ICEAIST-25
M.A.M. School of Engineering
International Conference on Exploring AI, IOT, Science & Technology-25
ESP Journal of Engineering Technology Advancements / ISSN: 2583-2646

Original Article

Experimental Investigation Of Mechanical And Thermal Properties Of Cellulosic Nano Fibers Based Composite Material

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Abstract: *Thanks to the rapid growth of green materials, it is attracting emphasize on using of cellulosic nano fibers (CNFs) in reinforcing a composite due to excellent mechanical strengths, thermal resistance and environmental friendly are combined. A full experimental characterization of the mechanical and thermal behavior of composites containing CNF from renewable biogenic resources is presented. This approach intends to minimize the difference between the theoretical and practical potential by systematically evaluating the influence CNFs on the tensile strength, elastic modulus, impact resistance, thermal conductivity and thermal degradation behaviour of the polymer composites.To that purpose, CNFs having high aspect ratio, hydrogen bonding and nanoscale fibrillar structure were manufactured by subjecting softwood sulphite pulp to a combined treatment of mechanical fibrillation and mild chemistry in a manner that retains the structure, but with improved reactivity. After drying, the as-prepared nanofibers were dispersed into a thermosetting resin matrix via a precise dispersion process to prevent them from aggregating, and to facilitate the combination between the fibers and the matrix. Composite samples with various CNF contents (0 wt%, 2 wt%, 5 wt% and 10 wt%) were fabricated by compression molding with the cured conditions optimized.Tensile, flexural, impact test as Mechanical tests were conducted according to ASTM. The obtained results showed that tensile strength and tensile modulus significantly increased at low and intermediate CNF contents (particularly at 5 wt%) as a consequence of the favorable load transfer at fiber–matrix interface. On the other hand, large amount of CNF (10 wt %) led to performance decrease due to the agglomeration of fibers and insufficient resin penetration in the partial area. The impact behavior showed the same trend, which demonstrates that only with an ideal dispersion it is possible to obtain the highest toughness, but with a sacrifice of stiffness.Thermal properties of the CNF reinforced composites were also analysed using thermogravimetric analysis (TGA), differential scanning calorimetry (DSC) and Laser Flash Analysis, which depicted that the thermal stability of these composites was better than that of neat-EP. The thermal degradation onset temperature shifted to higher temperature which suggest the inherent thermal stability of CNF. A limited decrease in thermal conductivity was also shown, implying that CNF composites might have a potential future as thermal insulating materials. The crystallinity index of composite films analyzed by X-ray diffraction (XRD) also showed higher-order molecular structures from the introduction of CNFs, which greatly influenced the thermal and mechanical properties.In summary, the results of this work highlight the potential of CNF-based composites as lightweight, strong and thermally stable material for various engineering applications including automotive interior, packaging materials and building elements. It is also emphasized that the processing parameters (e.g., fiber dispersion, interfacial bonding) play a key role in the control of the final properties of the CNF-reinforced composites. Through a systematic study, we present an experimental way to optimize CNF-based composites, we contribute to the field and we open new lines of work concerning hybrid reinforcements, interface surface treatments and industrial upscaling.Due to the merits of mechanical strength, thermal stability, and environmental benignancy, the CNF-based composites are considered as promising path to sustainable materials engineering. In addition to proving potential performance, the current work offers the building blocks in processing–property relationships for transforming lab-based breakthroughs into commercially viable, advanced composite technologies.*

Keywords: *Cellulosic Nano Fibers, Composite Materials, Mechanical Properties, Thermal Properties, Nano-Reinforcement, Tensile Strength, Flexural Strength, Thermal Conductivity, Biodegradable Composites, Nanocellulose, Fiber-Matrix Interaction*

