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

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***Abstract*—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) fibre loading variations. The results showed that the mechanical properties of alkali-treated composites were improved relative to the untreated fibre-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% fibre loading composites. This makes the rice straw fibre-reinforced composites at 30% fibre loading competitive against the commercial standard bumper with maximum tensile strength of 8.08 MPa and impact strength of 23.31 J cm^{-1}.**

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

I. Introduction

Natural fibre-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 fibres, 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 high degree of flexibility and less machine tool wear during machining [2–6]. The life cycle assessment for NFC compared to glass fibre composites, also showed that they have lower environmental impacts, higher fibre 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 behaviour [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].

Fibre loading has been indicated by numerous studies 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 [10–13], but also extended to thermal properties and chemical resistance [14]. In the application of natural fibres, 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 fibre-matrix adhesion [15].

Aside of the fibre loading, natural fibres have a lignin (wax) layer that is found throughout the fibre surface that causes poor bonding between the fibres and the matrix [1–6, 16]. This makes the adoption of the natural fibres take a detour by the needs of modifying the fibres for a better engagement with the matrix. The aim is to improve the adhesion between the fibre surface and the polymer matrix, as well as increasing fibre strength [5, 8]. The current observed trend for the natural fibres modification favours chemical modification (alkaline, silane, permanganate, peroxide, isocyanate, acetylation, acrylonitrile grafting, and maleated coupling treatment) over physical modification [2] and the alkali treatment is one of the most used chemical treatment for natural fibres. Sodium hydroxide (NaOH) is used to remove the hydrogen bonding in the network structure of the fibres, thus increasing the fibres surface roughness [5, 6, 17]. Many studies have been emphasizing the improvement on mechanical properties of the composites after the treating the fibres with NaOH [3, 18, 19].

Abundant sources for natural fibres are available for further exploration, and rice straw is one from many sources of natural fibres that has been widely tested for composite applications [20–27]. The natural fibre has been investigated in its utilization for cement-based composites [24] and natural filler for injection moulded high-density polyethylene (HDPE) [26]. An optimization effort has also been conducted to achieve the possible highest impact strength for polymer composites application [25].

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 fibre-reinforced polymer composite for automotive bumper applications. The effect of fibre loading was evaluated where raw (untreated) and alkali-treated fibres were used as the reinforcement materials. Parameters such as tensile strength, impact strength, as well as microscopic structure observation were determined to identify the range of the fibre 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 fibres (RSF) from the stem of Asian rice plant (Oryza sativa) were collected from the South Province of Sulawesi, Indonesia. The straws with a minimum length of 270 mm were selectively chosen for further cleansing process from dirt and impurities. The cleaned fibres 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 fibres. The chemical composition of RSF that covers lignin, cellulose, and hemicellulose, as well as the mechanical properties of the fibres can be seen from Table 1.

TABLE I
CHEMICAL COMPONENT OF RICE STRAW [20], [27-30] AND THE MECHANICAL PROPERTIES OF RICE STRAW [25], [27], [31]

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 the testing purposes.

B. Alkali Treatment of Rice Straw

The RSF that underwent an alkali treatment process (RSF_{NaOH}) were immersed in a NaOH solution at 5 wt.% concentration for 2 hours at room temperature. The treated fibres were then rinsed with distilled water to remove the remainder NaOH solution from the fibre 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 fibres until the whole fibres reached their constant weight. For the RSF without NaOH treatment (RSF_{Raw}), distilled water was used to replace the NaOH solution in the immersion process.

