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Fabrication of Reinforced Oil Palm Trunk Fibers with Rubber and Plastic Resin using Industrial Manufacturing Techniques for Prosthetic Applications

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ABSTRACT : *This paper focuses on applying nano-cellulose structured material for the development of a novel prosthetics limbs. In this research, Oil Palm Trunk fibers was used as the main source of nano-structured cellulose raw material. The material was fabricated using extrusion molding whereby fibers and other ingredients were combined to fabricate the composite. Mechanical properties of the new material such as compression and tensile tests were performed to ascertain the suitability of the material's performance to be used in prosthetics. From the study, it was found that oil palm trunk fiber has a great potential to be used in the application of prosthetics. High performance composite resulted when undergoing compressive forces and with proper additives and supplementary material. A combination of oil palm trunk fibers along with elastomers, additives and Thermasite's resin suits the prosthetic applications. The project has demonstrated the possibility of developing a new prosthetic applications material using nanocellulose structured material using industrial manufacturing techniques.*

KEYWORDS - *Extrusion, Industrial manufacturing techniques, Oil Palm Trunk fibres, Prosthetics limbs, Tensile*

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I. INTRODUCTION

There are many humanitarian foundations and efforts around the world, that can donate prosthetics to areas of need. However, due to extremely high costs of the current western designs and artificial limbs, the numbers of donations are quite small. This has led to people living in areas not represented by the foundations or poorer communities are forced to resort to crude imitations made from wood or bamboo. These make-do artificial limbs are constructed without regard to comfort or safety standards. Some even go on with their lives without these prosthetics and suffer from restrictive living conditions due to the absence of certain limbs. The lower-limb prosthesis has come a long way from the days of primitive wooden peg legs to present day electronically controlled prostheses. This is evident in new approaches in prosthetic sockets design, modern prosthetic knee mechanisms, more functional prosthetic feet, and advanced manufacturing techniques. As well as an increase in patients' expectations, more and more requirements are placed on the prosthesis, above all on its functionality, reliability, and safety. The current favourite for modern day artificial limbs and prosthetics would be metallic materials, such as titanium, stainless steel, magnesium, Co-Cr alloys, because they have excellent tensile strength, fracture toughness and fatigue stability and reliable mechanical strength, with minimal long-term toxicity to the host locally as it is biologically inert to the human body. Titanium is often the material of choice due to a favourable combination of biocompatibility, corrosion resistance compared to conventional steel and Co-Cr alloys [1].

With all the advantages of using metallic materials, they also come with disadvantages. One of which is the extremely high costs of these materials. Titanium, Co-Cr alloys, magnesium and stainless steel are very expensive and not abundantly available, which makes it harder for poorer communities and amputees to obtain properly functional prosthetics. This has led these communities to result to homemade prosthetics which cause even more damage to their bodies and some even live without prosthetics and suffer terrible living conditions. Next, studies have shown that alloys in the body is associated with an increased risk of development of cutaneous and systemic hypersensitivity reactions due to accumulated metallic toxicity [2]. Besides that, due to relatively high modulus of these metals compared to natural bone tissue, leads to stress shielding and consequent osteopenia which further degrades the living quality of amputees [3]. The objective of any design, therefore, is to match these stiffness characteristics as closely as possible [4]. The tensile strength should not be much higher than that of a bone to prevent stress shielding of the bone which leads bone decay (osteopenia). Nanofibers are interesting reinforcements but are often very costly. Wood cellulose nanofibers have the potential to be widely used due to the low cost associated with recently introduced economical disintegration procedures. Stelte & Sanadi (2009) first described nano fibrillated cellulose from wood pulp. Wood fibers cooked in a chemical solution to yield a high cellulose content were used as starting materials [5]. Nakagaito and Yano (2008) used such nanofibers in composites [6]. Nanocomposites based on wood cellulose nanofiber networks show high strength, high work- of-fracture, low moisture adsorption, low thermal expansion, high thermal stability, high thermal conductivity, high optical transparency, and also exceptional barrier properties [7].

