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Reinforced Composite as a Feeder for 3D Printing Application

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ABSTRACT

Kenaf fibre has a low environmental impact because it is recyclable, light density and strong to be used as a product. Natural fibres, especially kenaf fibre, are undertilised and understudied in 3D printing technology. 3D technology is gaining traction to replace traditional methods because it saves cost and production time. This study focuses on producing kenaf composite materials that can be used as a feeder for 3D printing. This study used different fibre compositions (20,25,30) % mixed with polypropylene set at 190 ˚C temperature, 45 rpm speed, and 25 minutes. The material was left to cool to form clot to go through for the rheology process, and injection analysis was performed *using Autodesk Moldflow Insight 2014. This study showed that a mixing temperature of 190 ˚C was suitable for forming a high shear mechanism. Kenaf fibre was treated in an alkaline solution of NaOH to 3 hours to prevent damage to the surface of the filler fibre in composites. Kenaf fibre at 6% of NaOH solution reaches a higher value for mechanical strength and roughness, resulting in better mechanical interlocking between the fibres and the matrix. In addition, analysis from Autodesk Moldflow Insight 2014 reveals that at 200 ˚C injection temperature pretend, the shear rate is higher creating smoother melt flow characteristics.*

Keywords: Kenaf composites; 3D printing; simulation; shear modulus

INTRODUCTION

Natural fibres composites are proposed to substitute synthetic fibres composites due to several advantages such as biodegradability, renewability, recyclability, abundance, permeability, corrosion resistance, high degree of flexibility, hygroscopicity, non-toxicity, capability of releasing moisture, no release of harmful substances to health, non-irritation to the skin, competitive mechanical properties, reduced energy consumption, less abrasiveness to processing equipment, and minimum waste disposal problems (Ramesh 2016a). Natural fibres are more appealing to the automotive industry as one of the alternatives to replace fibreglass reinforcement in the plastic matrix and provide many advantages over synthetic fibres such as weight and price reductions, and eco-efficiency. Kenaf fibre is used in various applications including paper products, absorption, and building materials, while kenaf reinforced composite materials are widely used in the manufacture of automotive components because they can reduce environmental pollution by storing carbon in the body of a vehicle (Hassan et al. 2017).Several vehicle manufacturers use natural fibres for vehicle components. For example, Audi, BMW and Mercedes brands have been using flax fibres and hem fibre to produces interior door panels, parcel shelves, and dashboards (Peças et al. 2018). Toyota uses kenaf fibres and fibreglass as reinforcement in several plastic components, targeting to produce 15% of plastic parts from renewable or recycled materials (Peças et al. 2018). The automotive industry uses conservative processes to produce natural fibre composites such as heat-press, injection moulding, extrusion, fibres-mats, and cooling (Peças et al. 2018). Additive manufacturing, also known as three-dimensional (3D) printing is the process of combining two or more types of different materials to make a 3D product. 3D printing involves a wide range of methods, materials and equipment that have grown rapidly and changed the manufacturing process and logistics methods used in industry 4.0 (de Antón et al. 2020). Additive manufacturing also produces complex geometry that can reduce manufacturing and machining costs (Ngo et al. 2018).

Based on various selections of materials, polymer 3D printing has found applications in the aerospace industry to create complex lightweight structures, the architecture industry for structural models, the field of arts for artefacts or education, and the medical field for tissue and organ printing. However, most polymer 3D printing products are still used as prototype concepts rather than functional components because the pure polymer products built by 3D printing have low functional strength and load (Wang et al. 2017). The number of companies selling additive manufacturing increased from 49% in 2014 to 97% in 2016, with 49% manufacturing metal additives (Ngo et al. 2018). This industry is dominated by advanced research, prototypes, and applications in the aerospace industry. Aerospace is one of the industries where many additives are applied, and the leading industry players are Airbus, Boeing, Nasa and Lockheed Martin, who invest heavily in the development of this technology (Gisario et al. 2019). Polyactic acid (PLA), which reinforces jute fibres, are successfully produced as a filament and 3D printing using Fused Deposition Modeling (FDM) technology (Matsuzaki et al. 2016). The method was carried out by using 2 types of nozzles in 3D machines. The first nozzle was for jute fibre, during the second nozzle was for polylactic acid polymer. Matsuzaki et al. (2016) conducted a 3D printing of a dumbbell shape out of reinforced jute fibre composite materials, as shown in Figure 1.

