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Development of Interior and Exterior Automotive Plastics Parts Using Kenaf Fiber Reinforced Polymer Composite

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Abstract: The integration of sustainable components in automotive parts is in growing demand. This study involves the entire process, from the extraction of kenaf cellulosic fibers to the fabrication of automotive parts by applying injection molding (sample only) and Resin Transfer Molding (RTM) techniques. Fibers were pretreated, followed by moisture content analysis before composite fabrication. The composite was fabricated by integrating the fibers with polypropylene, maleic anhydride polypropylene (MAPP), unsaturated polyester, and epoxy resin. Mechanical tests were done following ASTM D5083, ASTM D256, and ASTM D5229 standards. The RTM technique was applied for the fabrication of parts with reinforced kenaf long bast fibers. RTM indicated a higher tensile strength of 55 MPa at an optimal fiber content of 40%. Fiber content from 10% to 40% was found to be compatible with or better than the control sample in mechanical tests. Scanning Electron Microscope (SEM) images showed both fiber-epoxy-PE bonding along with normal irregularities in the matrix. The finite element simulations for the theoretical analysis of the mechanical performance characteristics showed higher stiffness and strength in the direction parallel to the fiber orientation. This study justifies the competitiveness of sustainable textile fibers as a reinforcement for plastics to use in composite materials for automotive industries.

Keywords: kenaf fibers; polypropylene; mechanical properties; automotive parts; composite materials; polymer composites; cellulosic fibers; cellulosic composite; sustainable composite; sustainable plastics

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1. Introduction

Considering the industrial demand for a high strength-to-weight ratio material, sustainable engineering materials translate to reduced fuel consumption and carbon dioxide emissions. The possibility of achieving functional properties has promoted the wide application of kenaf fiber-reinforced composite material in the development of automotive parts. Most recently, kenaf fibers have been employed among other natural fibers in combination with plastics [1,2]. Kenaf fibers have scalable manufacturing values with multi-functionalities and diverse value additions for industrial profit. Kenaf fibers possess low density with high strength and stiffness [3]. They have the attention of researchers due to their sustainability and environmental friendliness. Moreover, the world is going to embrace smart manufacturing, Industry 4.0, with the gradual integration of green production [2,4]. Additionally, the recent and continuing global crises raised the demand for more use of biobased materials to be less reliant on fossil fuels and to increase sustainability [5,6]. In response to these long-term aims, recent research showed that kenaf fibers possess properties that could allow them to replace glass fibers with some modifications and the addition of additives that are conducive, especially in less strength-demanding applications [5]. The utilization of natural fibers has diversified applications in developing new

engineering materials such as door panels, seat backs, headliners, dashboards, car bumpers, interior parts, package trays, furniture, packaging, buildings and constructions, military vehicles, aircraft spare parts, household applications, furniture composite panels, wood-replacement products, bio-based material, and nanomaterials with comparative economic benefits [7,8]. Additionally, kenaf fibers are gaining more popularity in many engineering applications, particularly in the automotive industries and pulp and paper technology due to their good mechanical properties, short growth life cycle of 150 days, and high economic and industrial value, as demonstrated by Ford Auto Manufacturers [9,10]. According to the American Plastics Council, nearly 50% of vehicles' interiors are made of polymeric materials, and sustainable plastics are becoming of higher industrial demand [11]. The use of natural fiber cellulose can cause an estimated 25% reduction in car weight, which would be equivalent to saving 250 million barrels of crude oil [12]. Natural fiber composites have also been embraced by European car manufacturers and suppliers for door panels, seat backs, headliners, package trays, dashboards, and interior parts [13]. Further, 15.7 million passenger cars were manufactured in European Union countries in 2011, and over 30,000 tons of natural fibers were utilized, showing that, on average, every passenger car in Europe contains natural fibers [14]. More consideration is given to kenaf fibers owing to their fiber properties, such as bast fiber, which has low density, low cost, good toughness, suitability for recycling, acceptable strength properties, and biodegradability [8,15]. Considering all these aspects, Ford Motors, General Motors, and Toyota announced their interest, while BMW, Audi, and Volkswagen decided to use kenaf fibers in their auto parts production long ago [10,13,16–18].