In another research done, high-quality cellulose nanofibers can now be obtained from wood pulp fiber at low cost. The term nano fibrillated cellulose (NFC) is used. These nanofibers have high length/diameter ratios, diameters in the 5–40 nm range, and intrinsically favourable physical properties (i.e. a cellulose crystal modulus of 134 GPa) due to the highly ordered extended chain conformation of cellulose [8]. Suitable organic materials for the development of nanocellulose fibre should be selected from wood pulp, cotton, flax, tire rubber, pineapple husk, rice husk and similar materials. This would keep costs down, recycle waste, and contain naturally occurring cellulose fibres within them. Natural fibers can easily compete with glass in terms of stiffness, especially on a weight basis. However, tensile strength, compressive strength, and especially the impact strength of NFCs are relatively low. Oil palm biomass can be converted to a wide range of value-added products that can be clustered into bio-based chemical, nanomaterial, biofuel. Abundantly available in Malaysia. Only 10% of the oil palm plant is economically valuable, used to produce oil, whereas the remaining 90% is constituted of oil palm trunk (OPT), oil palm fronds (OPF), empty fruit bunches [9]. Main chemical compositions of the hemp fibers used are determined, on average consisting of 72% celluloses, 19% hemicelluloses, 5% lignin, and others. The average tensile strength of hemp fibers used is 886 MPa and modulus 66 GPa [10]. The use of agricultural residues pulp fibers, as a replacement for hazardous asbestos fibers, glass fibers, in cement and concrete composites have found many practical applications, mainly in developing countries that require low-cost construction materials. This crystalline structure results in a high Young's modulus, reported to be 114 GPa with a theoretical Young's modulus being as high as 60 GPa with a tensile strength of 200 MPa [11].

Thus, this study aims to develop a new material from an organic source that is widely abundant, cost efficient, chemically, and biologically inert or friendly and with variable and easily tweaked mechanical properties for the application of prosthetics.

II. EXPERIMENTAL

The natural fiber used in this study is oil palm trunk fibers (OPT) and ground tire rubber (GTR). The resin used to bind the composition will add strength to the composite form. The novelty of this study is the combination of a nano-cellulose material and rubber with a plastic resin for composite fabrication due to homogenous dispersion and distribution of fibers during fabrication process. These materials are widely abundant in Malaysia, hence its cost effective. They have lower tensile strength compared to current material being used which is titanium. The materials used are an organic non-reactive material. The overall fabrication process is done in two stages as shown in the Fig 1 below.

