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Comparative advantages and application of polymer-based materials: Prioritizing natural fibres as reinforcement in building structures

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Abstract

Climate change and uncertainties in energy transition continue to increase the risk of environmental pollutions. The need for new materials derivable from organic materials have opened several new frontiers in research and innovation. Polymer-based materials (PBMs), considering its versatility, have shown their potentials in engineering structures and, the results are promising and far-reaching. PBMs possesses excellent thermal, mechanical and chemical properties, which necessitated significant research interest in these materials, resulting in their involvement in building and construction works. However, as their needs widened, spanning all human endeavours, it therefore important to establish how best these materials could be deplored in the face of climate change. Part of what is necessary as we explore these materials, is to report how best these materials could be applicable in building and construction works due to their low thermal conductivity's values and their biodegradability properties. The application of natural fibres is noticeable everywhere with possibility of being used the more if containment measures are put in place to reduce its vulnerability. This review paper x-rays the natural fibre materials as a reliable reinforcement in building structure and this assertion is premised on its peculiarities and thermal properties. As established in many published papers, natural fibre is of lower thermal conductivities values, compared with other materials in building reinforcements. This discussion would be all encompassing, providing details on how natural fibre could assist in energy conservation in building and equally saves considerable cost in construction works.

Keywords: Structures, Natural fibre, Thermal conductivity, Polymer, Building

1. Introduction

The quest for materials with distinctive properties has been ongoing for several years in order to tailor their properties to specific industrial applications. This has necessitated cutting-edge research in science and technology to evolve materials that are environmentally friendly after their end use [1]. Polymer-based materials have become one of the highly patronised materials in view of their enhanced electronic and optical properties that complement their functionalities for such applications. The core advantages of polymer materials are to reinforce a structure against chemical and corrosion attack as against conventional materials [2]. This was part of their initial development plan following the World War II. Their involvement in chemical process equipment was first reported in the early 1950s when some chemical processes and pulp bleaching companies commenced with polymer materials to replace strong metals such as iron and metallic alloys. At present, polymer reinforced composites are extensively used in chemical and allied industries, and their foray in building and construction appears the most recent [3].

According to the American Composites Manufacturers Association, the application of polymer in industries and construction works account for about 22% of total polymer composites export in 2010 which is about 528million lbs, as against an astronomical demand projection of polymer demand in the quantity of 3.3billion metric tonnes in the developing countries alone between 2021 and 2040. Polymer composites have grown in leap and bound over the years going by their mass production for automotive and structural applications, and several other applications. In construction works, it was observed that the corrosion-resistant polymer materials used in lieu of steel materials have resulted in the modern concrete making roads and structure which last beyond expectation [4, 5]. Reports also had it that, some modular fibre reinforced bridge decks are often eight times lighter and four times stronger than the metallic reinforced concrete bridge decks [6]. This innovation could help to reduce downtime and traffic tie-ups as replacement of component parts of these structures becomes necessary. Couple with their low self-weight properties, polymer materials can enhance the load-carrying capacity of old structures after part replacement with any reinforcing fibres [7].

Significant advantages of polymer materials are their tendency to offer additional benefits regarding energy conservation and environmental sustainability. This was evidenced in many life cycle assessment papers [8, 9] where in terms of unit performance, polymer reinforced materials have considerably lower convective energy. As reported in literature, per every unit length of I-beam, polymer reinforced I-beam consumes about 43% of embodied energy as against steel reinforced I-beam requiring 57% of entire embodied energy. Also of concerns is the greenhouse gas emission (COx) attributed to fibre reinforced beam [10]. In many published works [11, 12], this is insignificant and about 75% less than what steel I-beam generates with the environmental impact index of

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polymer reinforced I-beam being 20%. It is also noted that the comparative embodied energy advantage reported in this paper is based on definite applications and performance. Construction works have been characterised with waste of different composition as shown in Figure 1. These wastes from construction is a challenge going by the nature of these wastes and the disposal options available to contain them. Metal and glass are of diverse composition in nature and their disposal must be segregated to avoid difficulty in the waste management options. This also applies to other wastes as illustrated in the figure.