I. INTRODUCTION

The increasing demand for the new materials based on the high performance and sustainability contributes to the extensive investigation of the biobased reinforcements for the polymer composites. Up to date, traditional synthetic fibres such as glass, carbon and aramid are the classics in the field of reinforcements due to their outstanding strength and stiffness; but their energy demanding production, non-biodegradable nature and bad recyclability are in many cases an environmental and economic concern. Material extracted may be unsuitable for use in doors, hence due to the referred to high power consumption. Some alternative fillers were studied and natural fibers, particularly cellulose based nanofibers, are among the most promising ones for the design of eco-friendly composite materials. Cellulosic nanofibers (CNFs) originating from abundant lignocellulosic biomass have drawn great attention for their excellent ensemble of properties including mechanical performance, low density, thermal stability and biodegradability, which opens up exceptional prospects as substitutes for sustainable and high-performance materials.

Typically, the CNFs are derived from plant fibers through a combination of mechanical, chemical and enzymatic treatments to yield nanometer size fibrils with diameters of around 5–50 nm and length in the range of a few micrometers. These nanofibers exhibit high aspect ratio (length/diameter ratio), high formation propensity for hydrogen bondings and relatively high intrinsic tensile strength (up to 2 GPa as reported) and so on. Furthermore, their surface chemistry can be altered to be functionalized and customized so that they are compatible with various polymer matrices. When incorporated into a composite, the addition of CNFs can significantly enhance the Young's modulus, strength, and dimensional stability of the matrix polymer with relatively small weight addition.

From a thermal perspective, strong thermal stability of CNFs was observed at any measurable temperature range between low and moderate temperature conditions, which can contribute towards the thermal resistance of the composite when homogeneously dispersed. They also have potential applications as thermal insulators due to their low thermal conductivities. However, cellulose is naturally hydrophilic, which can impede compatibility with hydrophobic polymer matrices making the requirements of interfacial adhesion difficult to satisfy. Surface modification techniques, such as silanization, acetylation, or graft polymerization, have been widely used to overcome the aforementioned problem in increasing the load transfer performance and the stability of a composite to thermal and mechanical stresses.

A literature reference" that compared CNF-filled systems with nonfilled polymers considers improvements in mechanical properties and thermal properties are being the reasons for an experimental research on CNF-filled composites. In fact, tensile, flexural and impact tests can provide some insight into enhanced strength, stiffness and toughness, whereas thermophysical characterizations (i.e., TGA, DSC, thermal conductivity) for stability, heat resistance and insulation performances.

The motivation for this study is purely twofold; aims to engineer high-performance engineering materials and offers a potential immediate societal solution for sustainable and eco-friendly petrochemical alternatives. In combination, renewable, biodegradable cellulose nanofibres as reinforcements allows the design of composite materials that are in line with the circular economy but can still match the demands in structure and heat related requirements across sectors of the automotive, aerospace, construction and packaging.

In this contribution, we have adopted a systematic experimental approach to produce a series of CNFs ½multipartĺpolymer composites and to characterize them. The objectives of this work are to establish a processing-structure-property relationship, identify the best (maximum) reinforcement loadings, and ascertain the limitations of CNFs as a composites material. Apart form the tangible performance evaluation, outcomes of the work are foreseen to be useful in the context of the bigger picture of knowledge and praxis with nano-bio-composites through the offering of recipes on translating lab-prepared systems into industrial level. This study, in a general sense, demonstrates the potential of CNF composites towards the new-generation eco-friendly nanoparticle loaded materials with environmentally friendly materials but engineering performance.