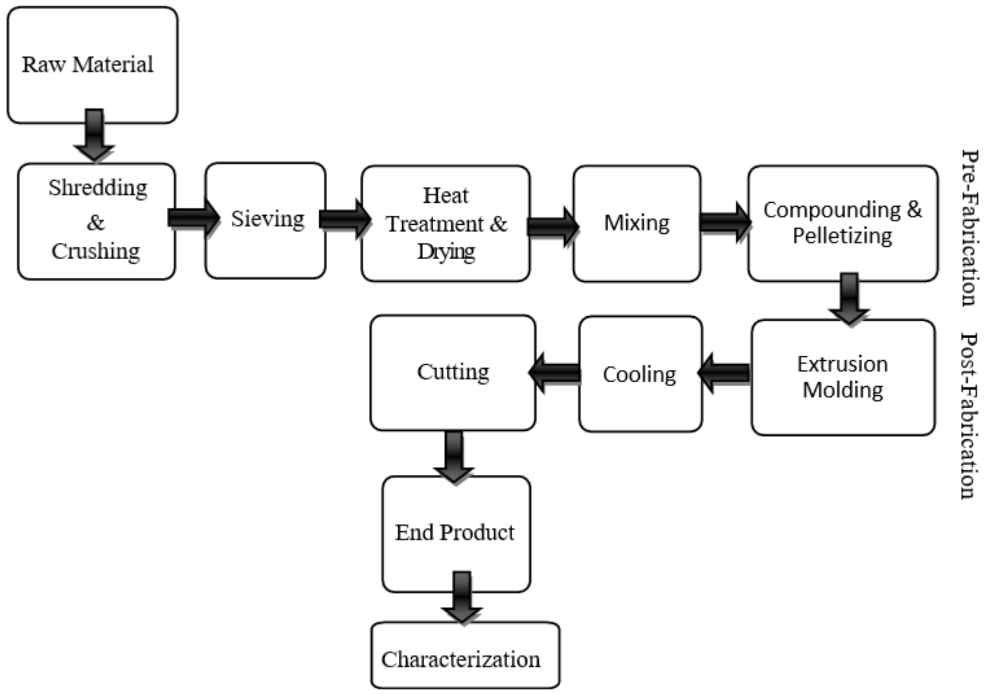


Fig 1 Overall Fabrication Process Flow

The first step in the fabrication process is to prepare the raw material, Oil Palm Trunk, which arrives in sawn log form, into a workable medium. To convert the material into this medium, it is first put into a crusher which breaks the logs into smaller chunks and then into a shredder which further reduces the size of the material and into fibre strands and later into a powder form. The roughly shredded fibres are then put into an industrial sieve that uses high frequency vibration along with varying mesh sieve sizes to segregate the powder into a course powder and fine powder, both of which will be used in the formulations for fabrication. The powders of different coarseness are separately loaded into heating & drying chamber to kill any present microorganisms and a weak alkaline treatment is then added to remove lignin which is present in organic cellulose materials. This is then followed by drying which is carried out at low temperatures over a duration of over 24 hours to remove any moisture content to prevent weaknesses or expansion and/or contractions in the finished product. A lower and constant temperature is chosen to prevent any alterations in the nano structure of the cellulose material. In the mixing stage, the oil palm trunk fibres in powder form is mixed with Thermasite's proprietary resin which arrives in pellet form and is comprised of recycled HDPE plastics, binders and wax. Ground tire rubber is also added for certain formulations. The mixing drum ensures an even spread of each component in the mixture and prepares it for compounding. Compounding extrusion is a process that mixes one or more polymers with additives. The feeds may be pellets, powder and/or liquids. In compounding, various materials are mixed and melted, generally in an extruder of some type and then pelletized. This pelletized material is subsequently processed into a finished or semi-finished part by either moulding or extrusion. In the second stage, the plastic extrusion molding process usually begins with a thermoplastic in the form of pellets or granules. They are usually stored in a hopper before they are delivered to a heated barrel. The molten plastic is then forced through a shaped orifice, usually a custom steel die with shape of the cross section of the intended part, forming a tube-like or continuous workpiece. Extrusion molding maintains a constant cross-section. A Counter-rotating twin-screw extruder is used in this process because they excel in applications where heat sensitive polymers and low temperature extrusion for fibers and foams. The counter rotating twin screw can either have parallel or conical screw configuration. The fibre and polymer are in the same polymer size, usually 40 mesh pellets obtained from the compounding stage. Advantages of counter-rotating twin screw extrusion include its low screw rpm and low shear mixing and it is a proven technology. Disadvantages include that a drying system is required, a size reduction system for fed materials may be necessary, a pre-blending system is required, which is all true and present in this project's case. The composite is extruded at a temperature of 170°C-200°C through a flat plate die. The inclusion of wax is necessary for the smooth flow of the composite through the die. The condition of the die is paramount to the surface of the finished product and ensures it is free of surface defects and scratches. The speed of extrusion which is about 8 meters/hour is, carefully calculated and monitored to ensure the extruded component is properly and evenly formed. Factors such as, material, screw size and barrel size affect the speed of extrusion. The extrudate is immediately cooled from 170°C-200°C to 50°C-60°C. This process is done using water as the coolant and is continuous to ensure an even cooling of the product. This helps reduce the likelihood of weak spots and defects. Every extruded shape must be cooled to a temperature at which it will solidify and maintain its desired dimensions. The final stage, cutting, is performed by cutting the finished product which currently is still in continuous flat plate form into desired lengths. This is all pre-programmed into the machine's computer. From these cut plates, desired shapes for specimen testing can be later hand cut and shaped.