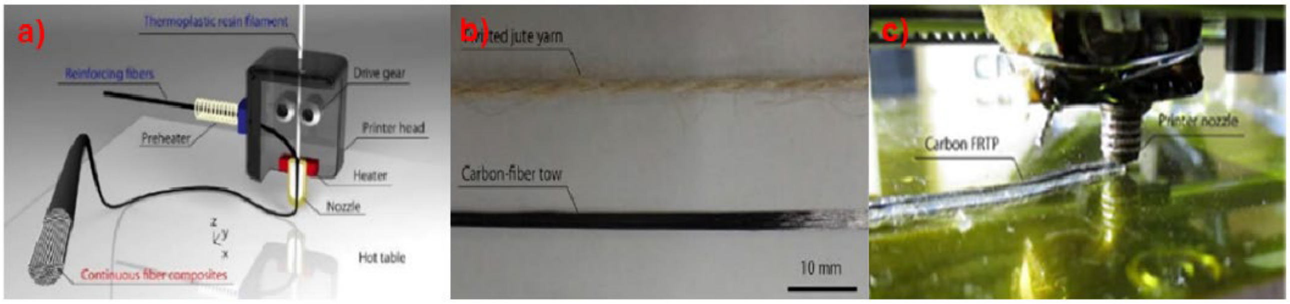

FIGURE 1. (a) Schematic of the 3D printer head used to produce continuous fibre reinforced thermoplastics using in-nozzle impregnation based on FDM, (b) the thermoplastic resin filament and reinforcing fibres are sent to printer head separately, (c) continuous carbon fibre-reinforced composites are manufactured using a 3D printing process (Matsuzaki et al. 2016).

The advantages of using FDM technology are low cost, high speed, simplicity, deposition ability of various materials simultaneously, and various extrusion nozzle designs (Carneiro, Silva & Gomes 2015). For Fused Filament Fabrication (FFF), the process can print polymer reinforced carbon fibre by adding the fibre into thermoplastic filaments. To increase mechanical properties, reinforcement can also add additional functions to materials such as electroconductivity, high thermal conductivity and biocompatibility (Blok et al. 2018). Natural fibres are produced from 3 main factors: plants, animals and minerals, with plants and animals being renewable resources (Raman Bharath, Vijaya Ramnath & Manoharan 2015). The main difference between animal and plant fibres is that the former consists of protein as the main constituent while the latter consists of cellulose (Balla et al. 2019). The most commonly used materials for synthetic fibres are glass, carbon and aramid (Matsuzaki et al. 2016). The properties of natural fibres vary depending on the composition and chemical structure associated with the type of fibre and the growing conditions, extraction methods, harvesting methods, harvesting time, treatment methods and storage methods (Raja et al. 2017).

Generally, a high fibers content is required to achieve high material performance (Ramesh 2016b). The other factor that affects the properties of composites is the processing parameters used. Therefore, appropriate techniques and parameters must be carefully selected to produce optimal composite products. The composite properties are determined by the interface bond between the matrix and reinforcement due to incompatibility (Hui 2019). The main factor in the weakness and performance of composites is the incompatibility of the composite due to the differences between the matrix and the natural fibres, resulting in poor interface adhesion (Hui 2019). Chemical treatment or modification of natural fibres, including kenaf uses coupling agents containing functional groups to increase the bonding strength with hydrosol groups from natural fibres (Ramesh 2016b). The methods that can change the surface characteristics of natural fibres can be categorised into chemical, physical and mechanical methods. Physical methods are more environmentally friendly methods because they reduce the polarity difference between fibres and matrix, while chemical methods help reduce the degradation caused by moisture absorption (Balla et al. 2019). The commonly used coupling agent is maleic anhydride and silane because of their properties that can modify the kenaf surface and achieve improved bonding of the polymer matrix interface angle between the fibre and the matrix, which can improve the mechanical properties in the composite (Faruk et al. 2012). Maleic anhydride coupling agent doubles the increase in mechanical properties such as tension and bending compared to silane treatments (Balla et al. 2019).

Chemical treatments are performed to remove lignin from the surface of natural fibres until the surface becomes coarse, reducing the number of hydrosol groups and increasing compatibility with the hydrophobic polymer matrix (Hui 2019). Modification using alkali treatments are important to break down the hydrogen bond in the network fibre structure to increase the roughness on the fibre surface. During alkaline treatments, hemicellulose is removed and the interfibrillar area becomes less compact and less rigid, allowing the fibres to rearrange themselves according to the direction of tension formation (Ramesh 2016c). One of the significant challenges in 3D printing is determining the appropriate material pressure and shear rate to allow composite to form with adhesion between fibres and matrix (Balla et al. 2019). Shear rate and pressure are affected by the type of material and printing technology used. However, additive manufacturing technology offers design flexibility and the production of complex components to enhance the functionality and performance of the final product.