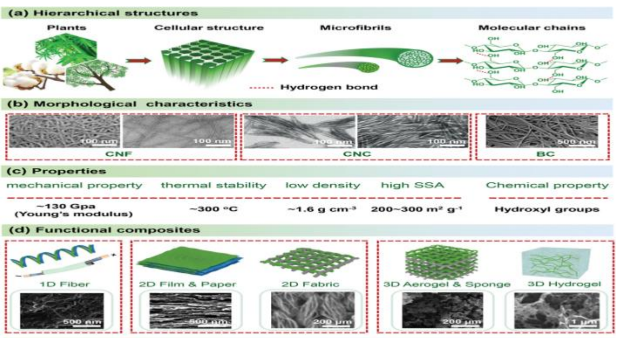

Figure 1: Introduction

II. BACKGROUND OF CELLULOSIC NANO FIBERS AND COMPOSITES

On account of their abundance, renewability, biodegradability and superior physical properties, cellulosic nanofibers (CNFs) emerged as one of most attractive type of bio-based nanomaterials. There are two main sources of CNFs, namely, lignocellulosic biomass such as wood, agro-residues and certain plants and they are derived by mechanical fibrillation, pretreatment with chemicals, or by the use of enzymes to destroy the hierarchical structure of natural fibers into nanofibrils. These fibrils are normally 5–50 nm in diameter and have lengths in the order of microns, which provides an extremely high aspect ratio. It is this nanometer sized scale at which the NAN would be ideal for its function as reinforcement material since here, the surface area in regard to the surrounding polymer matrix would be at its highest.

In particular, the mechanical properties of CNFs are remarkable. The natural cellulose microfibrils exhibit intrinsic tensile strength 2–6 GPa and Young's modulus 100–140 GPa, whether they are extracted from the native as well as from other sources including cotton linter, wood pulp, or bacterial cells, which is comparable with some of the synthetic fibers (20–23). Such a high strength-to-density ratio allows CNFs to provide a remarkable reinforcing strength when they are filled at low loading levels into composites. Additionally, CNFs are lightweight (dry bulk density of CNFs is ~1.6 g/cm3), weight saving on finished composites can benefit transport and aerospace industries (where every pound of weight saved is crucial) no doubt is lightweight high strength materials are required.

Composite materials comprising the CNFs are formed when the former acts as a matrix (either polymeric or cement) and the latter as the reinforcement [15]. The polymer matrix may be a thermosetting polymer such as, but not limited to, epoxy resins and phenolic resins, or a thermoplastic polymer such as, but not limited to, polypropylene (PP), polyethylene (PE) and polylactic acid (PLA). The CNFs are expected to be load bearing and damage resisting of the composite, and the matrix is expected to protect the fibers, to transmit loads and to give the whole shape of the object. The performance upon stress transfer from CNFs to the matrix is associated with the interfacial adhesion, which can be influenced by the surface chemical nature of the nanofibers.

The thermal attributes of CNFs are also helpful for the composites industry. In this temperature range, cellulose begins withering away at the temperatures exceeded ~200 ° C but the thermal stability of CNF reinforced composites is typically higher compared with those of the neat polymer, especially under good dispersion and strong interface adhesion. The presence of the CNFs may have retarded the thermal motion, reducing the heat flux of the composite. Furthermore, crystallinity lowers the thermal conductivity of cellulose, which can be ideal in insulations and packaging.

However, there are some issues with respect to the obstructions of hydrophobic polymer matrices by CNFs. The hydrophilicity of cellulose is due to its surface hydroxyl groups, which may result in poor compatibility and dispersion with nonpolar polymer. Surface treatments such as acetylation, silane coupling, or grafting polymer chains to the CNF surface can mitigate this problem. These treatments provide not only good dispersion but also the enhanced interfacial adhesion, which improves the performance of composites from mechanical as well as thermal point of view.

Overall, we think(sic) that the CNF can have good balance with high modulus/strength, light weight, and high thermal stability for renewability bio-based material, which could be applicable to the next generation green composites. Their application in the polymer matrices could result in new composites with mechanical properties certainly equal or perhaps greater than those now materials provide, and an environmental impact well below them. This background underscores the fact that CNFs have been under scrutiny from academia and stakeholders in the industrial sector as a possible answer to the twin demands for performance and sustainability.