Fig 2 Shredding & Crushing

Fig 3 Sieving

Fig 4 Heat Treating and Drying

Fig 5 Mixing

Fig 6 Compounding and Palletizing

Fig 7 Industrial Scale Extrusion Moulding

Fig 8 Cooling and Cutting

A total of 3 different compositions were made to fabricate 3 different materials which were tested via **tensile** and **compression** stress tests. These materials consisted of course oil palm trunk (OPT) fibres, fine oil palm trunk (OPT) fibres, resin which consisted of recycled plastic and bonding agents (proprietary to Thermasite), and wax to aid in the extrusion process. The compositions are as follows;

Table 1 Material Composition

Specimen	OPT Fine	OPT Course	Thermasite Resin	Rubber	Wax
001	66%	3%	33%	-	1%
002	33%	33%	33%	-	1%
003	39%	15%	33%	10%	1%

Table 1 shows that Specimen 001 and 002 consists of Oil Palm Trunk fibres in varying grains while Specimen 003 has the inclusion of recycled tyre rubber. Rubber was added with the intention of further strengthening the material while providing more elasticity. Each formulation was carefully calculated and discussed with Thermasite Sdn Bhd to ensure that the extrusion process would be smooth and maintained a one third proportion of their proprietary resin which consists of recycled plastics in the form of HDPE pellets.

Upon the completion of the fabrication process, the materials will be subjected to two tests, namely, compression testing and tensile testing to characterise its mechanical characteristics and ability to handle loads. Compression testing is used to determine how a product or material reacts when it is compressed, squashed, crushed or flattened by measuring fundamental parameters that determine the specimen behaviour under a compressive load. Besides that, it also assesses the strength of components and characterises the compressive properties of material. Compression tests were conducted two times as per the ASTM D695 code for compression testing method for rigid plastics. Tensile tests are used to determine how materials will behave under tension load. In a simple tensile test, a sample is typically pulled to its breaking point to determine the ultimate tensile strength of the material. The amount of force (F) applied to the sample and the elongation (ΔL) of the sample are measured throughout the test. Material properties are often expressed in terms of stress (force per unit area, σ) and strain (percent change in length, ε). To obtain stress, the force measurements are divided by the sample's cross-sectional area ($\sigma = F/A$). Using this information, the Young's modulus can consequently be calculated and compared. Tensile tests were conducted three times as per the ASTM D638 code for tensile testing method for plastics for this study.

III. RESULTS

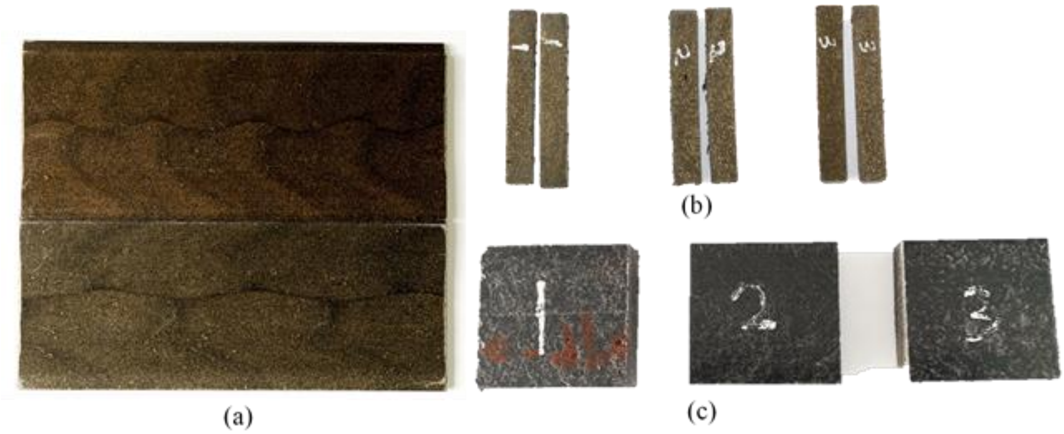
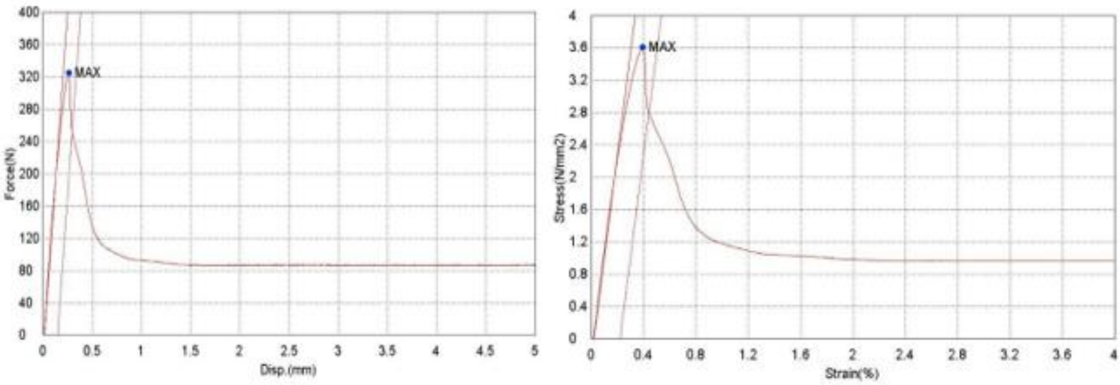


