roofing.

In another work, Sain et al. (2004) explored the flammability of natural fiber with polypropylene and sawdust/rice husk filled polypropylene composites by using horizontal burning rate and oxygen index tests. These authors went further to study the effect of flame retardants on zinc borate in combination with magnesium hydroxide. It was noted in their findings that magnesium hydroxide can only reduce the flammability of natural fibre filled polypropylene composites by about 50%. Their works also showed little effect when magnesium hydroxide was used to reduce the flammability of natural fiber. Although, natural fibres find usefulness in major application as a result of their product cost, their flammability still raise a lot of concern which may not exclude structural application.

In a similar paper, Szolnoki et al. (2015) used phosphorus to reduce the flammability of hemp fibre reinforced polymer composites. The authors applied fire retardant onto the surface of fabrics by immersing pre-heated dry fabric into a cold phosphoric acid solution. The result showed that the mechanical properties of the composite was slightly affected which may not reduce the flammability of natural fibre composite. Elsabbagh et al. (2017) also established the possibility of reducing the melting temperature and thermal stability of natural fibre reinforced composite.

The authors only used flame retardant which could not significantly produce substantial improvement. Part of the process employed was to mix Jute, flax and kenaf with Polyamide 6 (PA6) in a pellet form as shown in Figure 5. Figure 6 further shows that the heat release rate (HRR) of natural fibres reinforced composite tend to decrease with higher content of flame retardant substance. In a case of composite with 22.5% flax fibre and 20 wt % flame retardants, the heat release rate is noticed to decline by 50%.

**Conclusion:** Application of natural fibres is growing and will continue to dominate market environment for years to come. The reasons may not be unconnected with its abundance in nature, and environmental friendliness. Automobile industries will find this material useful for ages in terms of weight saving of component part and energy reduction. In real life, natural fibre will continue to be new materials for reinforced polymer composites for different structural applications. However, as their manufacturing process remain unsynthesized with no specific methodology, hence their mechanical and material properties will remain unresolved for sometimes. The drawback to natural fibre application as highlighted has not been resolved and no substantial progress has been published in this regard. Existing mathematical and numerical models developed to predict the properties of natural fibre reinforced composites are sometime not accurate due to the difficulty of having reliable input data. In another vein, modelling of natural fibre is difficult by either traditional cylinder or shear-lag model as a result of varying diameter of the natural fibre along its length. The enormity of research along this problem is huge as many issues raised in past works are yet to be solved. Re-designing natural fibre reinforced composites with properties alignment toward structural application will no doubt enhance the market base of natural fibre.

**Acknowledgement:** The authors would like to appreciate comments received form the anonymous reviewer which have improved the quality of this.
work. Appreciation also goes to authors of many literature which provides foundational understanding of this work.

REFERENCES

Abdellaoui, H; Bensalah, H; Echaabi, J; Bouhfid, R; Qaiss, A (2015). Fabrication, characterization and modelling of laminated composites based on woven jute fibres reinforced epoxy resin. Materials & Design, 68: 104-113.

Abiola, O. S; Kupolati, W. K; Sadiku, E. R; Ndambuki, J. M (2014). Utilisation of natural fibre as modifier in bituminous mixes: A review. Construction and Building Materials, 54: 305-312.

Adekomaya, O; Jamiru, T; Sadiku, R; Huan, Z (2016). A review on the sustainability of natural fiber in matrix reinforcement–A practical perspective. Journal of Reinforced Plastics and Composites, 35, 3-7.

Adekomaya, O; Jamiru, T; Sadiku, R; Huan, Z (2017a). Minimizing energy consumption in refrigerated vehicles through alternative external wall. Renewable and Sustainable Energy Reviews, 67: 89-93.

Adekomaya, O; Jamiru, T; Sadiku, R; Huan, Z (2017b). Negative impact from the application of natural fibers. Journal of Cleaner Production, 143: 843-846.

AyIRMIS, N; Jarusombuti, S; Fueangvivat, V; Bauchongkol, P; White, R. H. (2011). Coir fiber reinforced polypropylene composite panel for automotive interior applications. Fibers and Polymers, 12: 919-926.

Bledzki, A; Gassan, J (1999). Composites reinforced with cellulose based fibres. Progress in polymer science, 24: 221-274.

Deshpande, A. P; Bhaskar Rao, M; Lakshmana Rao, C (2000). Extraction of bamboo fibers and their use as reinforcement in polymeric composites. Journal of applied polymer science, 76: 83-92.