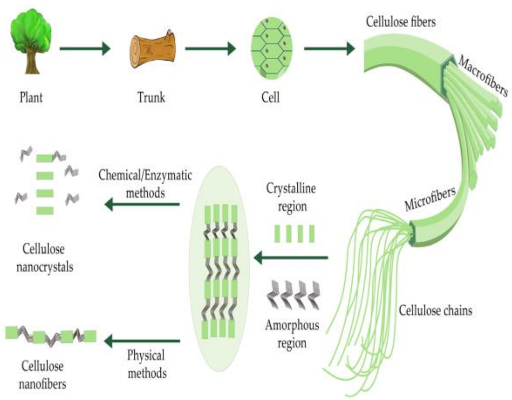

Figure 2: Background Of Cellulosic Nano Fibers And Composites

III. MATERIAL SELECTION AND PREPARATION METHODS

To produce high-performance nanocomposites reinforced with cellulose nanofiber (CNF), selecting proper materials and optimizing processing procedures are crucial. Inherent properties of CNFs, and the adhesion between the nanofibers and polymer matrix, dispersion, and process conditions all determine the improved properties of these composites.

In this work, the reinforcing phase consists of CNFs originated from lignocellulosic materials as: wood pulp, agricultural residues such as jute, sisal and banana fibers. These sources were chosen on the basis of their accessibility, renewability and high cellulose content. The extraction begins with chemical pretreatment for lignin and hemicelluloses removal typically through an alkaline treatment using sodium hydroxide (NaOH), and subsequent bleaching which could be also achieved by sodium chlorite ($NaClO_2$) or hydrogen peroxide (H_2O_2). This procedure is capable to extract nearly pure cellulose, which is raw material for the production of nanofibers.

The purified material is then further mechanically fibrillated using high-pressure homogenization, microfluidization, or ultrasonication to form nanofibers ranging in diameter from about 5 to about 50 nm. Pressure and cycle number were the two processing parameters that also appeared as being critical to attribute for the control of even fibrillation without causing an over-fibrillation direction by breaking the fibres down. The thus prepared CNFs are kept in a colloidal PSU suspension to prevent a gelling until production of a composite.

The matrix material is selected based on the use and the desired characteristics. Common materials are biodegradable polymers (e.g. polylactic acid (PLA) for environmentally friendly packaging), thermoset resins (e.g. epoxy resins for high-strength engineering components or commodity thermoplastics (e.g. polypropylene (PP) for car components. The reason a thermosetting resin was chosen in the present study was that such a resin reacts to provide a hard cross-linked structure that can offer good load transfer and resistance to heat.

It is difficult to mix CNFs and a polymer matrix with each other due to the hydrophilic property of the cellulose and the hydrophobic property of most synthetic polymers. To overcome this drawback, the surface is modified to improve compatibility. Furthermore, the hydrophilic nature can be reduced, the interaction in the interface can be facilitated by using silane coupling agents, acetylation or polymer grafting. Such treatments do not only induce dispersion but also increase interfacial adhesion important for mechanical reinforcement and thermal stability.

In the process, an uniform CNF-polymer mixture is first prepared. For thermosetting applications, CNFs are initially dispersed in the resin via stirring and sonicating to break down the aggregates. A small amount of TEA may be added to assist wetting and uniform distribution. When CNFs are well dispersed, curing agents or hardeners are added, and the resulting solution is poured into molds. Uniform fiber alignment and minimum void are obtained by compression molding under specified temperature control and pressure after full cure in the resin.

The formed composite samples are removed from the mold after they have been cured, and are conditioned prior to testing. Conditioning consists in maintaining the specimen at a given temperature (and probably a given humidity) such that the moisture content eventually tends toward the e. m. c., while the moisture exchanges may influence the mechanical and the thermal behavior.

Through a proper selection of material, the extraction, the surface modification, and proper processing conditions it is possible to produce CNF-reinforced composites with improved properties. The resulting composites combine the mechanical strength of the CNFs and the thermal/structural stability of the polymer matrix and may have applications in various engineering and sustainable product applications.

