A Comparative Analysis on the Mechanical Properties of Abaca, Banana, and Coir Fiber Reinforced Polymer Rebars

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Abstract: The researchers conducted a comparative analysis between abaca, banana, and coir FRP rebars to introduce more local and ecological composite materials to the construction industry. This research aims to analyze the mechanical properties of abaca, banana, and coir FRP composites and determine the appropriate chemical treatment and fiber content to yield the most optimum values for each. The values of each composite were compared to each other through bar graphs. The data collected from previous studies were limited to the mechanical properties of tensile, flexural, and impact strength and chemical treatment and fiber content parameters. The type of chemical treatment and the amount of fiber was different among the three NFRP composites. Moreover, abaca had the highest flexural strength, the banana had the highest tensile strength, and coir had the highest impact strength.

Key Words: FRP composite; natural fiber; rebars; mechanical properties; NFRP

1. INTRODUCTION

Rebars are reinforced in concrete structures to increase concrete's tensile strength due to its tension weakness (What is Rebar? Types and Grades of Steel Reinforcement, 2018). Deformed steel rebars are frequently used; however, these types of rebars are corrosive and expensive. Researchers have proposed fiber-reinforced polymer (FRP) rebar as an alternative. They are characterized as lightweight and high strength-to-weight ratio (El-Hassan & El Maaddawy, 2019). FRP rebars are composite materials made of polymer matrix with reinforced fibers (Belarbi & Acun, 2013). Fibers of FRP's are usually synthetic (Begum & Islam, 2013). However, synthetic FRP composites have serious disadvantages: high cost, high density, non-renewable, and high energy consumption. Synthetic FRP composite production results in increased carbon emissions (Sanal & Verma, 2018). The architecture, engineering, and construction industry consume approximately 23% of national energy and produces 40% of carbon emission (Seungho & Seunguk, 2017).

The research problem covers Sustainable Development Goals, 12 & 13, and 9 & 11. Natural FRP (NFRP) rebar is recognized as an ecological alternative to synthetic FRP rebar. Their advantages include low cost, low density, sustainability, and minor damage to processing equipment (Punyamurthy, Sampathkumar, Ranganagowda, et al., 2014). In this study, NFRP rebars, specifically abaca, banana, and coir FRP, were compared. Abaca, banana, and coir fibers are leaf fibers (Mohammed et al., 2015) available in the Philippines. They are used in producing FRP rebars due to their immense mechanical strength, resistance to saltwater damage and decaying, long fiber length, high tensile and flexural strength (Punyamurthy, Sampathkumar, Bennehalli, & Badyankal, 2014).

This research aims to analyze and compare the mechanical properties (tensile, flexural, and impact strength) of abaca, coir, and banana FRP composites, investigate their mechanical properties when chemically treated, and determine the appropriate fiber content for each. This study may benefit civil and structural engineers, students, and future researchers in finding more local and affordable resources in reinforced concrete and masonry structures.

2. METHODOLOGY

2.1 Nature of Data

The study used secondary sources published from 2010-2020. Sources were collected from databases of Google Scholar, Science Direct, and EBSCO hosts. The numerical data of the mechanical properties were arranged into tables and graphs in Microsoft Excel.

2.2 Identifying Research Objectives

Peer-reviewed journals were used to provide general information about NFRP composites. The study focused on three natural fibers: abaca, banana, and coir fibers. Studies have shown that each kind of NFRP composite requires a certain amount of fiber content and a specific type of chemical treatment to achieve optimum mechanical properties. This led to the formulation of the main research objectives for the study.

2.3 Data Collection

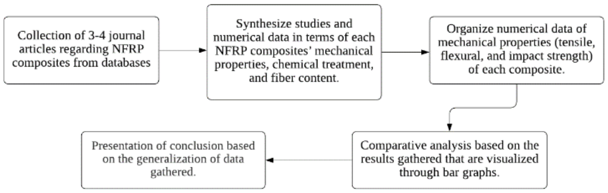

Figure 2.2 *General Procedure of the Study*

Above is the general procedure of the study. Three to four journal articles per composite were chosen based on their abstract. Selected articles provided the effect of fiber content and chemical treatment on mechanical properties. Parameters such as fiber length and type of matrix were excluded. Upon synthesis of the studies, numerical data of each NFRP composites' mechanical properties were collected. The data collection was patterned after a literature review of natural FRP composites by Mahir et al. (2019).

2.4 Data Organization and Analysis

The researchers arranged numerical data of mechanical properties: tensile, flexural, and impact strength into tables. Abaca, banana, and coir FRP composites had separate tables showing their mechanical properties, corresponding fiber content, and chemical treatment. Mahir et al. (2019) arranged each resin type into tables that show its corresponding fiber type and content and chemical treatment.

Table 2.1 *Sample table*

Fiber content (wt. %)	**Chemical treatment**	**Tensile strength (MPa)**	**Flexural strength (MPa)**	**Impact strength (mJ/mm²)**	**Authors**
40	Benzene diazonium chloride	-	-	7.68	(Punyamurthy, R. et al, 2014)

Each mechanical property had a bar graph that compared the most optimum mechanical properties of each composite. Another review about natural FRP composites conducted by Vigneshwaran et al. (2020) used bar graphs to compare tensile, flexural, and impact strength among different polypropylene types of natural fiber composites.