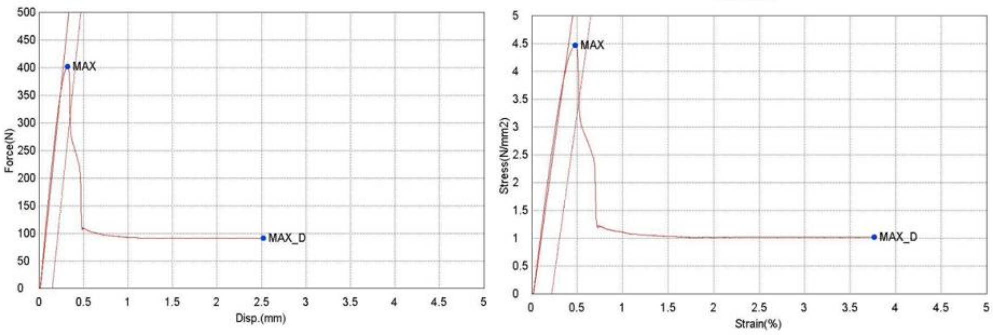
Fig 9 fabricated specimen after extrusion process

Fig 9 shows the fabricated specimen after extrusion process. From Fig 10b, we can identify the tensile strength which is the maximum stress the material can withstand before fracturing. The tensile strength is 3.605 N/mm^2 which effectively converts to 3.605 MPa. The Modulus of Elasticity or Young's Modulus, E is 12.86 MPa. The maximum percentage of elongation is 0.3952%. From Fig 10a it can be observed that the material was able to withstand 324.4 N of force throughout its cross-sectional area before fracturing. The material's tensile strength and Young's Modulus is observed to be quite low. Fig 11 shows the tensile strength for specimen 002 is 4.465 MPa. The Young's Modulus, E resulted 10.94 MPa. The maximum percentage of elongation is 0.4822%. It can be observed that the material was able to withstand 401.8 N of force throughout its cross-sectional area before fracturing. The specimen 002 material's tensile Strength is slightly higher than that of specimen 001. However, the Young's Modulus for specimen 002 is observed to be higher compared to Specimen 001. Fig 12 shows the force vs displacement graph and stress vs strain graph for Specimen 003. The tensile strength is 3.556 MPa and its Young's Modulus, E is 11.78 MPa. The maximum percentage of elongation is 0.4176%. Specimen 003 material was able to withstand 320.05 N of force throughout its cross-sectional area before fracturing. The material's tensile strength is slightly lower than that of specimen 001and specimen 002 and Young's Modulus is observed to be between specimen 001 and 002.