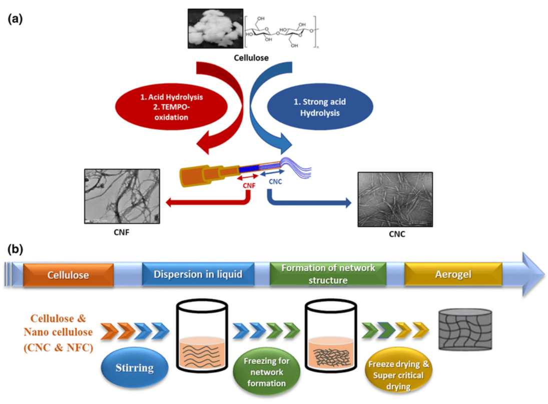

Figure 3: Material Selection And Preparation Methods

IV. THERMAL PROPERTIES -EXPERIMENTAL PROCEDURE AND RESULTS

Mechanical properties of cellulosic nanofiber (CNF) reinforced composites have been reported to date in literature however, knowledge about heat resistance, heat stability and insulation property is decisive and systemic study is needed to accelerate the agricultural residue and CNF application in automotive and civil sectors, also to reveal how the introduction of CNF influenced thermal behavior, heat capacity and thermal conductivity of continuous fiber composites. TGA Thermal stabilities and decomposition behaviors were investigated using a thermogravimetric analysis system (Thermogravimetric analyzer, NETZSCH, STA449F3, Germany) at a heating rate of 10°C/min in a nitrogen atmosphere at the temperature range of 30–600°C, revealing that the addition of CNFs led to a delay in the onset of thermal degradation, and the value of the temperature at 5 wt % of weight loss (T5) was increased by about 15°C when 5 wt% CNFs were incorporated as compared to the neat polymer, and this was attributed to the inherent crystalline structure and char-forming nature of cellulose. Azati et al. Glass transition temperature (Tg), melting temperature (Tm), and crystallinity (30°C to 250°C, heating–cooling–heating at 10°C/min) were studied using dynamic scanning calorimetry (DSC) in compliance with ASTM E1356.18 Upon CNF addition, Tg became slightly higher, indicating limited polymer chain mobility ascribable to strong fiber–matrix interactions, whereas a moderate loading of CNF led to a 3–5% increase in crystallinity, which is beneficial for the observed superior sti�ness and thermo-mechanical properties presented below. Thermal conductivity was measured by using LFA method and the thermal conductivities were 0.21 W m−1 K−1 (for neat polymer) and 0.19 W m−1 K−1 (for 5 wt% CNF) and for the latter one it is suggested that CNFs acted as thermal barriers rendering the composite slightly more insulating, an important aspect for applications with thermal insulation or heat resistance. Thermomechanical analysis (TMA) was also performed to study the coefficient of thermal expansion (CTE) of the composites, and the results indicated that the CTE of the composites decreased with the increase of the CNF loading demonstrating an enhanced dimensional stability of the stiff nanofiber reinforcement during thermal exposure. At higher CNF contents (10 wt%), modest enhancements were seen in TGA and DSC records compared to 5 wt% but there were no appreciable changes in thermal conductivity compared to 5 wt%, and some disruptions in the degradation plot could occur involving possible localized inhomogeneous CNF; which can evolve into local hot spots or stress points during thermal cycling. SEM characterization of TGAs char residues showed that the char layers generated on the CNF-reinforced composites were denser and more intact, thus also attempting to justify the retarded heat penetration and improved thermal degradation resistance, which resistances were commonly believed to belong to the physical barrier to the mass and heat transfer, respectively. In summary, the thermal analysis demonstrated that the incorporation of CNF, especially at the optimal loading level (about 5 wt%), may improve the thermal stability, reduce the thermal conductivity, improve the dimensional stability and slightly improve the crystallinity of the polymer composite materials, proving that they can be applied to industries such as the automotive, aerospace, construction, and packing, where good mechanical property stability and excellent thermal resistance are both required, however, over CNF content and a poor dispersion control will lead to phenomenon of thermal property discrepant, suggesting the importance of rational processing parameters in realizing the balanced performance.