Kenaf fiber enables tailored material design and competing engineering design requirements, such as high strength, moldability, paintability, surface finish, and thermal stability up to 190–210°C, along with a high aspect ratio (length-to-diameter ratio) and excellent reinforcement for polymeric materials [8,19]. Kenaf fibers are among the fastest-growing types of reinforcement for polymeric material. They are being increasingly used in composites for automotive applications. The economic value of the kenaf plants is rooted in their growing period of about 120–150 days and two annual production periods, yielding 15–20 tons per hectare (dry weight) with 3–5 tons (20%) consisting of fiber [20]. The fiber comprises two types of materials: the long fiber (bast) and the short, woody-like fiber (core), present at the innermost part of the kenaf stem. The bast-to-core ratio is almost 30:70 (*w/w*) [21]. The chemical composition of the kenaf plant is a major concern for researchers due to the presence of cellulose, lignin (responsible for roughness), pectin, hemicellulose, and waxes. Kenaf is a hydrophilic material, and this water-loving property leads to mechanical failure over time due to water uptake and the formation of a hydrogen bond. Researchers have developed several chemical treatments and morphology modifications of kenaf to improve its mechanical stability, such as maleic anhydride, hybridization, and silane acetic anhydride [22,23]. Several researchers have investigated the use of kenaf fibers as an alternative to glass fibers with thermoplastic polymers to produce automotive parts in the recent past. Davoodi et al. [24] used the hybridization of kenaf fibers and glass fibers in an epoxy matrix. The results showed similar performance to the glass fiber-epoxy in terms of tensile strength, Young's modulus, flexural strength, and flexural modulus. However, impact strength was found to be lower. On the other hand, Mohd Radzuan et al. [25] investigated the mechanical properties of polypropylene and untreated kenaf fiber composite. The results showed significantly improved mechanical properties, which strongly recommended the use of kenaf fibers as an alternative to other reinforcement materials for automotive parts production. Several other studies found improved mechanical properties using kenaf fibers as reinforcement with unsaturated polyester and epoxy resin [26–28]. Unsaturated polyester is a thermoset resin that is cheap, conducive for structural applications, and compatible with kenaf fiber reinforcement in composite fabrication [29]. Epoxy, which is one of the widely used thermoset resins in high-performance structural composites for the automotive and aircraft industries, is known for its better adhesion to different substrates, superior mechanical properties, and lower post-curing shrinkage. However, it

is comparatively expensive and takes longer to cure [30]. To address the brittleness and weak crack-resistance issues of unsaturated polyester, the modification of unsaturated polyester resin by epoxy through reactive blending can result in an interpenetrating and crosslinked hybrid polymer network that exhibits superior characteristics compared to the neat resin. This modification enhances the overall behavior of the composite, leading to substantial improvements in mechanical, thermal, and dynamic mechanical properties, ultimately enabling high-performance applications [31]. On the other hand, maleic anhydride polypropylene (MAAP) acts as a coupling agent (compatibilizer) and helps increase the compatibility between kenaf fibers and the matrix and, thus, reduces the water absorption and swelling of the composite [32,33]. Kenaf fibers have been used as a reinforcement filler to make composites (thermosets) for the fabrication of higher structural parts to use in automobiles and aircraft in substantial research. However, there is little to no research that demonstrates any comparative study between injection-molded (thermoplastics) and RTM-made composite parts (thermosets) in this particular area of research. Therefore, the objective of this study was to use kenaf fibers as a reinforcement material with both thermoplastics and thermoset polymers to develop composite and automotive parts with the subsequent investigation of mechanical properties and morphology. The study focused more on the comparison of the properties of samples rather than their manufacturing techniques, which has been noted in the limitations section.

2. Materials and Methods

2.1. Materials

The kenaf fibers were collected from the experimental kenaf garden of the Federal Institute of Industrial Research (FIIR), Nigeria. The thermoplastic and thermoset resins, along with other chemical agents including polypropylene, maleic anhydride polypropylene (MAPP) compatibilizer, unsaturated polyester, epoxy resin, hardener (Epicote 816), acetic acid, and NaOH, were supplied by the Technology Incubation Center in Nnewi, Nigeria.

2.2. Methods

2.2.1. Fiber Delignification

Kenaf stems were processed semi-mechanically, separating the bast and core portion of the stems. The two portions of the fiber strand were the primary reinforcement for the experiment. Cellulosic fibers of kenaf were extracted by chopping the separated bast and core portions into 2–3 mm size flakes, followed by ball milling to an 80 µm particle size. Fiber delignification was carried out in a controlled system of 5–10% alkali treatment for 3 h at 50 °C. The alkaline-treated fibers were washed thoroughly with distilled water and in an acetic acid medium to keep pH controlled at 7 and dried at 105 °C to improve the fiber/matrix adhesion.

2.2.2. Moisture Content Analysis

Usually, the moisture content of the composite feedstock materials beyond the acceptance level affects the mechanical properties of the final composite [34]. Moisture content analysis of kenaf fibers and polypropylene was done to investigate the effect of alkaline treatment on the fibers and the compatibility of the polymer with the composite using a moisture analyzer (A&D MS-70, Tokyo, Japan).

