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Effect of Fiber Loading and Alkali Treatment on Rice Straw Fiber Reinforced Composite for Automotive Bumper Beam Application

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***Abstract*— Natural fiber-reinforced composites (NFC) comprise the principal subject for the wide-ranging research in the material industries with lower costs. The use of rice straw as the reinforcement material for polymer composites intended for car bumper application is reported. This study was aimed to evaluate the composite mechanical properties of tensile and impact strength, as well as the microscopic structures, under the alkali treatment of NaOH and 10, 20, 30 and 40% (v/v) fiber loading variations. The results showed that the mechanical properties of alkali-treated composites were improved relative to the untreated fiber-reinforced composites. The highest tensile strength was observed at 14.75 MPa together with the highest impact strength at 23.52 J cm^{-1} for the alkali-treated and 30% fiber loading composites. This makes the rice straw fiber-reinforced composites at 30% fiber loading competitive against the standard commercial bumper with a maximum tensile strength of 8.08 MPa and impact strength of 23.31 J cm-1. The precise claim of alkali conduct with sodium hydroxide indicates the improvement of tensile and impact strength of the RSF-reinforced composites. This study also shows fiber loading provides various mechanical properties of the composites. The rice straw fiber, at 30% fiber loading attached with the alkali treatment comprises an alternative material to reinforce a polymer composite for automotive bumper application with a viable tensile and effect strong point against a marketable bumper.**

***Keywords*— rice straw; alkali treatment; fiber loading; automotive bumper; natural fiber composite.**

I. INTRODUCTION

Natural Fiber-Reinforced Composites (NFC) are among the leading subject for the extensive research in the material industries to lower costs and profit margins [1]. The driving force behind the research is the inexpensive cost of natural fibers, recyclability, and the desirability of green products [2]. Also, the properties of the NFC that are light in weight, low in density, strong, resistant to corrosion, with a high degree of flexibility and less machine tool wear during machining [2]–[6]. The life cycle assessment for NFC compared to glass fiber composites, also showed that they have lower environmental impacts, higher fiber content for equivalent performance, and better end-of-life incineration that results in recovered energy and carbon credit [7].

In the automotive industry, NFC applications demand a good quality on mechanical properties, particularly impact strength, flexural properties, ultimate breaking force, processing suitability, and crash behavior [8]. The uses of NFC have also been proven to be viable for more than a decade in a certain number of automotive parts [4, 8]. The research for automotive applications is for most of the time involved the systematic selection of NFC materials and the tests of their mechanical properties, such as tensile strength, impact strength, Young's modulus, and flexural properties [9], [10].

Numerous studies have indicated fiber loading as one of the main factors that significantly influence the quality of a composite. Studies towards the physical and mechanical properties were majored not only in the observations of tensile and flexural strengths [11]–[14], but also extended to thermal properties and chemical resistance [15]. In the application of natural fibers, various loading range has a wide range of response conforming to its source. The reason could be varied conditional to the experimental parameters, but one major reason is the reduction in the fiber-matrix adhesion [16].

Aside of the fiber loading, natural fibers have a lignin (wax) layer that is found throughout the fiber surface that causes poor bonding between the fibers and the matrix [1–6, 17]. This makes the adoption of the natural fibers take a detour by the needs of modifying the fibers for better engagement with the matrix. The aim is to improve the adhesion between the fiber surface and the polymer matrix, as well as increasing fiber strength [5], [8], [18]. The current observed trend for the modification of the natural fiber favors chemical modification (alkaline, silane, permanganate, peroxide, isocyanate, acetylation, acrylonitrile grafting, and malleated coupling treatment) over physical modification [2],

[19] and the alkali treatment is one of the most used chemical treatment for natural fibers. Typical chemicals used for alkali pretreatment are sodium hydroxide (NaOH) and potassium hydroxide (KOH) [20]. However, the former was found to be more superior in terms of effectiveness for biomass solubilization [21]. NaOH has been used to remove the hydrogen bonding in the network structure of fibers, thus increasing fiber's surface roughness [5], [6], [22]. Many studies have been emphasizing the improvement on mechanical properties of composites after treating the fibers with NaOH [3], [23]-[25].