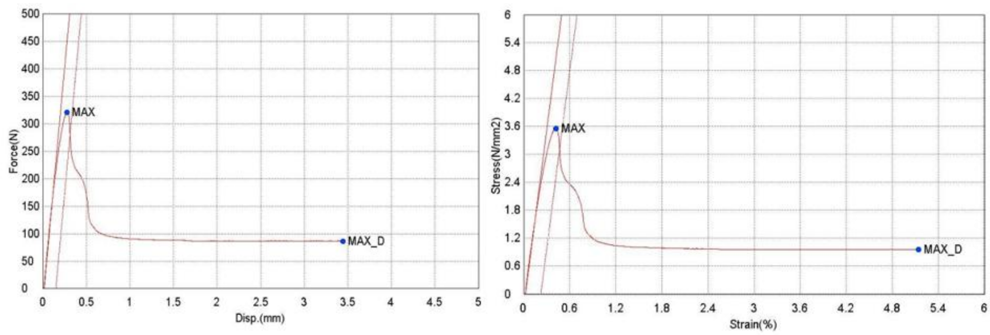
(a) (b)

Fig 10 Specimen 001 (a) Force vs Displacement graph (b) Stress vs Strain Graph



(a) (b)

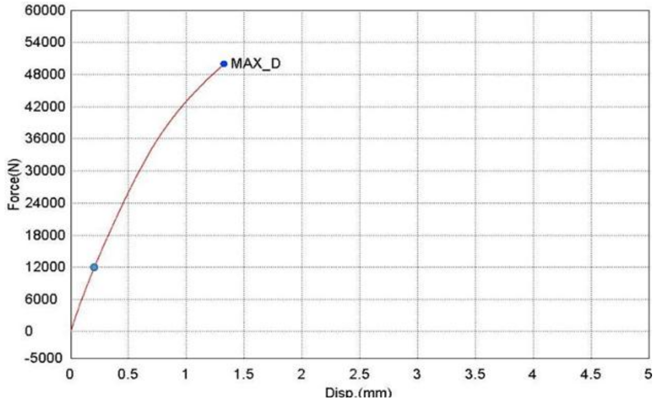
Fig 11 Specimen 001 (a) Force vs Displacement graph (b) Stress vs Strain Graph



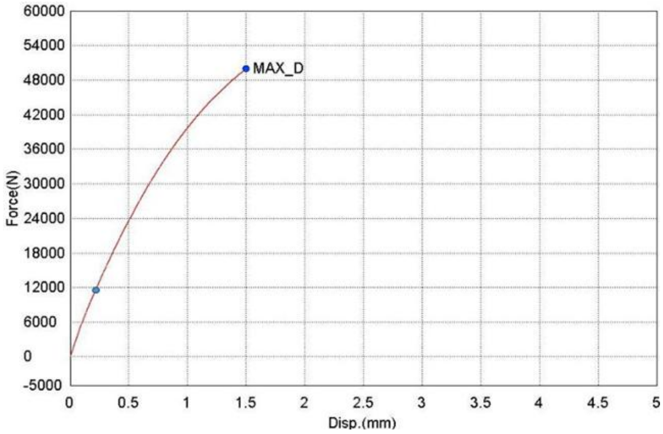
(a) (b)