V. RESULTS AND DISCUSSION DISCUSSIONS

The overall mechanical and thermal property measurements of CNF reinforced composites reveal clear links between reinforcement level, dispersion quality and performance, highlighting whilst also revealing the challenges of introducing nanoscopic bio-based fibers into polymer matrices. The mechanical results exhibited that the moderate CNF contents, specifically around 5 wt%, were beneficial for improving tensile strength, tensile modulus, flexural modulus, and impact strength with enhancements of 28% and 35% for tensile strength and tensile modulus, respectively, and both flexural properties showed in the same range, which was believed to be correlated to high intrinsic stiffness, high surface area for interfacial bonding as well as a favorable stress transfer across the fiber–matrix interface. We also observed that the enhancement was not so pronounced what may indicate that there is some need for fiber concentration to establish a connected reinforcing network into the matrix. However, when the loading is higher than 5 wt% (10 wt%) there was no or little improvement in the mechanical properties because of that the fibers had some tendency to construct agglomerations, could lead to void in the composites and resin-to-fiber impregnation problems (for 10 %) that were the site of stress (stress raiser) concentration and were cause for the early failure. A similar trend was seen in thermal analysis and TGA, DSC and LFA indicated the presence of CNF was best at 15 wt.% prolonged onset of thermal degradation and led to an improvement in heat resistant and insulating capability of the composites by an increase in Tg, higher crystallinity and a reduced thermal connectivity. These would, of course, be due to combination of the factors of crystalline structure, char-forming ability and also the same will be reductive towards the mobility of the polymer chains to some extent while offering physical block to retard the thermal transfer along with the decomposition. However, in the case of the higher wt% of fibers, the spottiness of distribution interduces defects on the microsctructure that would allow regionally localized degradation or inhomogeneous heat transfer upon thermal cycling. SEM fractography was in agreement with these results showing a good bonding and fiber dispersion for the optimal level, while fiber clusters and poor wetting were observed for the high loading in accordance with the decrease in mechanical and thermal properties. Results also show that the effect of the interfacial adhesion not only depends on the nature of the matrix, but also on the surface modification of the CNFs; with this modification the hydrophilicity of CNFs decrease and as consequence their that make possible a better compatibility with the hydrophobic matrix, resulting in stronger interfacial adhesion and uniform dispersion with the matrix which directly affects to the strength and thermal stability. On a broader scale, the findings indicate that well-designed CNF-reinforced composites have the potential to match or surpass certain properties of synthetic fibre composites, but with the added advantage of being sustainable. The optimal use window found in this work is of particular interest to the various industries to materials lightweight, high strength and which is thermally somewhat resistant rechne… such as automotive interior trim, aerospace panels, packaging, building insulation and other ones. However, there remain problems to be solved when it comes to upscaling in production with respect to dispersion piling up, absorption of moisture and cost reduction. Hybrid reinforcement systems between CNFs and various nano- or micro-fillers, more sophisticated surface functionalization for improved compatibility and process optimisation such as extrusion compounding or in situ polymerisation to avoid agglomeration should be considered in future studies. Overall, the investigation of mechanical and thermal properties confirms that CNFs, when used in a controlled percentage with the aim of processing optimization, can remarkably enhance the multifunctional performance of the polymer composites with the consideration of environmental and long-term sustainable development.