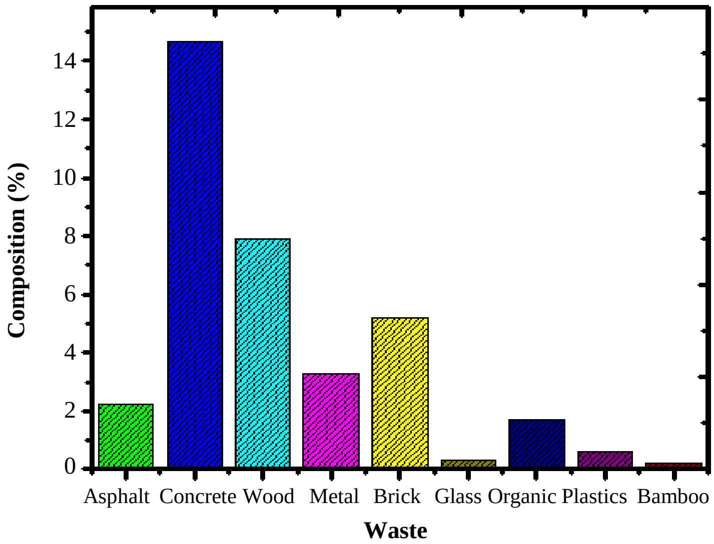

Figure 1 Different compositions of waste from construction works

It is also of concerns that fibre reinforced composites, are being used as a replacement of wood for poles or cooling towers. This will help to rid the environments of chemically processed wood where preservatives from these utility poles constitute environment hazards and risk to the underground water. According to these authors [13-15], over 600 million lbs of preservatives are used for wood in the United States every year, with the high projection in the foreseeable future. The evolution of fibre reinforced composites will further reduce the estimated embodied energy required in construction works thereby improving safe climate and enhance biodiversity system. The polymer composites are made of natural fibres and biodegradable resins or as it may also involve the integration of synthetic materials depending on the area of application [16]. While polymer reinforced materials enjoy patronage in construction and buildings, it is also very important to elaborate on specific interest of polymer-reinforced composite that is more instrumental in energy conservation in building and wall reinforcement. Natural fibre-reinforced composites are competitor material as compared to synthetic fibre reinforced materials in view of their attributes including specific stiffness, high strength and lightweight.

Reports [17] have shown that bio-based by-products or biodegradable materials are often deplored as reinforcements in many structural constructions. Some of these biobased materials include, rice husks, bagasse, coconut fibres, corn cobs, nutshells and other wastes that could be recycled naturally without environmental setbacks [18]. Some of the renewable sources from natural fibres are of considerable interest in engineering application considering their ultimate disposability after their life cycle. Further to this, natural fibres reinforced composites are notable for sustainability, great accessibility, fast renewability, desirable properties and comparable cost advantage. In order to enjoy full optimal properties of these materials, there is need to understand the detailed structural, morphological and mechanical properties of these bio-based fibres for optimizing service life performance [19]. Natural fibre reinforced composites have specific features as this makes them suitable for hybrid reinforcements forming a single matrix. In like manner, individual component part (fibre and matrix) retains its physical and chemical properties, which they shared as a supporting strength complementing one another [20].

Biobased material are organic source derived from plants and animals while their energy source are from sun, and tapping carbon dioxide from the environment, and discharging oxygen back into the nature through photosynthesis. These plants are reprocessed and reclaimed as feedstock for composite applications through natural carbon sequestration approach [21]. Part of the advantage derived from this process is that these reclaimed composites offer high performance and low cost provide carbon sequestration. Several of the reclamation processes often result in significant energy savings [22]. In a typical example, it was shown that per unit weight of embodied energy used for rough sawn timber is 20 times lesser than steel and 200 times lesser than aluminium; per ton of material. In another paper [23], findings showed that waste sawn timber absorbs over 400 kg of carbon while steel releases over 600 kg of carbon and aluminium releases over 7,700 kg of carbon [24]. These assertions have been corroborated in many literatures [25, 26]. In terms of their embodied energy, natural composites generally offer ten-fold superiority in terms of mechanical strength and reinforcement as against metallic materials [27].