2.2.3. Composite and Parts Fabrication

Polypropylene-g-MAH (graft copolymer of PP and maleic anhydride compatibilizer) was pelletized with a ratio of 10% to 60% fiber content (fiber size < 1 mm) using an intermeshing, co-rotating, twin-screw extruder for the injection molding process. The basic plastic processing techniques were carried out for the injection molding samples' development. The ejected samples were developed using processing conditions at 180 °C (feed zone), 195 °C (transition zone), and 200 °C (metering zone), along with an injection rate between 10 cm^3/s to 20 cm^3/s and injection pressure of 150 MPa to 170 MPa. On

the other hand, RTM was applied for the fabrication of composite samples integrating reinforced kenaf long bast fibers (1–8 cm) at a ratio of 10% to 60% with unsaturated polyester, epoxy resins, and epoxy hardener (Figure 1). Three different automotive parts were fabricated from the RTM composite samples: the boot spoiler, bumper, and test pies sample. However, samples were made from both processing techniques according to the ASTM test requirements.

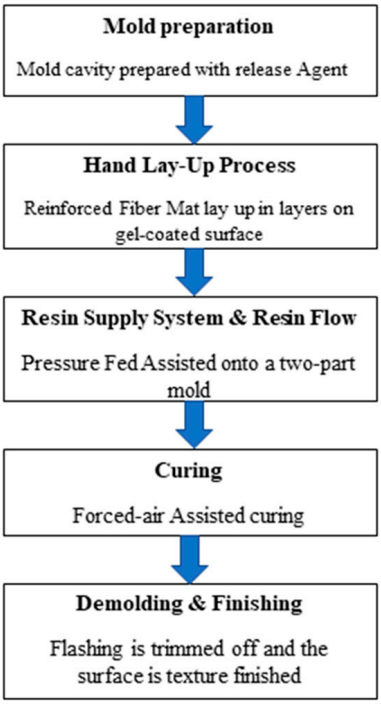


Figure 1. Resin Transfer Molding (RTM) Process.

2.2.4. Mechanical Properties Testing

Mechanical properties play a major role in how the end product will behave during the operation [35–37]. The mechanical properties, such as tensile strength and elongation, were done following the ASTM D5083 standard, whereas flexural strength and Izod impact strength testing were done following the ASTM D790 standard and ASTM D256 standard, respectively. Mechanical testing was done using a Testomeric testing machine (model: M500-25KN). For ASTM D5083, the samples were prepared as per the dimensions of 150 mm × 30 mm × 5 mm of different fiber content. The crosshead speed was 200 mm/min. The samples went through increasing loads, and the machine stopped at the failure of the samples. The respective loads from start to breaking were recorded. For ASTM D790, the force that was needed to bend the sample under a three-point loading condition was measured from the deflection of the sample. The deflection of the sample was measured from the crosshead position. A minimum of five samples were sliced to dimensions of 63 × 13 × 5 mm. To determine the impact strength in kJ/m^2, the amount of energy absorbed during impact was divided by the cross-sectional area of the samples. All tests were done for a control sample of PP along with injection-molded and RTM parts.

2.2.5. Water Absorption Testing

A water absorption test was conducted according to ASTM 570-98 (2020) to determine the amount of water that the fabricated reinforced composites can absorb. The samples for optimal fiber content for injection-molded parts (tensile strength at 30%) and optimal fiber content for RTM parts (tensile strength at 40%) were tested and compared with the control sample and untreated composites. These samples were immersed in distilled water, and the water bath temperature was regulated at a specified temperature of 50 °C for 24 h. After the immersion period, the samples were removed from the water, wiped dry, and

weighed to determine the amount of water absorbed. The amount of water absorbed is calculated as a percentage of the initial weight of the sample. The following equation was used to measure the water absorption percentage:

$$WA\% = ((W_f - W_0)/W_0) \times 100 \quad (1)$$

where W_0 = Initial weight of the sample (g), and W_f = Final weight of the immersed sample after 24 h (g).

2.2.6. Simulation

The finite element simulations for theoretical analysis were done by AutoFem analysis software (AutoFem Lite x64 3D, version 3.5, Autodesk, San Francisco, CA, USA) with a speed impact of 13.3 m/s (48 km/h), as recommended by the Federal Motor Vehicle Safety Standard (FMVSS 208) to predict the crashworthiness during collision [38]. Theoretical analysis of the composites was done based on three-dimensional (3-D) designed parts created using SolidWorks (version SP5, 2018) software for the injection molding process. The material properties were chosen based on the purchased materials, and the default element size was selected.