The selection of the right temperature based on the material has effects on the productivity and quality of the mould because high temperatures produce low viscosity and better rheology properties that can increase bonding between the matrix and the fibres and reduce the product cavity (Kabir, Mathur, and Seyam 2020). Printing speed has less impact on product tensile strength, but it increases production costs. Low production rates, also low feed rates, can increase composite bonding (Ye et al. 2019). There are several problems with producing composite filament feedstocks for 3D printing, such as merging, compounding and extrusion processes in the preparation of composite filaments that can damage natural fibres due to exposure to high temperature and pressure. Extrusion temperature must be increased as the polymer viscosity increases with the fibre concentration to facilitate the process of producing natural fibre composite filaments; but, this process has the potential to adversely affect the stability of natural fibres (Balla et al. 2019). The use of necessary thermoplastic matrices appropriate to the fibre and the type of processing are examined to address the issue.

Several studies have been conducted on polymer processing, especially in rheological studies, to build inexpensive and processable thermoplastic moulds to produce products using injection moulding processing techniques (Wan Abdul Rahman, Sin & Rahmat 2008). Injection moulding is the most widely used technique in the plastics industry because of the dimensional accuracy of the products produced, the ability to produce complex geometric products, products with thin walls, the short manufacturing cycle and the manufacturing repeatability of the product (Santos et al. 2015). However, only 5% of the world market uses thermoplastic materials fortified with natural fibres for the injection moulding process. Computer-Aided Engineering (CAE) software developers have developed injection moulding flow analysis simulation software to help predict and overcome problems encountered during the injection moulding process (Wan Abdul Rahman, Sin & Rahmat 2008). The CAE software specialising in injection moulding available on the market includes Moldflow and Moldex3D. Injection moulding simulation software assists the flow pattern of molten polymer in the mould during the moulding, packing, and cooling processes (Wan Abdul Rahman, Sin & Rahmat 2008). Controlling and determining the melting temperature for injection mould are very important as both directly affects the melting viscosity factor (Chin How & Azuddin 2017). Accurate melting temperature control can reduce preparation time, ensuring consistent product quality, and melting viscosity can affect translation injection speed, rotating screw speed and cavity time pressure profile (Chin How & Azuddin 2017). The injection temperature of the moulding injection depends on the type of material used and the filler material (Santos et al. 2015).

METHODOLOGY

Thermoplastics polymer matrix type polypropylene (PP) grade automotive 850 was chosen for this study because of its good performance during processing and suitability as a polymer matrix material in reinforced composites produced using injection moulding techniques. PP polymer type SM850 was in pallet form. Short kenaf fibres was used in this study obtained from the outer skin layer of its stem. This kenaf fibre was obtained from the National Kenaf and Tobacco Board (LKTN), Pasir Putih, Kelantan, Malaysia. Selections of short filler-shaped kenaf fibres were extracted from the outer bark and inner core found on the trunk of the kenaf tree. Firstly, kenaf fibre modification with alkaline treatment. The main factors in the weakness and performance of the composites produced are the incompatibility of the composites due to the differences between the matrix and the natural fibres, resulting in poor interface adhesion (Hui 2019). Although alkaline treatments improve the mechanical properties of kenaf fibres, they will cause damage to the fibres if high-concentrated or inappropriate alkaline solutions are used (Hamidon et al. 2019).

Alkaline NaOH solution with a concentration of 6% was used in this study because the solution optimises the mechanical properties of the fibre without causing damage. Kenaf fibre was soaked in the NaOH solution 6% concentration with distilled water for 3 hours at room temperature. After 3 hours of immersion, the fibres was removed and rinsed with distilled water to remove the NaOH solution. The fibre then was soaked in distilled water with 1% acetic acid to neutralise the remaining NaOH molecules were still attached to the kenaf fibres. The kenaf fibre was rinsed with distilled water before being dried in the oven at 80 ˚C for 24 hours to ensure complete drying.