The involvement of fibre-based materials in structural building have reduced the use of convectional materials such as synthetic and other fossil fuel-based composites [28]. These fossil fuel sourced materials have a long history of releasing large quantities of COx into the nature contaminating water and climate. As established in many papers [29], one ton of cement releases over one tons of Cox into the environment while one ton of natural fibres absorbs one ton of COx from the atmosphere. Studies have shown that over 3 billion tons of cements are consumed yearly in building, and with gradual replacement of cement-based concrete with natural-fibre reinforced composites, there would be significant energy savings and reduction of carbon footprint. In Figure 2, attempts were made to analyse the derivates from the construction wastes in term of the technology to recover these wastes. Findings shows that four technologies are being used for this recovery while electricity, heat, fuel, and recycled materials are derivatives recovered. Part of the information from this illustration is that, this reclamation process is capable of generating employments through various stages as discussed. It is also observed that heat, electricity, fuel could be sourced from this process as shown. While efforts are being sustained to recover useful materials, this process could also provide sustainable energy in the meantime.

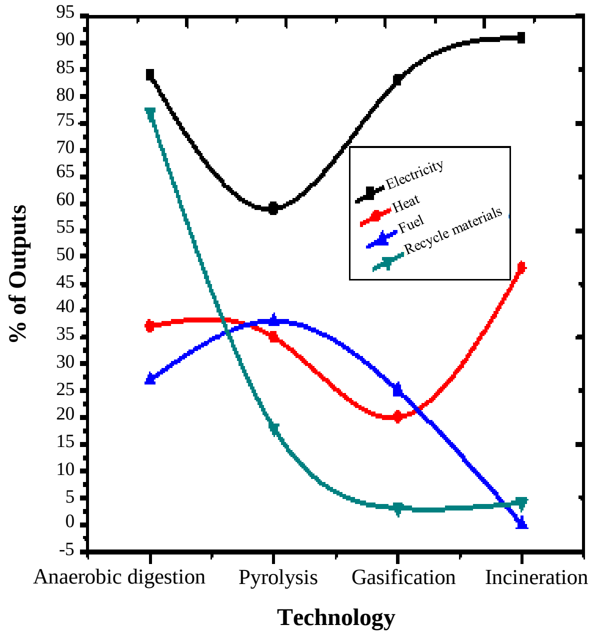

Figure 2 Distribution and composition of energy-mix from construction waste

2. Environmental concerns arising from convectional construction materials

The unprecedented use of materials in construction and demolition industry is partly responsible for the production of waste and its aftermath effects [30]. These wastes are increasingly noticed in all facet of human life impeding vehicular movement and causing havoc to the environment. Reports have indicated that in the EU construction industry alone, wastes emanating from these industries account for about 30% of the waste generated in the neighbourhood. Just lately and in the reports released by the Environmental Protection Agency of the United States [21], findings have shown that, the waste emanating from the construction and demolition wastes (CDW) was in the range of 170 million tonnes in the USA, while China is projected to record over 250 tonnes in the year 2030 amid global C&D waste management market nearing $37.1 billion by 2025 with a high projection in the near future. These wastes arising from several activities in construction works, and involving partial demolition of infrastructures and other maintenance activities.

It is also necessary to report some of the polymer reinforced materials which also emanate from these CDW. Some of these materials include metals, glass, gypsum, wood, plastic, asbestos and various other polymers, while few can be recycled, significant proportion is non-biodegradable [31]. Some of these plastic materials are of synthetic and non-renewable sources which constitute environmental menace for years to come. However, the contributing factors to this menace is the lack of knowledge on the part of the CDW mangers on how to characterise the compositions and other properties (i.e. quantity, quality, type and real cost) prior to their disposal or reclamation process [32]. In several instances, these CDW are often dump in construction sites for filling without sorting. It is also of concern that, most small and medium enterprises, which constitute largest vendors in the construction and demolition industries, want to excavate the waste as quickly and as cheaply as possible thereby compromising waste management masterplan [20]. These vendors are often unaware that most of these wastes are to be sorted based on their compositions to afford appropriate measures of reclamation.