2.2.7. Morphology Analysis

A morphology analysis was done by Scanning Electron Microscopy coupled with energy-dispersive X-ray spectroscopy (SEM-EDX) using Phenom ProX (Thermo Fisher Scientific, Phenom-World BV, Eindhoven, The Netherlands). The voltage mode was 15 KV with a full backscatter detector (BSD). It provided SEM images of different fields of view (FOV), such as 200 µm, 100 µm, 80 µm, and 50 µm, along with the weight concentration and atomic concentration of the available elements in the sample composite.

3. Results

3.1. Moisture Content Analysis

The effects of the alkaline treatment on both treated and untreated fibers were significant in reducing the moisture content (Figure 2). The alkaline treatment increased the cleanness and reduced the roughness of the fiber surface. The reduced roughness suggested that the alkaline treatment reduced the impurities, hemicellulose, and lignin content of the fibers and improved fiber adhesion and thermal stability during processing [39]. As the impurities are reduced, the free volume, hemicellulose, and lignin content decreased too, which was reflected in the overall moisture content in the treated samples, while PP did not have a significant impact on alkaline treatment.

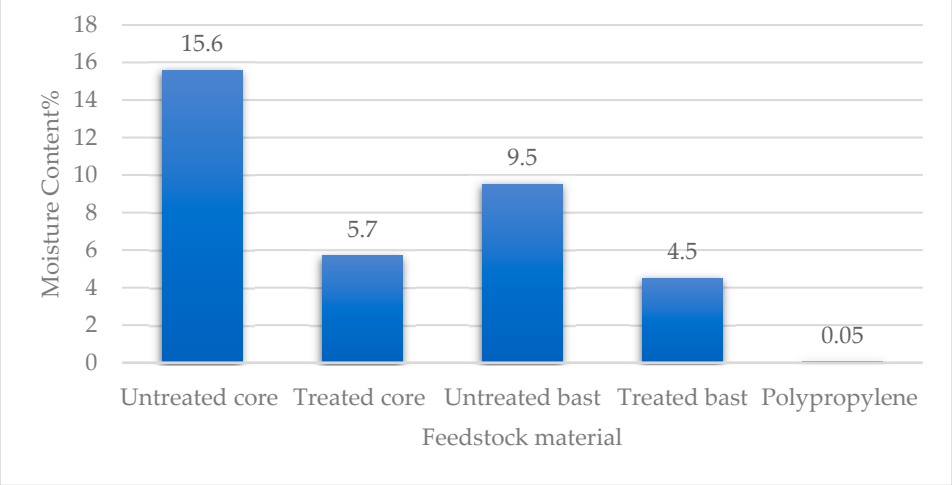


Figure 2. Moisture Content of feedstock materials.

3.2. Mechanical Properties

3.2.1. Tensile Strength

The experimental results of tensile strength in Figure 3 show that the fiber content significantly affects the mechanical properties of the composite material. There is significant strength enhancement at 30% optimal fiber content for injected parts (38 MPa) and at 40% optimal fiber content for RTM (55 MPa) due to the reinforcing effects of the fibers. As the fiber content increases, the tensile strength of composite material continues to increase as fiber shows well-dispersed and good reinforcement. However, at higher fiber contents of more than 30% for injected parts and more than 40% for RTM, the tensile strength decreases drastically due to the increased stiffness and brittleness of the composite material. The obtained results are pertinent to previous studies [40]. Moreover, in injection molding, kenaf fibers degrade at higher temperatures, which affects mechanical properties [41]. The mechanical strength of the reinforced material is also associated with the morphology/chemical composition of the fiber, and specific processing techniques used to incorporate the fiber in the matrix (resin) could also influence its properties and tensile strength. The mechanical properties of fibers also increased with the level of fiber purity and cellulose content of the fiber in the reinforced composite material. In RTM, liquid resin was injected into the mold containing reinforcement material, and the resin was cured under heat and pressure. In injection molding, the resin was injected into the mold and rapidly cooled to solidify the material. These phenomena are supposed to lead to different tensile strengths of the resulting parts. Overall, the differences in mechanical properties between RTM and injection-molded parts are largely due to the different manufacturing processes and the resulting microstructure of the materials that exert differences in tensile strength.