C. Rice Straw Fibre Loading in Composite Fabrication

A single cavity glass-mould with the dimension of 270 mm × 50 mm was used for the preparation of tests specimen. The RSF-reinforced composites were fabricated using hand lay-up and open-moulding method. Four types of laminate with different RFS loadings of 10%, 20%, 30%, and 40% volume fractions were generated based on the laminate final volume at 270 mm × 50 mm × *t*, where *t* was the designated thickness of laminate in mm unit. Volume fraction was selected over weight fraction because the former form considers the porosity factor resulted in the process of composite making [32]. The processes were initiated by coating the mould surface with a commercial mould-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 fibres, 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 characterised in terms of mechanical properties for their tensile and impact strength according to ASTM D638 for tensile test and ASTM D256 for the impact test. A total of 5 replications for each test were performed at a room temperature where the resulted data were analysed 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 Izod impact tester for determining the impact resistance. The standard specimen for AST[illegible] was used with the 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% fibre 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 fibre loading factors contributed to the variation of tensile and impact strengths of the composites. The increase in fibre loading suggested an increase in the strength of the mechanical properties up until one fixed points. Additional fibre 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 fibres 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 fibre-reinforced composites, and 4.23 J cm-1 to 23.52 J cm-1 for the alkali-treated fibre-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 fibres [17, 18, [illegible]]. 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 fibre loading.

The raw RSF-reinforced composites lowest tensile strength value was recorded at 5.55 MPa at 40% fibre loading (v/v) while the highest value was observed at 14.30 MPa at 30% fibre loading (v/v). The better tensile strength values were expressed by the alkali treated RSF-reinforced composites with the lowest value of 6.99 MPa at 10% fibre loading (v/v) and a highest value at 14.75 MPa for 30% fibre loading (v/v). It was argued that the changes in fibre morphology and chemical composition after an alkali treatment can affect the bonding mechanism efficiency between fibres and matrix, leading to the better compatibility between them, and thus increasing the tensile strength [12, 34]. However, this is not to ignore the concentration factor involved in the treatment process, that may also affect the direction of the results [11, 17].

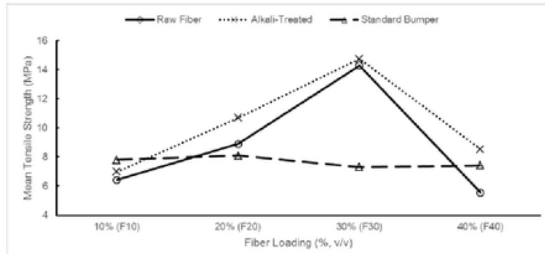

Fig. 1 Ultimate tensile strength exhibited by the RSF-reinforced composites at various fibre loadings.

The increasing trend of the tensile strength values can be observed as they reached their maximum at 30% fibre loading (v/v) for both raw and alkali-treated RSF-reinforced composites. The values sharply declined at the next fibre loading level of 40% (v/v) for both treatments. The increase of the tensile strength values until their maximum at 30% fibre loading for both raw and alkali-treated composites can be explained by the rule of mixture, where adding high strength fibres 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 increasing content of fibre [6, 8, 9, 11, 12].

It was also indicated that the alkali treatment has a correlation with the fibre loading factor [27]. 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) fibre loadings. Lower values were observed only for both raw and alkali-treated composites at 10% (v/v) fibre loading, and the raw RSF-reinforced composites at 40% (v/v) fibre 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 fibre loadings for the composites could result in a competitive outcome of bumper material tensile strength. The selective range of fibre content could really affect the interlocking mechanism where the matrix-to-fibre 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. [35] in the application of jute fibre for bumper beam application, where the fibre 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) fibre loadings compared to the raw RSF-reinforced composites. However, lower values were observed at 10% and 20% (v/v) fibre loadings for the same alkali-treated composites (Figure 2).

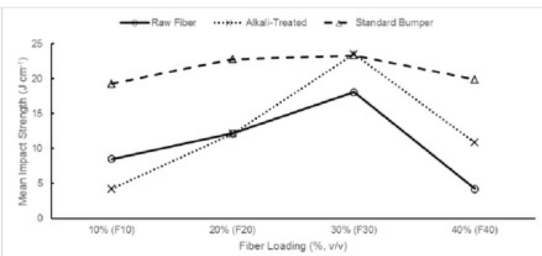

Fig. 2 Impact strength exhibited by the RSF-reinforced composites at various fibre loadings.