This study has 3 compositions of kenaf fibre filler which were 20% wt., 25% wt., 30% wt. kenaf fibre filler. Kenaf composite feedstock is prepared with the addition of kenaf fibre filler loads starting from the minimum percentage up to 40% wt. (Yang et al. 2010). For mixing process, the polypropylene would not melt completely even though the temperature was set at 190 ˚C, if the polypropylene is mixed with kenaf fibre first before the mixture put into the Sigma Blade machine. This causes the polypropylene matrix to not require the maximum temperature of 190 ˚C to melt successfully. Figure 3 (a) shows the results kenaf composites which depicts that polypropylene did not melt completely. The approach for the mixing process was altered by placing the polypropylene in the mixer machine for almost 15 minutes. Polypropylene melted successfully before the insertion of kenaf fibre. Then, the kenaf fibre filler was added to the mixer until the kenaf composite mixture was well-blended, which took up to 10 minutes. This is to prevent the occurrence of early decomposition effects on kenaf filler fibre due to excessive temperature exposure (Sun, Han, and Dai 2010).

The process of crushing the kenaf composite feedstock material was completed after the mixing process was successful. This process was conducted because the kenaf composite had formed clots after the mixing process. The form of the clots cannot be tested in the process of rheology because the testing process can only be done in the pellet form. Figure 3 (b) shows the kenaf composite in pellet form.

FIGURE 3. (a) kenaf composite which the polypropylene does not melt completely, (b) kenaf composite in pellet form.

Material characterisation analysis was the initial processing stage performed to identify the characteristics of kenaf composite feedstock material for 3D printing applications because chemical components influence the strength characteristics of reinforced fibre and also contribute to the improvement of mechanical strength and physical of polymer composite (Radzi et al. 2016). Skin type of kenaf fibre fillers have a higher value of cellulose of 54.44%, hemicellulose of 46.50%, lignin of 18.27%, and ash content of 8.50% than core type kenaf fillers as shown in Table 2. Fibres with high chemical components will be a contributing factor to the increase in mechanical strength characteristics of a polymer composite (Radzi et al. 2016). Sodium hydroxide (NaOH) solution with the concentration of 6% can increase the value of mechanical properties to the Young Module 11.88 GPa, tensile strength 267.69 MPa, and crack strain of 2.07% compared to other concentrations as shown in Table 3.

Chemical treatments can alter the structure of the fibres, increasing the roughness on the surface of the fibres and improving the mechanical interlocking between the fibres and the matrix (Hamidon et al. 2019). Figure 4 shows the results of SEM micrograph of the chemical treatment performed on kenaf fibres. As illustrated in Figure (a), untreated kenaf fibre has impurities on the surface, that can affect adhesion properties. Whereas treated fibre with a concentration of 6 % NaOH solution has a fibre without impurities on the surface. However, increasing the concentration of NaOH solution to 8% has caused damage to the surface, resulting in a decrease in mechanical characteristics.

TABLE 2. Chemical compositions of skin and core kenaf fibres fillers.

Characterisation	Skin	Core
Cellulose (%)	54.44	28.15
Hemicellulose (%)	46.50	28.63
Lignin (%)	18.27	12.88
Ash content (%)	8.50	1.90

TABLE 3. Effects of concentration on the mechanical properties of kenaf fibres.

Solution NaOH (%)	Young Modulus (GPa)	Tensile Strength (MPa)	Fracture Strain (%)
2	4.28	25.28	1.28
4	5.36	104.32	1.72
6	11.88	267.69	2.07
8	7.67	89.58	1.21
Untreated	9.02	129.10	1.35

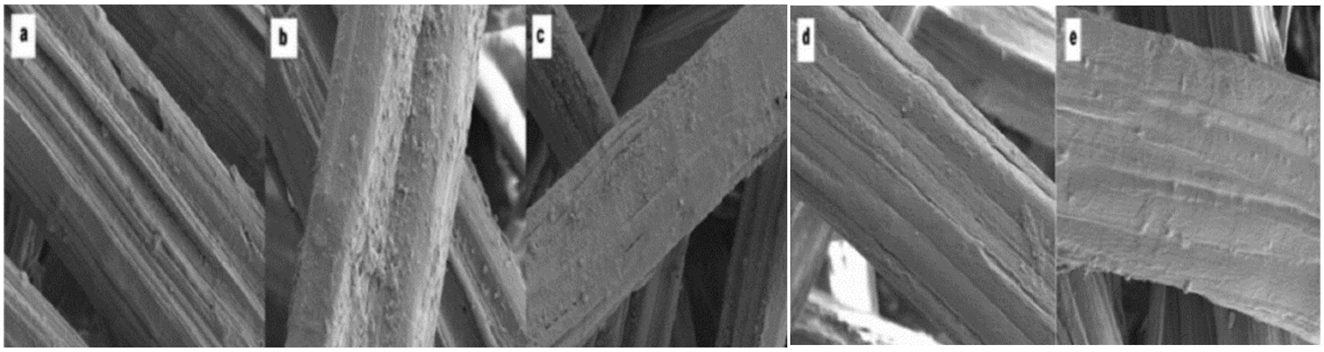

FIGURE 4. SEM micrographs of kenaf fibres, (a) untreated fibres, (b) 2% NaOH, (c) 4% NaOH, (d) 6% NaOH, and (e) 8% NaOH (Hamidon et al. 2019).