Abundant sources for natural fibers are available for further exploration, and rice straw is one from many sources of natural fibers that have been widely tested for composite applications [23]–[24], [26]-[30] . Rice straw has been investigated for its utilization in cement-based composites [27] and natural filler for injection-molded high-density polyethylene (HDPE) [29]. An optimization effort has also been conducted to achieve the possible highest impact strength for polymer composites application [28], [31].

Based on our literature research, the use of rice straw for polymer composites reinforcement in the automotive industry is scarcely reported. This study aims to evaluate the mechanical properties of tensile and impact strength on rice straw fiber-reinforced polymer composite for automotive bumper applications. The effect of fiber loading was evaluated where raw (untreated) and alkali-treated fibers were used as reinforcement materials. Parameters such as tensile strength, impact strength, as well as microscopic structure observation were determined to identify the range of the fiber loading that produces polymer composites with the said quality equal to or above a standard commercial polymer bumper.

II. Materials and Methods

A. Materials

Rice Straw Fibers (RSF) from the stem of Asian rice plants (Oryza sativa) were collected from the South Province of Sulawesi, Indonesia. The straws with a minimum length of 270 mm were selectively chosen for the further cleansing process from dirt and impurities. The cleaned fibers were then cut into an average size of 20 mm in length and 4.5 mm in width. Air-tight plastic containers were used to store the RSF to prevent water absorption and microbial attack towards the fibers. The chemical composition of RSF that covers lignin, cellulose, and hemicellulose, as well as the mechanical properties of the fibers can be seen from Table 1.

TABLE I
CHEMICAL COMPONENT OF RICE STRAW [26], [32], [32]-[36] AND THE MECHANICAL PROPERTIES OF RICE STRAW [30], [32], [37]

Component/Properties	Value (Range)
Cellulose (wt.% dry)	24.0 – 48.0
Hemicellulose (wt.% dry)	21.5 – 28.0
Lignin (wt.% dry)	4.0 – 9.9
Water content (wt.% wet)	6.8 – 88
Volatiles (wt.% daf)	80.1 – 98.2
Density (g m^{-3})	0.86 – 0.87
Young’s modulus (GPa)	24.67 - 65
Tensile strength (MPa)	435 - 450

The bio-composite matrix was made from the mixture of low viscosity thixotropic variant epoxy resin (ADR246TX, Adhesive Technologies NZ Ltd) with a density of 1.2 g cm-3, Young’s modulus at 2.7 GPa, and Poisson’s ratio of 0.4, and epoxy hardener (JN Duo Component Epoxy Adhesive) at the ratio of 1:1. A polymer car bumper from one of the types of low-cost green car (LCGC) distributed in Indonesia was taken as the material for the comparative study of tensile and impact strength. The bumper was cut and machined similar to the size of the RSF-reinforced composite specimen for testing purposes.

B. Alkali Treatment of Rice Straw

The RSF that underwent an alkali treatment process (RSFNaOH) was immersed in a NaOH solution at 5 wt.% concentration for 2 hours at room temperature. The used concentration was adopted from the similar treatment of NaOH towards the same materials [27], [36]. The treated fibers were then rinsed with distilled water to remove the remainder of NaOH solution from the fiber surfaces. This was done until the pH of the washing water reached the normal range for distilled water. A drying process at 33 ˚C followed the process to reduce the moisture content and dry the fibers until the whole fibers reached their constant weight. For the RSF without NaOH treatment (RSFRaw), distilled water was used to replace the NaOH solution in the immersion process.

C. Rice Straw Fiber Loading in Composite Fabrication

A single cavity glass-mold with a dimension of 270 mm × 50 mm was used for the preparation of test specimen. The RSF-reinforced composites were fabricated using hand lay-up and open-molding method. Four types of laminate with different RFS loadings of 10%, 20%, 30%, and 40% volume fractions were generated based on the final laminate volume at 270 mm × 50 mm × t, where t was the designated thickness of laminate in mm unit. Volume fraction was selected overweight fraction because the former form considers the porosity factor resulted in the process of composite making [34]. The processes were initiated by coating the mold surface with a commercial mold-release agent (Mirror Glaze/MGH 8) until it was cured sufficiently. Each laminate was built of three different orientations of unidirectional lamina at 0˚, 45˚, and 90˚ that laid out manually with a curing process of 4 h at a normal room temperature and condition for each unidirectional lamina. The laminating resin was applied by using a paint roller to consolidate the laminate, thoroughly wetting the fibers, and removing the entrapped air. All layers of RSF were added to build the designated laminate thickness at 5 mm for the tensile test and 4 mm for the impact test specimens. Each cured laminate was cut to their respective standard dimensions for the tensile and impact strength tests.