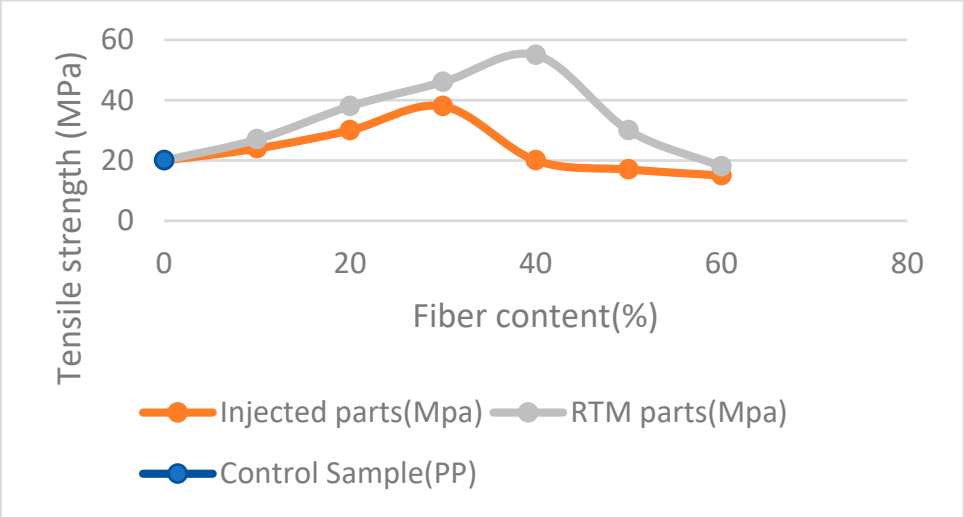


Figure 3. Tensile strength of composite samples at varying fiber content.

3.2.2. Elongation at Break

Figure 4 shows the elongation at the break of the composite samples with varying fiber content. At a lower fiber content (10%), the elongation at the break was not significantly affected due to the toughening effects of fiber acting as a reinforcement. As the fiber content increases from 20% to 60%, the elongation at the break decreases significantly due to an increase in the stiffness of the composite material by creating a stress concentration leading to microcracking and failure in the material, which is pertinent to the previous study [40]. The figure also demonstrates that RTM parts showed a higher level of elongation at the break all the way. This is because RTM is a thermoset process, which means that the resin cures at a specific temperature and time. This allows for the formation of a more uniform microstructure, which can also contribute to the higher elongation at the break of RTM parts. Moreover, the higher elongation at the break of RTM parts is due to a combination

of factors, including uniform fiber impregnation and controlled curing. These factors contribute to the formation of a more ductile material, which is better able to withstand deformation before it breaks.

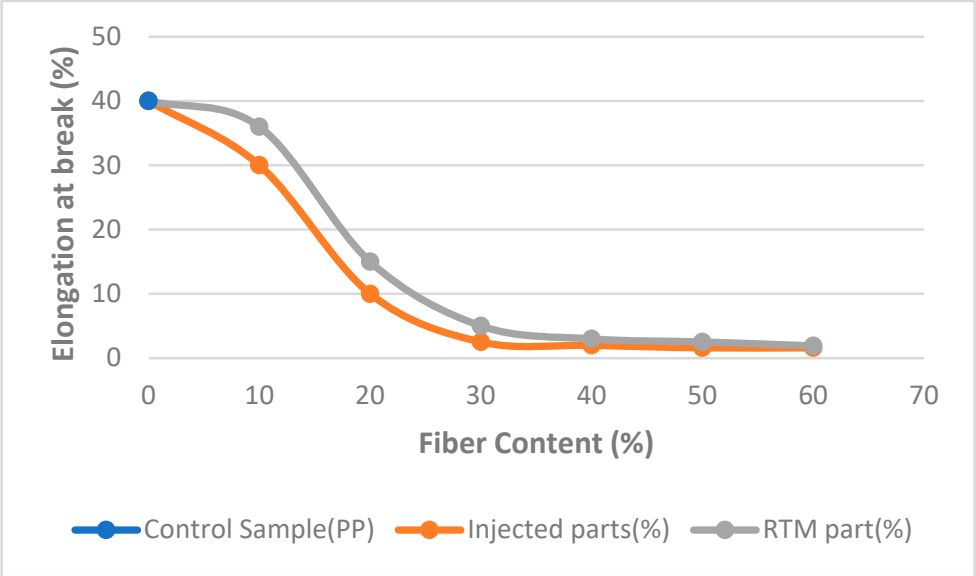


Figure 4. Elongation at break of composite samples at varying fiber content.

3.2.3. Flexural Strength

Figure 5 shows that at a lower fiber content (10%), the effect on flexural strength was limited for both the RTM and injected parts. Maximum flexural strength was recorded at 20% and 30% fiber content for the injection-molded and RTM samples, respectively. However, as the fiber content increases, the flexural strength decreases due to the increased stiffness and brittleness of the composite material. At higher fiber contents (40–60%), the flexural strength of the composite material decreases significantly, which is in line with the previous study [42].