Apart from the lack of knowledge on the part of CDW manger on the best disposal options, studies [33, 34] have also shown that these companies are not adopting source reduction of wastes as a way to reduce the quantity of CDW generation. In many cases, as a result of insufficient legislation on the part of government, significant proportion of these CDW are disposed by landfill. Having reviewed some of these practises in construction waste management, there is need for a great amount of time to allow players garner reasonable experience needed to evolve a sustainable waste management system. This haphazard approach to waste reclamation has discourage a lot of other interested partners in venturing into the reuse and reclamation of waste market [35]. Despite some of the extensive reports highlighting the concerns inherent in the CDW, it is also necessary to allay some of the fears as new materials are being designed to compensate some of the shortfall reported in respect to construction materials. Substantial part of CDW are carbon fibre and other thermosetting materials [36]. With the concerns and awareness, couple with the environmental impact occasioned by the production and recycling of these fibre reinforced composites, there is need to evolve an environmentally friendly materials sourced from natural resources. Figure 3 is a clear illustration of processed CDW in many developed countries, and part of the findings showed that recoverable products generate a reasonable income for every material subjected to the recycled plant. Also, the amount of waste generated per tonnes appear to be undulating with beams with bricks accounting for larger percentage of waste predominant on site.

A lot of reservation has also been advanced on the disposal of agro-waste from industrial crops and this is another serious concern in developing and emerging countries [37]. As agro-wastes becomes predominant, its application in sustainable composite materials may be explored as an alternative option for the construction industry. However, the prominent concerns identified in the application of the waste is generally predominant for all natural fibres and is the most critical factor aggravating cracks and failure of composites. This review article would discuss comprehensively latest efforts to contain these lapses amid excessive patronage.

3. Peculiarities of Natural fibre reinforced composite for reinforcement of wall structures

The involvement of fibre reinforced composites in construction purposes dated back 100 years and several factors necessitated those purposes. Chronic scarcity of metallic materials and the complicated production of these materials are driving factors prompting alternative materials in building [38]. The increasing population and housing deficit in the urban area equally put more pressure on some of the materials, raising their costs beyond limits. Part of the contributing factors is the global campaign on sustainable development goals (SDG) where nations are doing everything possible to mitigate climate change using biodegradable materials [39]. These concerns have raised a lot of credibility and uncertainties on some of the materials that are part of the risk factors. It is important to note that production of traditional construction materials have been flagged in many literatures in term of their huge fossil fuel required in their production. Studies have shown that bricks, cement, and steel, require considerable amounts of thermal and electrical energy as they undergo different stages of production.; thereby releasing more COx to the surrounding, contaminating air, water, and land bodies[40]. These highlights become the determining factors as materials are sought in construction works. Past and current researchers have identified various approaches on how to mitigate excessive energy demand in construction works in a viable and sustainable manner.

Concerns on biodegradability nature of convectional materials have necessitated ongoing research efforts including the evolution of sustainable building design in many sites. Notable of such strides is the development of green building materials which enhance the properties of some of the materials and minimize the foreseeable impacts from construction. Polymer reinforced composite is the umbrella body of synthetic and natural fibre reinforced composite. The synthetic component of these polymer materials appears to have hit a brick wall in terms of their further application in constructions. This may not have been unconnected with their inherent properties and reclamation process involved after their lifecycle. Several of synthetic plastic materials are sourced from fossil fuel and other related matters [11]. Their production and degradation after end use is not eco-friendly and a risk-factors to biodiversity system. In consideration of material properties and the demerits of synthetic materials, natural fibers derived from renewable vegetable sources will be a sustainable composite material for construction industry.

Natural fibres have several advantages amid conflicting reports. The abundant nature and relatively low cost of these materials put it an advantage in many applications [41]. Also, of interest in their properties include, regeneration and renewability, biodegradability, non-toxicity, low carbon releases, and noble performances (lightweight and well-structured strength, stiffness, and toughness) [42]. In many countries of the world where agricultural and industrial wastes have contributed to disposal problem, a feasible approach, is the reuse of these agricultural wastes in the form of sustainable construction material [43]. Studies [44, 45] have shown that these agricultural wastes are capable of reinforcing polymeric matrices in the most reliable form while offering weight reduction. Applying these natural materials as reinforcements in many constructions' application is a remedy to myriads of environmental challenges bedevilling the world [46]. Environmental pollution, increasing and uncertainties in global climatic weather conditions are some of the concerns disrupting the nature and its inhabitant. These has infiltrated into construction works as many of the building materials are part of the debris poising threats to construction workers amidst difficult disposal measures. Several of the containment measures have not yielded the desired results, as many of these debris are only re processed for land-filling, while in the developing countries, this measure is further completed by haphazard building plans.