D. Characterization

The fabricated RSF composites were characterized in terms of mechanical properties for their tensile and impact strength according to ASTM D638 for the tensile test and ASTM D256 for the impact test. A total of 5 replications for each test were performed at room temperature where the resulted data were analyzed for their mean values. The data were then compared against the obtained tensile and impact strength test resulted from a commercial standard automotive bumper material with the same ambient parameters and settings as the research specimens.

The tensile strength test used the five specimens by leaving them to break until the ultimate strength data can be observed. The specimen was shaped in a form of a dumbbell with an outer dimension of 250 mm × 25 mm × 5 mm. Each of them was securely held by top and bottom grips to RME 300 Series Electromechanical Universal Test Machines. During the test, the grips are moved apart at a constant rate to pull and stretch the specimen until failure. The force and its displacement were then continuously monitored and plotted on a stress-strain curve, and the strength was calculated from the maximum load at failure of the tensile stress.

The impact strength of the samples was measured by the Izod impact tester for determining the impact resistance. The standard specimen for ASTM was used with a size of 127 mm × 25 mm × 4 mm. The test specimen was supported as a vertical cantilever beam and broken by a single swing of a pendulum. The macro-examination on the physical structure of the composites cross-sectional area was conducted through a metallography test (WILD MPS Photo Macro), according to ASTM E340. Two metallographic specimens from the composites made of 30 and 40 volume% fiber loading were observed without specimens etching at the 6× and 12× magnifications.

III. Results And Discussion

The mechanical test results indicated that the alkali treatment and fiber loading factors contributed to the variation of tensile and impact strengths of the composites. The increase in fiber loading suggested an increase in the strength of the mechanical properties up until one fixed point. Additional fiber loading beyond those points was leading to an opposite effect on the declining strength of the said properties. Further observations also revealed that the RSF-reinforced composite has a sustainable strength over standard commercial bumper produced by the related car manufacturer. The ultimate tensile strengths for the RSF-reinforced composites ranged from 5.55 MPa to 14.30 MPa for the raw fibers and 6.99 MPa to 14.75 MPa for the alkali-treated sources. Meanwhile, the impact strength varied from 4.22 J cm-1 to 18.08 J cm-1 for the raw fiber-reinforced composites and 4.23 J cm-1 to 23.52 J cm-1 for the alkali-treated fiber-reinforced composites (Table 2).

A. *Ultimate Tensile Strength*

The alkali treatment with NaOH solution improved the ultimate tensile strength of the RSF-reinforced composites (Figure 1). This result was supported by other studies on the application of alkali treatment towards natural fibers [22], [23], [38]. The overall test results for the tensile strength revealed that the alkali-treated RSF-reinforced composites have always higher mean values compared to the raw RSF-reinforced composites at all levels of fiber loading.

The raw RSF-reinforced composites' lowest tensile strength value was recorded at 5.55 MPa at 40% fiber loading (v/v) while the highest value was observed at 14.30 MPa at 30% fiber loading (v/v). The alkali expressed the better tensile strength values treated RSF-reinforced composites with the lowest value of 6.99 MPa at 10% fiber loading (v/v) and the highest value at 14.75 MPa for 30% fiber loading (v/v) as shown in Table II. It was argued that the changes in fiber morphology and the chemical composition after an alkali treatment can affect the bonding mechanism efficiency between fibers and matrix, leading to better compatibility between them, and thus increasing the tensile strength [13], [39]. However, this is not to ignore the concentration factor involved in the treatment process, which may also affect the direction of the results [12], [22].

The increasing trend of the tensile strength values can be observed as they reached their maximum at 30% fiber loading (v/v) for both raw and alkali-treated RSF-reinforced composites. The values sharply declined at the next fiber loading level of 40% (v/v) for both treatments. The increase of the tensile strength values until their maximum at 30% fiber loading for both raw and alkali-treated composites can be explained by the rule of mixture, where adding high strength fibers to a matrix with adequate interfacial bonding should result in increasing tensile strength of the composite up to an optimum value, where the value will then decrease with the keep growing content for fiber [6], [8], [9], [12], [13].