Dong, W; Liu, H.-C; Park, S.-J; Jin, F.-L (2014). Fracture toughness improvement of epoxy resins with short carbon fibers. Journal of Industrial and Engineering Chemistry, 20: 1220-1222.

Elsabbagh, A. 2014. Effect of coupling agent on natural fibre in natural fibre/polypropylene composites on mechanical and thermal behaviour. Composites Part B: Engineering, 57: 126-135.

Elsabbagh, A; Steuernagel, L; Ring, J. (2017). Natural Fibre/PA6 composites with flame retardance properties: Extrusion and characterisation. Composites Part B: Engineering, 108, 325-333.

Fakirov, S. (2007). Handbook of engineering biopolymers: homopolymers, blends and composites, Hanser Verlag.

Fidelis, M. E. A; Pereira, T. V. C; Gomes, O. D. F. M; De andrade silva, F; Toledo filho, R. D (2013). The effect of fiber morphology on the tensile strength of natural fibers. Journal of Materials Research and Technology, 2: 149-157.

Ho, M.-P; Wang, H; Lee, J.-H; Ho, C.-K; Lau, K.-T; Leng. J; Hui, D. (2012). Critical factors on manufacturing processes of natural fibre composites. Composites Part B: Engineering, 43: 3549-3562.

Kabir, M; Wang, H; Lau, K; Cardona, F. (2012). Chemical treatments on plant-based natural fibre reinforced polymer composites: An overview. Composites Part B: Engineering, 43: 2883-2892.

Lau, K.-T; Hung, P.-Y; Zhu, M.-H; Hui, D (2018). Properties of natural fibre composites for structural engineering applications. Composites Part B: Engineering, 136: 222-233.

Mechraoui, A; Riedl, B; Rodrigue, D. (2007). The effect of fibre and coupling agent content on the mechanical properties of hemp/polypropylene composites. Composite Interfaces, 14: 837-848.

Mitch, D; Harries, K. A; Sharma, B. (2010). Characterization of splitting behavior of bamboo culms. Journal of materials in civil engineering, 22: 1195-1199.

Nayak, S. K; Dixit, G; Appukuttan, K. (2012). Sisal fiber (SF) reinforced recycled polypropylene (RPP) composites. International Journal of Plastics Technology, 16: 150-165.

Novais, R. M; Buruberri, L. H; Ascensão, G; Seabra, M. P; Labrincha, J. A. (2016). Porous biomass fly ash-based geopolymers with tailored thermal conductivity. Journal of Cleaner Production, 119: 99-107.

Pérez-pacheco, E; Cauich-cupul, J; Valadez-gonzález, A; Herrera-franco, P. (2013). Effect of moisture
absorption on the mechanical behavior of carbon fiber/epoxy matrix composites. *Journal of materials science*, 48: 1873-1882.

Ramamoorthy, S. K; Skrifvars, M; Persson, A. (2015). A review of natural fibers used in biocomposites: plant, animal and regenerated cellulose fibers. *Polymer Reviews*, 55.

Ramesh, M. 2016. Kenaf (Hibiscus cannabinus L.) fibre based bio-materials: A review on processing and properties. *Progress in Materials Science*, 78: 1-92.

Sain, M; Park, S. H; Suhara, F; Law, S (2004). Flame retardant and mechanical properties of natural fibre–PP composites containing magnesium hydroxide. *Polymer Degradation and Stability*, 83: 363-367.

Santamouris, M. (2016). Cooling the buildings – past, present and future. *Energy and Buildings*, 128: 617-638.

Szolnoki, B; Bocz, K; Soti, P. I; Bodzay, B; Zimonyi, E; Toldy, A; Morlin, B; Bujnowicz, K; Wladyka-Przybyłak, M; Marosi, G (2015). Development of natural fibre reinforced flame retarded epoxy resin composites. *Polymer Degradation and Stability*, 119: 68-76.

Väisänen, T; Haapala, A; Lappalainen, R; Tomppo, L. (2016). Utilization of agricultural and forest industry waste and residues in natural fiber-polymer composites: A review. *Waste Management*, 54: 62-73.

Vigneault, c., Thompson, J., Wu, S., Hui, K. C. & Leblanc, D. I. 2009. Transportation of fresh horticultural produce. *Postharvest technologies for horticultural crops*, 2, 1-24.

Yao, W; Li, Z (2003). Flexural behavior of bamboo–fiber-reinforced mortar laminates. *Cement and concrete research*, 33: 15-19.

Zakikhani, P; Zahari, R; Sultan, M; Majid, D (2014). Extraction and preparation of bamboo fibre-reinforced composites. *Materials & Design*, 63: 820-828.