4. Thermal resistance and insulating features of natural reinforced composite

Transportation and building subsectors of global economy, are part of the emitter of CO_2. Their contribution to greenhouse gas is predicated on activities involving stages of their operation [47]. In a paper [29], buildings and construction activities contribute about 45.6% CO_2 emissions as quantified by their fossil fuel consumption in the range 47.6% of entire energy delivery. Insulating materials have helped in no small measures in the management of energy and maintaining a comfortable and serene room temperature in buildings [48]. As it stands now, several thermal insulating materials are available for construction and majority of these materials are synthetic fibres in nature. Some of these materials could effectively serve as a better thermal resistance but with dire environmental concerns amid human health challenges. These issues largely impede the involvement of these materials in several building works. The need to source for alternative materials to serve as insulating materials in building remain the reliable approach of energy conservation in building. Reinforcement of wall structure with materials of lower thermal conductivities is another novel approach that could reduce heat infiltration through wall buildings. As ambient temperature rises, so also the proportion of energy demand in building rises. Recall, in most homes, refrigeration and air-conditioning provide comfort against heat and the energy required to power these devices is based on the thermal load and changes in ambient temperature [23]. Moreover, reports have indicated many ways to enhance the sustainability of insulating materials used in construction works; an easiest approach is the consideration of materials via the practises of modern technological developments and re-alignment of component parts of fibre and matrices forming the composite. The application of natural fibre as a replacement option to inorganic materials is as a result of their eco-friendliness and are harmless to human health.

Many research works [23, 32] have utilized several natural fibres and matrices to evolve bio-insulating building materials. Natural fibre and other biodegradable materials are of low thermal conductivity, low environmental impact, high porosity, low density, and renewability. Just recently, there have been several prototype on insulating materials developed from sugarcane bagasse, miscanthus, bamboo, coffee chaff, corn stalk, sunflower, rice straw, and date palms. The findings from this application indicated that these materials are capable of being used as thermal insulation for reinforcement of wall buildings. Oil palm trunks has also provided notable features for thermal insulating applications. As added advantage, Natural fibres contribute a huge role in the formation of natural fibre reinforced plastic composite (NFRPCs). It is also interesting to note that the production of NFRPSs also consumes lower and insignificant energy of about 9.55 MJ/kg as against the existing fibre-reinforced composites e.g., glass 54.7 MJ/kg [21]. Findings [49] have also shown that NFRPCs have low environmental impacts when compared with equivalent synthetic fiber reinforced composites. Products and insulating natural fibres emanating from the biobased resource are equipped with economical qualities like biodegradability, and renewability thereby raising their market volume and patronage. Figure 3 captures all the advantages associated with sustainable products and materials. Of paramount in this illustration is the benefit associated with natural fibre in term of revenue that comes from their production [6]. In addition, the land and nature abound for its cultivation many times. For instance, the production of flax and hemp fibres could yield seeds, and valuable oils with numerous uses, where it can be used as healthful supplements for patients. The waste generated from their production is also biodegradable and reclaimable toward the end of its life cycle [15]. In another case, coir strands which appears to be a by-product of an industry produces 64.3 billion fresh nuts per annum.