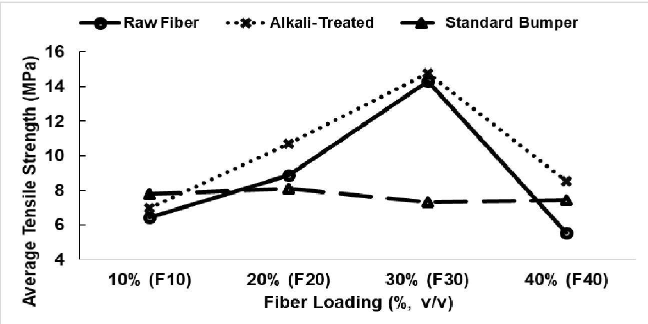

Fig. 1 Ultimate tensile strength exhibited by the RSF-reinforced composites at various fibre loadings.

It was also indicated that the alkali treatment has a correlation with the fiber loading factor [40]. Without alkali treatment, rice straw-reinforced composites tensile strength may decrease with the increasing of rice straw content. This could be rationalized by the poor surface interaction between the hydrophobic polymer chain and the hydrophilic rice straw surfaces where the hydrophilic rice straw cannot firmly adhere to the surface of the polymer chain and tend to agglomerate to each other at higher content.

Against the selected commercial bumper specimen, both RSF-reinforced composites exhibited higher mean tensile strength values at 20% and 30% (v/v) fiber loadings. Lower values were observed only for both raw and alkali-treated composites at 10% (v/v) fiber loading, and the raw RSF-reinforced composites at 40% (v/v) fiber loading. The higher mean tensile strength values that went beyond the commercial bumper tensile strength provided a good indication that the right alkali treatment application and fiber loadings for the composites could result in a competitive outcome of bumper material tensile strength. The selective range of fiber content could really affect the interlocking mechanism where the matrix-to-fiber load transfer occurred.

TABLE III
RESULTS SUMMARY OF THE ULTIMATE TENSILE STRENGTH AND IMPACT STRENGTH OF RSF-REINFORCED COMPOSITES

Fibre Loading (v/v)	Tensile Strength (MPa)			Impact Strength (J cm^{-1})		
	RSF_{Raw}	RSF_{NaOH}	Standard Bumper	RSF_{Raw}	RSF_{NaOH}	Standard Bumper
10%	6.43	6.99	7.80	8.51	4.23	19.28
20%	8.89	10.69	8.09	12.16	12.12	22.79
30%	14.30	14.75	7.31	18.08	23.52	23.31
40%	5.55	8.54	7.43	4.22	10.85	19.9

This is supported by Abishek et al. [41] in the application of jute fiber for bumper beam application, where the fiber loading factor essentially administered the resulted tensile strength.

B. Impact Strength

The impact test results showed variations over the expressed mean impact strength values from both raw and alkali-treated composites. The values were higher for the alkali-treated composites at 30% and 40% (v/v) fiber loadings compared to the raw RSF-reinforced composites. However, lower values were observed at 10% and 20% (v/v) fiber loadings for the same alkali-treated composites (Figure 2).

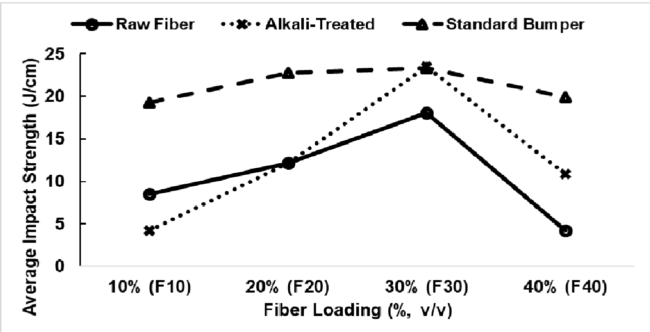

Fig. 2 Impact strength exhibited by the RSF-reinforced composites at various fibre loadings.

The highest mean impact strength value for raw RSF-reinforced composites was recorded at 18.08 J cm-1 from the 30% (v/v) fiber loading variable, while the lowest value was recorded at 4.22 J cm-1 from the 40% (v/v) fiber loading variable. The alkali-treated composites provided a wider range of impact strength values with a maximum point at 23.52 J cm-1 for 30% fiber loading composites and minimum point at 4.23 J cm-1 for 10% fiber loading composites. A comparative study by Alavudeen et al. [39] agreed upon where an alkali treatment promotes adhesion between the fibers and the matrix, thus improving the impact strength. Based on the study, the impact strength of untreated composites is 23 kJ m-2, whereas the alkali-treated composites were improved to 26 kJ m-2.