Fig 12 Specimen 001 (a) Force vs Displacement graph (b) Stress vs Strain Graph

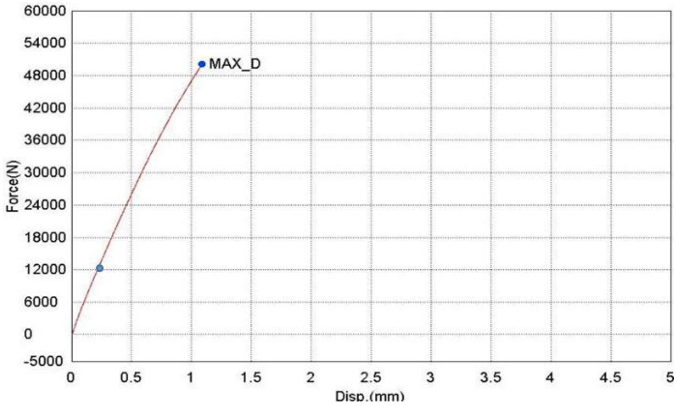
Compression testing were conducted as per the ASTM D695 standard for rigid plastics. Fig 13(a-c) shows the compressive strength for each composition. The compression test machine has a maximum load limit of 50kN. Due to the lab machine's testing limits, the test ended abruptly at 50kN of force. When the material exceeded the machine's capabilities, proper full data could not be collected, and calculations were not able to be done. Specimen 001 did not crack, have any visible changes or observable damage. However, we know for a fact that the material can withstand up to 50kN of loading and possibly even more due to the smooth and constant gradient. From the results, the Young's Modulus, E for specimen 001, specimen 002 and specimen 003 are 272.0 MPa, 196. 62 MPa, and 271.8 MPa respectively.



(a) Specimen 001



(b) Specimen 002



(c) Specimen 003

Fig 13 Force vs Displacement Graph for (a) Specimen 001, (b) Specimen 002, and (c) Specimen 003

Table 2 summarizes the results from all the tests performed on the specimen. The large degree in variance between the Young's modulus from the tensile test and compression test is to be discussed in the next section. The tensile test shows weakness in the material when it comes to elasticity and strength especially at lower thicknesses. The compression test validates the material's ability to perform well and not fracture during strong loading or experiencing compressive forces.

Table 2 Summary Tensile and Compressive Strength

Specimen	Young's Modulus (Tensile Test) MPa	Young's Modulus (Compression Test) MPa
001	12.86	272.0
002	10.94	196.0
003	11.78	271.8