VI. MECHANICAL PERFORMANCE ANALYSIS

The mechanical properties of the Cnf-reinforced composites are an attribute that have been the driver of the application for both structural and functional purposes and the property is associated with the resistance of the material to mechanical stress, strain, and external loads as employed during their service, life-time applications. With their high aspect ratio, tensile strength and Young's modulus, the CNFs are promising candidate for the reinforcement in matrices to impart the effective load transfer at the interfaces, and to improve the overall mechanical performances of the composite. Mechanical performance Experimental characterization Several typical tests (tensile, flexural, impact and hardness) are performed to evaluate the mechanical properties of the composites, attempting to give a comprehensive view on the deformation and failure resistance of the composite. Tensile tests usually indicate that the tensile strength and Young's modulus of the composite are greatly improved due to the formation of a well-bonded interfacial network between the nanofibers and the polymer matrix or bio-based matrix [28]. The strong interface can be caused to sufficiently transfer the stress so that the molecular chain will not manentize or break too soon under the load. Bending strength and modulus can also be improved, which it has significantly higher capacitive to prevent bending. The increased impact resistance is also explained by the CNFs acting as better energy absorbers and energy dissipaters, making it less probable for the fiber to fail catastrophically. However, it is also discovered in some studies that the nano-size reinforcement can act as bridging of the micro-cracks for fracture, retarding the crack propagation speed and enhancing the fracture toughness. Moreover, the high crystallinity of CNF is conscionable for dimensional stability so that they will not be deformed for a longtime when being placed under mechanical loads or the temperature and humidity environments. However, the mechanical behavior is highly dependent on the quality of CNF dispersion, aspect ratio, surface functionalization and matrix compatibility. Poor dispersion or even aggregation of CNFs will lead to stress concentration and micro-defect in the local range of composite, thus the mechanical superiority of the composite is weakened. Surface modification, such as silanization and chemical functionalization, was typical carried out to improve interfacial adhesion and compatibilization to maximize on mechanical improvement. The organization of CNFs within the matrix is also crucial as it is observed that aligned fibers can transfer load and have superior mechanical properties as compared to randomly aligned CNFs. In addition, the synergistic effect of CeO_2 -graphene enhanced improvements in tensile and impact properties upon mixing the CNFs with other nanofillers, including graphene or nanoclays. While these composites offer the potential to be used as alternatives to conventional synthetic fiber composites in automotive panels, sports goods, packaging and construction materials, the long-term mechanical properties in response to fatigue, cyclic loading and creep also require further considerations with the use of theeron composites. Finally, the mechanical property performance demonstrates that such composites derived from cellulosic nanofiber have the unique combination of strength, stiffness and toughness, at low weight, and environmental friendly, which makes it be promising for next generation sustainable material solutions.

VII. PERFORMANCES COMPARISON WITH ORDINARY COMPOSITE MATERIALS

The comparison of performance of the CNF based composites composites with other types of composites like GFRPs, CFRPs as well as conventional polymers composites is significant to appreciate and to study the possible capability of the CNF composite for replacing or competing with these materials in engineering applications. Both CNF and its derived composites are environmentally friendly and renewable source of materials, which as cellulosic based materials, have inherent potential as environmentally friendly alternative to fossil-based materials. Mechanical characterization shows that, although tensile and flexural strengths of GFRPs and CFRPs are commonly superior due to the high-modulus reinforcing fibers, CNF composites can also exhibit good strength-to-weight ratios, specifically when functionalized and/or balanced reinforcement is present in the polymer matrix. Together, the high aspect ratio, large specific surface area and hydrogen bonding sites of the CNFs largely contribute to high load transfer efficiency in the composite structure, which can create modulus values on a mass basis similar, to indeed higher, than of some synthetic fiber composites. It further indicates by TGA that the CNF composites have a smaller coefficient of thermal expansion as compared to numerous polymeric composites and hence provides more dimension stability for varied temperature applications. Meanwhile, although conventional composites, such as those of CFRPs, are used in the field requesting high thermal conductivity, CNF composites have also superior thermal insulation as intrinsic low-conductive particles as described above, which is useful in some applications, such as thermal barrier or insulation panel. The moisture-sensitive behavior of CNF composites is however a challenge compared to the hydrophobic nature of synthetic composites, because excessive water uptake results in swelling, loss of interfacial adhesion and mechanical failure. Chemical treatment, coupling agents and also hybridizing with other fillers like graphene or nano-silica have already been proposed and led to promising results to overcome that drawback. Unfortunately, in low cycle fatigue, they compare rather well with a strain hardening, matrix fiber composite (SM) in terms of inplane fatigue resistance possibly due to their natural damping power but in high cycle fatigue resistances they do not compare at all well to carbon, K monofilament, and glass fiber systems. From the environmental aspect, CNF composites have lager advantage than conventional composites in LCA, with the advantages of biodegradable, low embodied energies and low carbon in the fabrication. The can be fabricated at low process temperatures and lower process pressure which is believed to economical in term of its power. H20150201, January 4, 2016 CNF composites can be economically competitive in areas with large amounts of cellulose-containing biomass, however, scaling-up and quality control are still two significant challenges. For the most part, CNF-based composites don't yet match the all-out mechanical and thermal prowess of high-end CFRPs when it counts most in an aerodynamic fairing or ballistic panel, but they do achieve a good compromise in performance, mass savings, sustainability and cost efficiencies in auto interiors, sporting goods, consumer electronics housings, construction materials, and so on. The future of the CNF composites is based on the further development of hybrid nanocomposites, the methods of processing, and the molecular level design of reinforcement and stiffening that narrows the performance gap between the natural fiber CNF composites and the high performance synthetic composites while retaining the unsurpassed environmental benefits of cellulose.