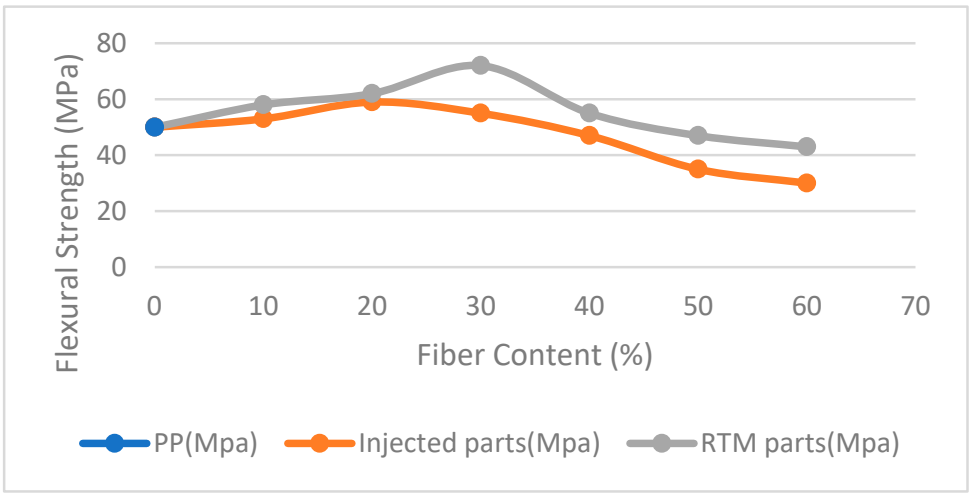


Figure 5. Flexural strength of composite samples at varying fiber content.

3.2.4. Izod Impact Strength

Fiber content shows a significant effect on the impact strength (Figure 6). At a lower fiber content of (10%), the impact strength of reinforced composite material for both the RTM and injection-molded parts showed slight reinforcement improvement. At a fiber content of 20%, the strength was significantly improved. However, as the fiber content

increases above 20%, the impact strength decreases due to the increased stiffness and brittleness of the composite material. At 40–60% fiber content, the composite material showed a gradual decrease due to poor fiber dispersion, higher misalignment, and higher free volume, which leads to stress concentration and defect in the material, which is in line with the previous study [43].

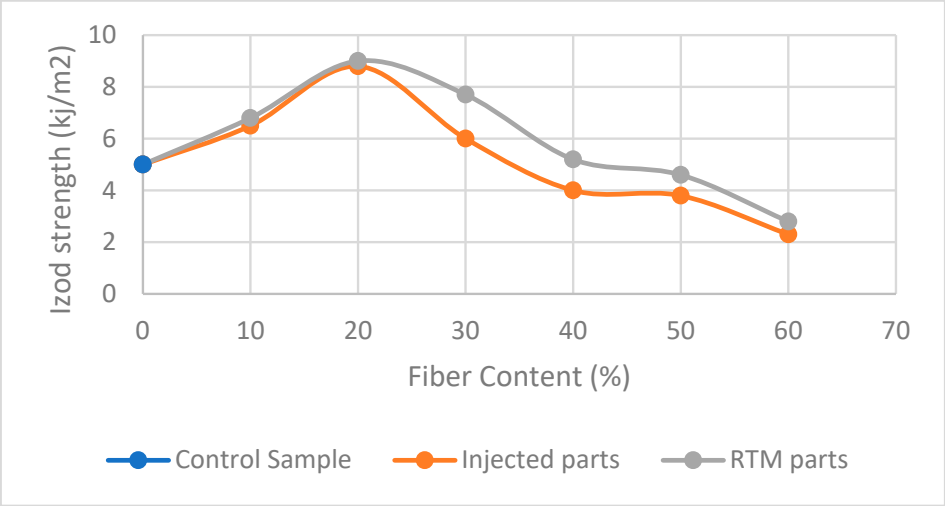


Figure 6. Izod impact strength of composite samples at varying fiber content.

3.3. Water Absorption

The effect of water absorption was observed to be more significant with the untreated fibers used in the reinforced composites than with those that contained treated fibers (Figure 7). The control samples showed no significant moisture as a non-polar material. Cellulose, in nature, is a polar material consisting of three hydroxyl(-OH) groups that form strong hydrogen bonds with water molecules, creating a partial negative charge on the oxygen atom and a partial positive charge on the hydrogen atom. These tendencies give cellulose a high affinity for water, primarily because it absorbs and holds onto water molecules [44,45]. Figure 7 shows that composite with a higher fiber content (40% of RTM) absorbed less water than composite with a lower fiber content (30% of injection-molded) and composite with untreated fibers, which is pertinent to the previous study on kenaf fiber composites [44].