The highest mean impact strength value for raw RSF-reinforced composites was recorded at 18.08 J cm^{-1} from the 30% (v/v) fibre loading variable, while the lowest value was recorded at 4.22 J cm^{-1} from the 40% (v/v) fibre loading variable. The alkali-treated composites provided a wider range of impact strength values with maximum point at 23.52 J cm^{-1} for 30% fibre loading composites and minimum point at 4.23 J cm^{-1} for 10% fibre loading composites. A comparative study by Alavudeen et al. [34] agreed upon where an alkali treatment promotes adhesion between the fibres 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 fibre 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 fibre added to 40% volume fractions. This can be probably attributed to the increase of the stiffness of the composites by the increase of fibre content [36]. Several studies showed that the different material selection and fibre loading may result to the variation of impact strength [13, 36]. It was shown that not only the impact strength has an opposite trend from the tensile strength, but also that the increase in fibre loading resulted in the lower value of impact strength.

In a 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) fibre loading composites. However, this could still be taken as a good indication that the appropriate adjustment in alkali treatment application and fibre 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 fibre loadings. The microstructure observation based on the metallographic techniques revealed that both composites with 30% and 40% fibre loadings were prone to voids (Figure 3 and 4).

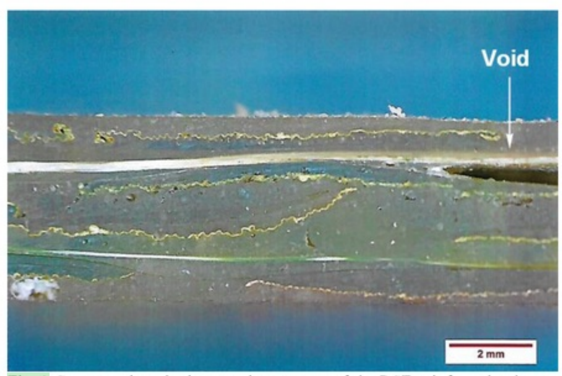

Fig. 3 Cross-sectioned microscopic structure of the RSF-reinforced polymer composite at 30% fibre loading (RSF_{NaOH}).

It is observed that the lower loading at 30% generally formed voids between the lamina layers. Increasing the fibre load to 40% further results in a higher number of voids located at the similar position relative to the lamina. This is possibly due to the changing resin flow dynamics as the fibre content increased.

A similar result was reported [32] on the making of fibre composites from plant fibre. The increase in the fibre 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 fibre content increased, there is no clear correlation between the fibre loading factor and porosity.

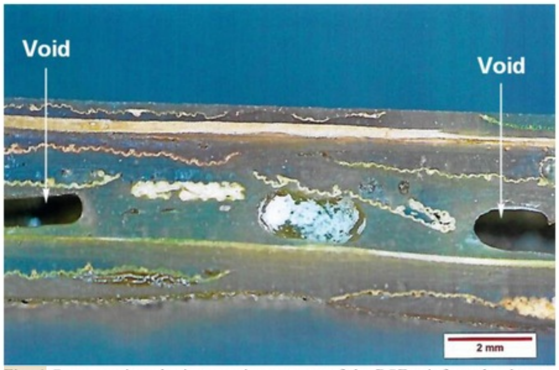

Fig. 4 Cross-sectioned microscopic structure of the RSF-reinforced polymer composite at 40% fibre loading (RSF_{NaOH}).

IV. CONCLUSIONS

The right application of alkali treatment with sodium hydroxide was proven to give an improvement in tensile and impact strength of the RSF-reinforced composites. It was observed as well that fibre loading provided a variation towards the mechanical properties of the composites, where 30% (v/v) fibre loading led to the maximum observable values of the composite tensile strength and impact strength.

In a reference to the comparative result of the mechanical properties, the rice straw fibre, at 30% fibre 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 fibre 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 fibres as an alternative material for composites, particularly for the bumper production in the automotive industry.

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