IV. DISCUSSION

As shown from the tensile and compressive strength result, the material did not perform as expected from prior research despite the use of strong materials. The material fell short of expectation due to its low tensile strength and low modulus of elasticity derived from the stress-strain graphs. This is largely due to the material's inherent brittleness especially at extremely low thickness. The material exhibited poor lateral strength at low thicknesses. This could be due to preparation method, ingredient composition, lack of elastomer additives, fabrication methods and possibly the packing of fibres in the finished material. From table 8, it was found that Specimen 002 performed marginally better than Specimen 001 and 003. This could be attributed to the higher course oil palm trunk (OPT Course) fibre content as compared to the other two specimens. However, it lowered the material's modulus of elasticity. A possible cause for low performance of the material could be due to the improper preparation of the oil palm trunk fibre. As it is a new material, proper preparation methods have yet to be standardised and each batch of fibre has to be treated accordingly. The fibres may not have been completely dried out before being compounded and may have contained higher than optimal of moisture content. This could severely affect the structural integrity of the material. High moisture content can cause swelling and plasticisation in the matrix by reducing the interfacial bonding of the fibres and matrix which as a result directly causes reduction in the tensile modulus which could be true in the case of this material [12]. The lignocellulosic characteristic of the oil palm trunk fibres is the main cause of high moisture content and has to further explored to ascertain the best treatment to ensure a low moisture content. The material was fabricated via extrusion molding, a process selected following the advice of industry experts, namely because it is a new material that has never been fabricated before. The material is still in its infancy, hence, it's properties and characteristics have yet to be fully understood. If injection molding was selected, the material would have been substantially stronger in all aspects. Through injection molding, the packaging of the fibres and resin would have been a lot tighter as compared to extrusion molding. Packaging refers to the compactness of the ingredients within the finished composite. However, injection molding is a process that is performed under high pressures and temperatures. As the material has yet to be fully understood, extrusion molding was selected because it works under lower pressures, over 50% less back pressure. This was to ensure fabrication was performed within safe parameters and to keep people and equipment safe from explosions or other safety risks involved with working with high pressure equipment. Similarly, specimens could have been fabricated by hand using molds and simply pouring it into said molds and letting it cure but through extrusion molding, the project is elevated to another level in its preparedness into mass production, the end goal of this material. This would help researchers further its cause and allows them to study and understand how it behaves in an industrial setting. From table 8, it can be seen that specimen 002, which contained more course oil palm trunk fibres (OPT Course), had better tensile strength but lower elastic modulus. This could be due to the course fibres being larger than that of the fine counterpart which allows it to cover more space in the packaging, allowing it to perform better. However, there was a reduction in elastic modulus. New compositions and formulation can be made to include a higher percentage of course fibres and perhaps the addition of fillers and elastomers to allow it to be stronger as well as more elastic. Due to time constraints and the on-going pandemic, new formulations could not have been made in time, tested and analysed. However, improvement strategies and formulations will be suggested to allow for future expansion of the project. The material exhibited promising performance during the compression test. It did not fracture or deform in any visible manner, while it did undergo a reduction in length by approximately 1mm, it returned to its original length within a few hours. The lab equipment used to perform the test had a maximum load limit of 50kN which translates to 5098.58 KG, on a small piece of specimen measuring 50mm x 48mm x 15mm. It is hard to pinpoint accurately and scientifically at what load the material would have undergone irreversible deformation, again due to it being a new material. If a full test was able to be conducted, more accurate data on its ability to handle load as well as the derivation of the Young's modulus would have been obtained. These data would have been significantly more promising and closer to the desired strength and mechanical characteristics that was aimed for. Upon analysis and research, ductile and brittle materials the compressive strength is usually significantly higher than the tensile strength. In this study, for prosthetics i.e. transtibial prosthetic, the material would mainly be exposed to compressive forces as opposed to tensile, as the weight of the patient would be pushing down on the prosthetic and not pulling. However, suggestions will be made on ways to improve all these mechanical characteristics and performance. One of the main concerns of the material is its poor tensile strength. Upon discussions with industry experts, it was found that to help increase its ability to handle tensile forces, it is recommended to firstly ensure the oil palm trunk fibres are thoroughly treated. A generalised recommendation would be to observe a minimum curing time of 2-3 hours at a regulated temperature of 80-85°C. A sample should then be taken to ensure its moisture content should be close to 0-5%. To increase the materials elastic properties, it is recommended that 5 % of linear low-density polyethylene (LLDPE) or 10% low-density polyethylene (LDPE) or a combination of both, not exceeding a total of 7%, should be added to the compounded resin. LLDPE & LDPE have a high degree of long and short sided chain branching which would strengthen the material as well as allow it to undergo higher tensile forces. Additionally, fillers could be introduced as well, such as $CaCO_3$ to further strengthen the material, but it should be noted this would increase the brittleness. To counter act this effect, more elastomers should be added into the mix. While an elastomer was used in Specimen 003, vulcanised rubber, it was only at 10% and it was recycled tyre rubber. A higher percentage could be used or even a higher quality rubber similar to those found in gloves. Another filler that could be used is ceramic powder which is known for its strength enhancing abilities. While selecting materials it is paramount to keep in mind the flow index of each material. Using material with high flow index for the extrusion process, reduces back flow and improves flow rate which results in better structural bonding and molecular cohesion.

V. CONCLUSION

The objectives of the project were to analyse nano-structured cellulose material, develop a new material from this organic source, characterize the material's mechanical properties and eventually proposing a suitable material to be developed and fabricated for the use of prosthetics. It can be safely said that the objectives have been fulfilled. Oil palm trunk fibres are a source of nano-structured cellulose material and it is extremely abundant in Malaysia. Oil palm trunk fibre has great potential to be used in the application of prosthetics. It exhibits high performance when undergoing compressive forces and with proper additives and supplementary material, it is capable of rivalling today's materials that are being used for prosthetics. A combination of course oil palm trunk fibres along with elastomers, additives and Thermasite's resin would be suitable to be developed into prosthetics. Future researchers can further study and investigate the mechanical properties of the material to achieve a more superior product. This material has the potential of lowering the cost of prosthetics, making it available to lower income groups, improving innumerable lives and changing prosthetics as we know them.

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