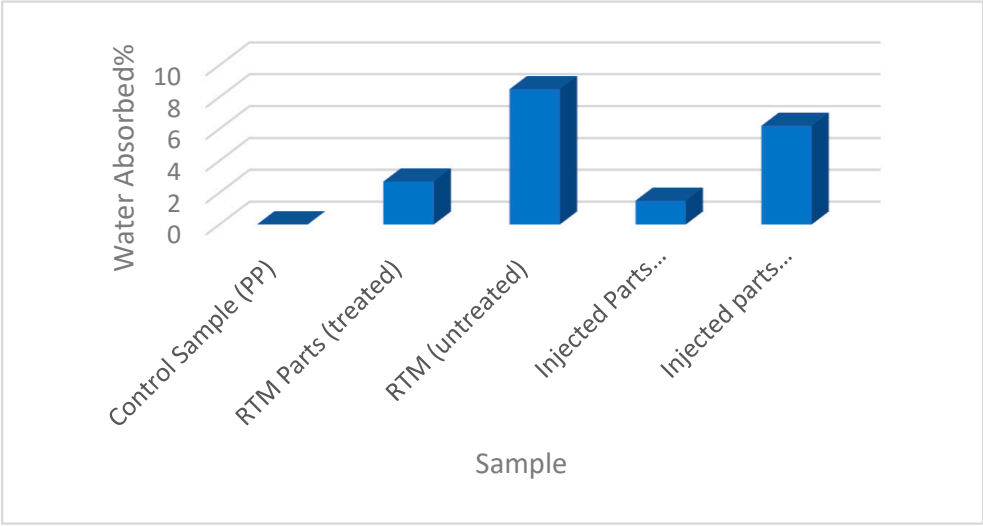


Figure 7. Water absorption test results.

3.4. Simulation

The bumper and boot spoiler application simulation was performed for the injection molding process, as shown in Figure 8, to predict crashworthiness during a collision. The central portion showed significant stress, while other areas showed low stress and strain. A low strain resulted in a material that is relatively stiff and resistant to deformation, while material with a higher strain resulted in material that is more pliable and easier to deform. The strain shows a relationship with the fiber orientation and alignment of the fibers in the composites. Randomly oriented fibers will have more isotropic mechanical properties, with similar stiffness and strength in all directions. Reinforced parts have higher stiffness and strength in the direction parallel to the fibers than in the direction perpendicular to the fibers. This is because the fibers provide reinforcement in the direction of their alignment and resist deformation in that direction. The simulation concludes that the central portion of the injection-molded sample will have comparatively more stress than other portions of the part.

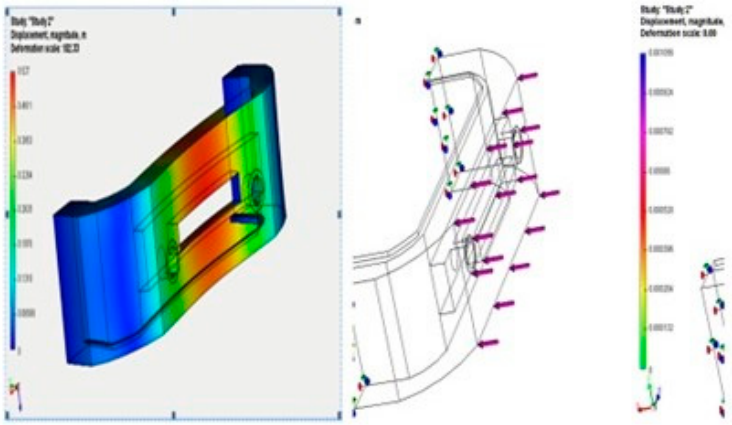


Figure 8. Simulations of displacement induced in the bumper.

3.5. Morphology Analysis

The morphology of the injection-molded composite material was investigated through SEM/EDX. Figure 9 shows surface irregularities, including brittle failure, fiber bending, micro-cracks, debonding, fiber debris, fiber defragmentation, pull-out fibers, and fracture areas in the parts. The thermo-oxidation degradation phenomena, along with fiber degradation due to higher temperature, brings about the reduction in molecular mass and, consequently, mechanical performance characteristics of the composite materials.