EFFECT OF INJECTION MOULDING PARAMETER ON MOULD FILLING BEHAVIOUR

The kenaf composite feedstock that was produced required rheology testing to further identify its homogeneity level before it was properly injected. However, in this study, the rheology method could not be implemented due to the constraint factor of the COVID-19 pandemic. The research involved changes to moldflow analysis that was done using Autodesk Moldflow Insight 2014 software. This analysis was performed using kenaf composite injection temperatures as variables of 190 ˚C, 200 ˚C and 210 ˚C. Kenaf composites would fail in two conditions: when the injection temperature exceeds 210 ˚C and below 190 ˚C. This is because extremely high injection temperatures cause the composite feedstock material to undergo thermal decomposition easily and leave a burning effect on the composite surface, whereas, at a very low processing temperature, the composite feedstock material does not completely melt and is too viscous to flow in the mould cavity (Koffi, Koffi, and Toubal 2016).

The use of low temperature will make it difficult for the polymer material to flow due to imperfect crystallization processes, while using high temperature weakens the thermal resistance properties of the molten material, especially to natural fibre reinforced composite materials (Ares et al. 2010). The result from Table 4 shows that the shear rate for injection temperature 200 ˚C is a good temperature to use. Shear rate decreases if the viscosity rate of the material increases (Ben Trad et al. 2020). High shear stress can reduce the effects of friction resistance between the composite materials involved, in creating smoother melt flow characteristics (Ou et al. 2014).

TABLE 4. Shear rate analysis data.

Injection Temperature (˚C)	Shear Rate (1/s)	Time (s)
190	14014	0.4695
200	72291	0.4699
210	14016	0.4684

The results of the average shear modulus show the shear strain in the X-axis direction, and the Y-axis fixed to the fibre orientation direction. The result of the average shear modulus is the average value of the fibre-over-thickness, which means it is calculated for each element on each laminate and all elements the average for all laminates. Table 5 displays the analysis data for shear modulus (fibre) performed with Moldflow software. As higher temperatures enhance the mobility to melt the composite material and increase the interfacial bonding to be produced, the sample at 210 ˚C has a larger shear modulus than the samples at 190 ˚C and 200 ˚C. Fibre orientation analysis is used to predict the behaviours of composite materials. Composite materials are considered fibre particles in viscous medium conditions. Injection temperature of 200 ˚C shows that fibre was in good orientation because the value approached one, as shown in Table 6.

TABLE 5. Analysis data for shear modulus (fibre)

Injection Temperature (˚C)	Shear Modulus (MPa)
190	763.3
200	769.3
210	769.4

TABLE 6. Analysis data for fibre orientation

Injection Temperature (˚C)	Average fibre orientation
190	0.9652
200	0.9818
210	0.9669

CONCLUSIONS

The process of producing kenaf composite as a feedstock and simulation analysis using Moldflow software had been investigated. The kenaf fibre experienced chemical treatments without any failure. The composition of kenaf composite can be produced in three (3) compositions which are 20%, 25% and 30% kenaf. The second stage of this research involved simulation analysis to identify the effects of injection moulding parameters on mould filling behaviour for kenaf composites using Autodesk Moldflow Insight 2014 software. Based on the results of Moldflow analysis, the optimum temperature for injection is 200 ˚C. However, the injection temperature range of 190 ˚C to 210 ˚C records that kenaf composites can be injected perfectly within the range with the injection pressure at 1300 bar, holding pressure at 1900 bar and the flow rate at 20 $cm3$/s. There are some suggestions for further research, such as including rheology tests and using a rheology machine. This is because the result of the tests can provide precise data and the flowability properties of kenaf composites for their use in 3D printing. Then, it is suggested that various kenaf composition data are conducted in Moldflow software. This allows researchers to make comparisons of various data for various compositions of kenaf reinforced polypropylene matrix.

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DECLARATION OF COMPETING INTEREST

None

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