The production of natural fibre insulation materials is expected to contain 60-70 % of natural fibre while the remaining portion is the adhesive and matrix [26]. During the end life cycle of these panels, the component part of the insulating panel, being 70% NFs is degraded by environmental dampness, temperature intensity, and the presence of bacteria. This degradation only decomposes the hemicelluloses, lignin, and cellulose of the fibres [46]. By so doing, the total failure of the properties of NFRPCs was achieved. The natural fibre insulating panel consisting the kenaf/POM composites were exposed to environmental dampness, water, and UV light in a closed chamber and the panels displayed lower tensile strength. These results could be attributed to the degradation of the cellulose, hemi-celluloses, and lignin which are the integral properties of any natural fibre. The impact of ambient temperature and atmospheric humidity was also studied on the biodegradability of jute/phenolic composite [50]. The results indicated that over one-half of elastic properties of these panels were reduced after their exposure to these conditions for over one year. In addition, swelling and dark spots were also noted on the natural fibre insulating materials due to the ultraviolent exposure. All these problems are some of the teething challenges reported regarding the application of the materials as reinforcing wall. Ongoing researches have proffered sustainable treatment to some of these drawbacks and it is discussed in the next outline.

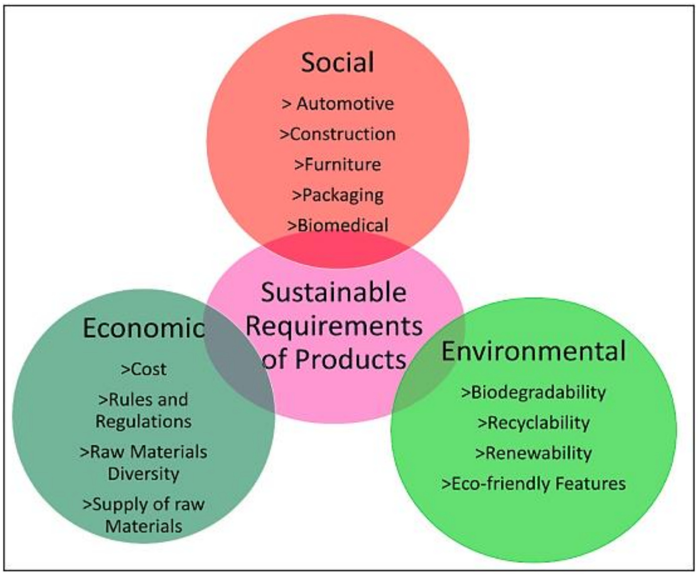

Figure 3 Advantages of sustainable materials [4]

5. Environmental concerns on natural fibres and the containment measures

Water absorption and hydrophic nature of natural fibre reinforced composite is a critical factor in the application of these fibre for reinforcing building structure [51]. Recall the primary reason for the wall support is to reduce heat infiltration through the external wall while the natural fibre absorbs these interferences in the long term. A typical wall support must possess attributes devoid of moisture vulnerability [21]. These concerns have put these materials on the spotlight in term of its ability for wall support. Part of the challenges have been the outdoor applications as these put more pressure on natural fibre reinforced composites for building purposes. Natural fibres are prone to humidity and moisture as a result of their hydrophilic constituent materials. These components are cellulose, hemicellulose, and other soluble components in relatively high quantity [19]. This makes water absorption a high-risk factor in the selection and performance evaluation of natural fibre composites.

As demonstrated many other structures, water absorption has been a major drawback to the performance and deterioration of composite materials. In the event that the reinforcing wall composite is susceptible to high water absorption, this makes it swells in all areas, and the water molecules permeate through all material parts with adverse effect on the matrix-natural fibres. Therefore, extensive and comprehensive study of natural fibre is necessary in evaluating their compatibility for internal or external construction. It has also been established that water absorption properties of natural fibres are subjected to several operating conditions as shown in external and internal reinforcing wall of matrix materials. These conditions are based on fibre underlying characteristics, i.e., fibre loading and orientation, component of plastic, interaction of fibre–matrix, additive for binding, surfaces and interfaces, void and pore sizes and external factors, pressure and temperature of the surrounding medium [42]. Sustained efforts on the part of researchers have been recorded in the literature which have reduced water absorption capacity of these natural fibres, such as the use of surface modification and treatment of these fibres. Also of interest is the use of additives such as compatibilizer or coupling agent, and the inclusion of nano-particles.