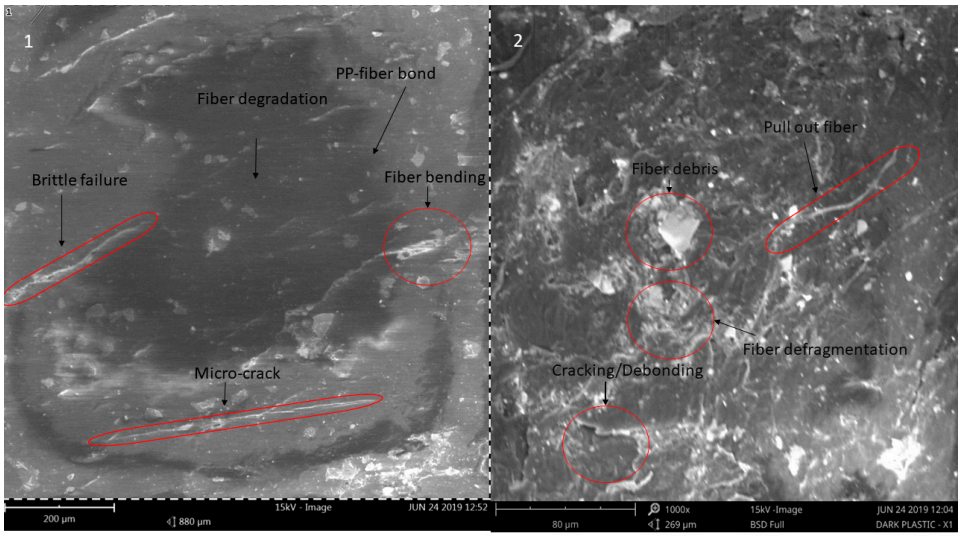


Figure 9. SEM/EDX images of the injection-molded composite sample.

4. Discussion

The inherent property of hydrophilicity of cellulosic fibers seems to be a significant drawback of using kenaf fibers as a reinforcement in plastic composites. Despite the pretreatment of fibers to reduce the moisture content, a significant amount of moisture remains compared to the control sample of PP. The water absorption test also aligns with this same fact. Mechanical performance characteristics in different fiber content percentages presented a significant improvement in most of the tests except elongation at the break. Fiber content from 10% to 40% was found to be comparable to or better than the control sample. RTM parts showed better elongation with 10% fiber content, yet the control sample possesses higher elongation. Being cellulosic materials, the reinforced kenaf fibers degraded at a higher temperature, which affected the mechanical properties of the final samples. The simulation showed that the central area of the part theoretically needs more mechanical strength, which can be adjusted based on more fiber content and fiber orientation. Moreover, fiber orientation plays a vital role in composite material strength, which will provide an RTM sample with more strength than an injection-molded sample. However, the produced part (Figure 10) did not go through any mechanical performance validation testing, such as a high-impact test, to compare the simulation results is a limitation of this study. The SEM/EDX suggests that more action is needed to compensate for the internal cracks and voids. The reduction of the moisture content and process temperature had better chances of reducing irregularities and internal cracks in the injection-molded sample.



Figure 10. Car parts produced from the sample composites.

5. Limitations and Future Research Directions

The purpose of this study is well defined pertaining to the previous research works in the same area [7]. However, this study focused more on the comparison of sample properties rather than focusing on processing techniques, assuming that processing techniques have been demonstrated in several studies already. Additionally, this study provided simulation and production of the parts. The simulation results reflected the partial analysis due to limited data availability. Moreover, the simulation figure is not complete due to data unavailability, as the research was done a couple of years back. The SEM images of the RTM sample were missing due to unavailable data, while several previous studies already analyzed the RTM sample in the recent past. However, the obtained issues with characterization tests need to be incorporated to see if further improvements could be achieved. The produced parts did not go through a collision test and other experimental verifications as per the available safety regulations. Thus, future research could be on the incorporation of the moisture control and elongation of reinforcement materials into the simulation, the production of parts, a high-impact collision test of the produced parts,

and comparative analyses of the obtained mechanical data that would provide a better understanding on the usage of kenaf fibers in areas of higher mechanical stress.

6. Conclusions

This study provides more understanding about products from renewable resources that are environmentally friendly at undoubtedly low cost and the mechanical property enhancements for polymeric materials to promote the integration of green materials and discourage carbon emission in the automotive industry to lead sustainable smart manufacturing [4,23,46]. Thus, this experiment incorporated two automotive part manufacturing methods incorporating kenaf reinforcement with demonstrations of the required simulation, design, and testing. The results of the experiment show that kenaf fibers comply with the characteristic mechanical performance tolerances for semi-structural parts reinforcement, such as automotive exterior and interior parts fabrication. A fiber content of 30–40% was found to increase the tensile strength of both injection-molded and RTM samples, while elongation at the break did not show any improvement with the increase of fiber content for both types of samples. On the other hand, flexural strength and Izod impact strength showed significant improvement at a fiber content of 10–30%. Moreover, the chemical treatment was found to have a significant impact on minimizing the moisture and water absorption of the tested samples. The orientation of fiber materials in the application has a significant impact on the properties of parts. The orientation of fibers in composite parts affected the strength and stiffness of the parts. In unidirectional composites, the fibers are oriented in the same direction, which resulted in a higher strength in RTM parts than in random orientation, which tends toward more impact resistance. Overall, kenaf fibers showed their strong candidacy to compete as a natural fiber reinforcement to produce sustainable and cost-effective composite materials in the production of automotive car parts.

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