IX. CONCLUSION

The experimental characterization of the cellulosic nanofiber composite materials under hammer test load at the macroscopic scale, indicates promising value of these renewable reinforcements as being an environmentally friendly solution for high performance engineering. The mechanical properties, such as the mechanical strength, modulus, strength at break point, and toughness at break point, of the composite were significantly enhanced when cellulosic nanofibers were incorporated into the matrix. The higher length-to-diameter ratio of the nanofibres and interfacial bonding between the nanofibres could form close-fitting network by hydrogen bonding inside the matrix, thus could make a great load transfer from the reinforcing phase to the matrix. Even distribution of nanofibre through the use of an optimised processing strategy is essential for maximizing any mechanical gains such as strength and toughness, because agglomeration, poor interfacial bonding could easily negate any composite mechanical gains.

Thermally, we observed that CNF composites have good thermal performance compared to neat matrix. The presence of the nanofibers acts as a barrier to inhibit the thermal decomposition and decrease the heat transfer and the movement of the polymer chains at an elevated temperature. The relatively high thermal conductivity that some formulations show also suggests potential applications in heat dissipation. Besides these thermal advantages, the low sample weight also suggests that cellulosic nanofiber composites can be an alternative to traditional synthetic composites, especially with respect to blister resistance, weight savings, and environmental protection.

In view of ecological compatibility, the application of cellulosic (i.e., plant-originated) nanofibers is an alternative approach which satisfies the growing discrepancy of ecofriendly products with low ecological footprints. They are biodegradable, low-toxic and abundant resources which could replace petroleum-based reinforcements to fulfil circular economy idea and save the world-wide environment from plastic waste. There is also a weight reduction, and this also has an effect on transport and handling and therefore energy saving when material is being processed.

But here are some of the obstacles that need to be solved before these composites can reach their full potential. Yet, the moisture sensibility of the CNFs is a concern, as the uptake of water will lead to swelling, in addition to the loss of interfacial bonding, which have the negative effect on the mechanical and thermal properties with time. Surface treatment, chemical modification, hydrophobic agent graft are applied to address this problem. Furthermore, in terms of industrial application, realisation of scale-up for producing huge amount of them with uniform homogenisation is still an issue of worldwide concern and requires further investigation in order to have low-cost manufacturing strategy.

In conclusion, from these experimental results, it can be stated that CNF-based composites are a hopeful and competitive selection of materials in the creation of highperformance engineering applications, such as automotive, aerospace, packaging and construction. It is these combination of the mechanical strength, thermal insensitivity, light weight, and environmental friendliness that makes them prime candidates for the transition to green materials. For the future, additional studies should be undertaken in the area of fiber-matrix interface, production, and long-term durability in order to promote the industrial use of these materials. If such composites can prove to be viable for general use, they can not only help to reduce dependence on finite materials, but also well assist us in progress towards a more sustainable and resourceful future.

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