Despite the intertwined results between the raw and alkali-treated RSF-reinforced composites, the variations in fiber loading presented a similar trend with the increase of mean test values as the loading reached 30% volume fractions, followed by sharp declines as the fiber added to 40% volume fractions. This can be probably attributed to the increase in the stiffness of the composites by the increase of fiber content [42]. Several studies showed that different material selection and fiber loading may result in the variation of impact strength [14, 42]. It was shown that not only the impact strength has an opposite trend from the tensile strength, but also that the increase in fiber loading resulted in the lower value of impact strength.

In comparison with the selected commercial, automotive bumper, the overall mean of impact strength values appeared to be lower than the values of the commercial bumper. The only point where the impact strength value can reach similar to the standard bumper impact strength value was when the alkali-treatment was applied for the 30% (v/v) fiber loading composites. However, this could still be taken as a good indication that the appropriate adjustment in alkali treatment application and fiber loading can give a comparable result against a commercial bumper beam.

C. Microstructure Analysis

The composition and the presence of voids can be observed from the sectional cutting view of the composites with different fiber loadings. The microstructure observation based on the metallographic techniques revealed that all composites from 10 to 40% fiber loadings were prone to voids (Figure 3).

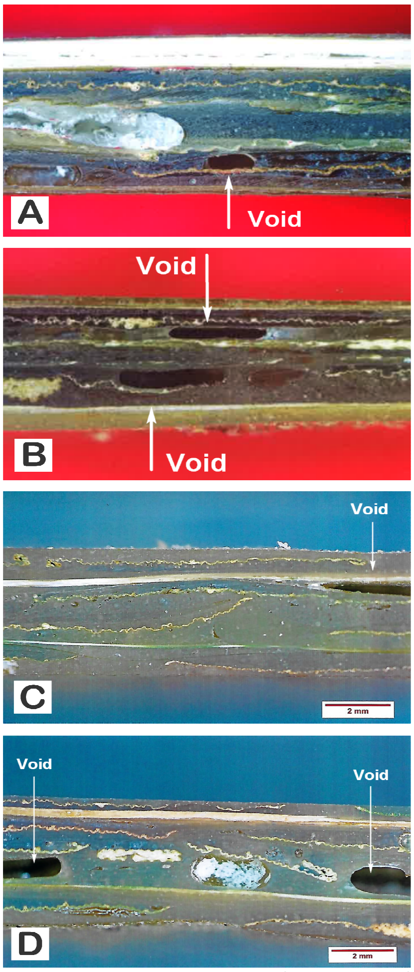

Fig. 3 Cross-sectioned microscopic structure of the RSF-reinforced polymer composite at 10% (A), 20% (B), 30% (C) and 40% (D) fibre loading (RSF_{NaOH}).

It is observed that the composites with 20 and 40% fiber loadings have a broader and higher number of voids. Regardless, voids from all range of fiber loadings seemed to be located at similar positions relative to the lamina. This is possibly due to the changing resin flow dynamics as the fiber content increased. A comparative result was reported [43] on the making of fiber composites from plant fiber. It was hypothesized that the increase in the fiber volume fractions of yarn composites was followed by the increased number of voids between the adjacent yarns. Despite the seemingly higher number of voids occurrence as the fiber content increased, there is no clear correlation between the fiber loading factor and porosity.

IV. CONCLUSIONS

The right application of alkali treatment with sodium hydroxide was proven to give an improvement in the tensile and impact strength of the RSF-reinforced composites. It was observed as well that fiber loading provided a variation towards the mechanical properties of the composites, where 30% (v/v) fiber loading led to the maximum observable values of the composite tensile strength and impact strength. In reference to the comparative result of the mechanical properties, the rice straw fiber, at 30% fiber loading coupled with the alkali treatment, can be used as an alternative material to reinforce a polymer composite for automotive bumper application with a competitive tensile and impact strength against a commercial bumper available in the market. For this specific study, the 30% RSF fiber loading coupled with the alkali treatment was proven to have a better and competitive result in car bumper application The result of this study can be used as a reference for the further research and development in the application of natural fibers as an alternative material for composites, particularly for the bumper production in the automotive industry.

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