Natural fibres are comparatively of more moisture content and lower strength as against synthetic fibres [52]. Several pre-treatments were developed targeting these drawbacks and the results are far-reaching. Researchers [53] have developed pre-treatments that have improved the compatibility of natural fibre with polymer matrices and improve the chemical and mechanical properties of these materials. The alkali treatment method has been used effectively and it is the least complex and very economical and have served well in enhancement of NFs with epoxy resin. The reagent like coupling agent, NaOH and the alkali treatments have been studied in many literatures [54, 55] with improvements in results. The results showed that NaOH concentration in the proportion of 1, 5, and 10 % were noted in the emerging composites and length of time required to submerge the filaments (0, 24, and 48 h) with conflicting results on the fibre surface morphology. Several workers [56] studied the chemical treatment on sugar and palm fibers. It was noted that there was increase in interfacial properties of treated fibre as against untreated fibre.

Other researchers [53, 57] reported the water absorption of polylactic acid (PLA) composites with 15% and 70% of kenaf core and found an increasing water content in the proportion of 7.5% to 70% filler content. This rise was attributed to the hydrophilicity of kenaf plant, containing core and bast. The contributing factor responsible for high water absorption is a function of high voids and pores between the PLA matrix and kenaf fibre. In another paper, PLA reinforced composites contained about 25% of untreated elephant grass fibres showed a high amount of water absorption as against some composites with 5% to 20%. In some of the experimental works [45, 49] involving alkali-treated grass fibre, it was noted that the water absorption was declined by 6.1%. This result corroborated similar PLA-based composite study where the authors varied the content of the composite with fibre loading of 25%. Part of the findings also indicated that the composite with natural jute fibres continued the highest water absorption in the range of 9.9%, as against that of elephant grass fibres which produced considerably lower content. In another papers [25, 26], the alkali-jute(treated)/ PLA composites showed significant reduction in water absorption in the order of 6.5%, 5.6% and 4.4% for 5%, 10% and 15% NaOH concentrations. As it relates to surface treatment, several papers [58, 59] have also reported some of the effect of coupling agent on the natural fibres. PLA/kenaf composites was treated with the coupling agent (3-glycidoxypropyl trimethoxy silane (GPS) with results indicating continuous reduction in water content of these composite in the range of 1% to 5% as against non-treated composites. It is interesting to have a higher fibre loading in any composite in order to improve the mechanical performances of such composites. For higher fibre contents, it must have been treated in order not to distort the dimensional stability with the increasing water absorption of these composites.

6. Conclusion and future works

The use of natural fibre reinforced composite in building and wall reinforcement has attracted extensive attention in view of their comparative advantage. This review paper comprehensively x-rayed the properties of the natural fibre composite for building. In the paper, we could identify some of the state-of-the-art studies on the water absorption of natural fibre composite including the polymer matrix composites. Several attempts involving the modifications of this fibres to improve water resistance are also discussed. The authors have also established that the introduction of these fibres in form of fibre loading in the resin is capable of increasing the water absorption capacity of the emerging composite. The water content of these fibres is also a function of different other factors depending on the matrices and fibres, incremental fibre loading, addition of additives, treatment of fibre or modification of matrix, and in other climes hybridization. In the light of what was discussed in this paper and other literatures, the following findings are established: (a) water absorption is largely dependent on the fibre loading (b) interfacial chemical treatments and modification of matrix at appropriate concentrations is capable of reducing water absorption, (c) the additives could enhance the binding and interfacial properties of the fibre and resin to reduce the water absorption resistance of composites, and (d) the inclusion of more than two fibres and nanofiller (hybridization) optimally lowered the water absorption. In this paper, several water absorption tendencies were noted for various natural fibres reinforced polymers, but we have also established that the treated or modified composites have strong water resistance than the existing construction materials. In the near future, there is need to focus on the production of green composite with biodegradable polymeric matrix and high loading natural fibre for sustainable building reinforcement. As a precautionary measures, one may recommend further research and investigation to unravel many of the fibre reinforced composites with high water absorption intakes. This remains a great concern in many literatures in order to guarantee their durability and long-term stability for commercial outdoor application. There is also need for detailed analysis on the sustainability of the natural fibre in construction and several other developmental purposes in view of their vulnerability to moisture interaction and changes induced by climatic weather changes.

7. Acknowledgement

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