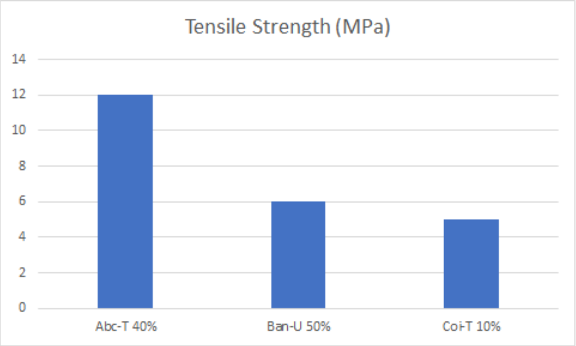

Figure 2.2 Sample Bar Graph

3. RESULTS AND DISCUSSION

3.1 Chemical Treatment and Fiber Content

Chemical treatment aids in the polymer-fiber adhesion by improving compatibility between the hydrophilic fiber and hydrophobic polymer. SEM micrographs analyzed by Rahman et al. (2009) show that untreated abaca fibers display multiple fiber pullouts, micro-voids, and fiber agglomeration resulting in poor fiber-matrix adhesion while treated fibers display better fiber-matrix adhesion. SEM micrographs show that chemical treatment removes hemicellulose and lignin in the fiber, resulting in increased surface roughness (Punyamurthy, Sampathkumar, Bennehalli, Patel, et al., 2014). In table 3.1, benzene diazonium chloride ($(C_6H_5N_2)Cl$) treatment is mainly included in abaca FRP composites since this treatment exhibit a significant increase in tensile, flexural, and impact strength (Punyamurthy, Sampathkumar, Bennehalli, & Badyankal, 2014). $(C_6H_5N_2)Cl$ treatment lessens the hydrophilic nature of fibers to increase fiber-polymer compatibility through the coupling reaction with the -OH group, producing diazo cellulose compound.

Mechanical properties of abaca FRP composites increased towards the fiber content of 40% then gradually decreased when the fiber content is more than 40% (Punyamurthy, Sampathkumar, Bennehalli, Patel, et al., 2014). As observed in the SEM micrograph analyzed by Punyamurthy, Sampathkumar, Ranganagowda, et al. (2014), the composite with more than 40% fiber content has excess fiber not homogenized with the polymer, while the composite with less than 40% fiber content has fiber fractures which caused inefficient stress transfer. This being the case, 40% fiber content is the most appropriate amount.

Table 3.1 *Mechanical Properties of Abaca FRP composite*

Fiber content (wt.%)	Chemical treatment	Tensile strength (MPa)	Flexural strength (MPa)	Impact strength (mJ/mm^2)	Authors
40	Benzene diazonium chloride	-	-	7.68	(Punyamurthy, Sampathkumar, Bennehalli, Patel, et al., 2014)
40	Benzene diazonium chloride	73.5	81.2	6.81	(Punyamurthy, Sampathkumar, Ranganagowda, et al., 2014)
10	Benzene diazonium salt	31.2	55.1	4.5 x 10^{-5}	(Rahman et al., 2009)
25	Benzene diazonium salt	28.7	56	5.3 x 10^{-5}	(Rahman et al., 2009)
40	Benzene diazonium chloride	73.1	-	-	(Punyamurthy, Sampathkumar, Bennehalli, & Badyankal, 2014)

In table 3.2, alkaline treatment for banana fibers exhibited the most optimum mechanical properties. Alkaline treatment removes hemicellulose and other non-cellulosic substances from the fiber surface thus, improving fiber-matrix adhesion and tensile strength (Komal et al., 2018). SEM micrographs show that alkali-treated banana fibers have clean surfaces and slightly separated fibers (Prasad et al., 2016). The alkaline treatment provides better flexural strength by improving fiber stiffness.

Mechanical properties of untreated fibers decreased when fiber content increased due to weak fiber-polymer compatibility (Prasad et al., 2016). Significant fiber content caused stress transfer inefficiency between the fiber and polymer. This trend is also observed in the tensile strength of treated fibers (Komal et al., 2018). Impact strength decreased as untreated fiber content increased, but improvement in values is seen in the fiber content range of 15%-30%. Although, for the flexural strength of treated fibers, it is observed that values increased as fiber content increased due to improved fiber stiffness. 50% fiber content displayed excellent results to withstand large load amounts (Aswin et al., 2014). In terms of flexural strength and impact strength, 60% fiber content exhibited maximum values.

Table 3.2 *Mechanical Properties of Banana FRP composite*

Fiber content (wt.%)	Chemical treatment	Tensile strength (MPa)	Flexural strength (MPa)	Impact strength (mJ/mm^2)	Authors
20	-	13.5	22.5	-	(Chester, P., & Jordan, W., 2017)
50	-	112.58	64.68	9.48	(Aswin et al., 2014)
60	-	98.34	77.21	11.2	(Aswin et al., 2014)
25	Alkali treatment	10.9	19.2	11.8	(Prasad, N., Agarwal, V. K., & Sinha, S., 2016)
25	Acrylic acid treatment	10.7	19.9	12.3	(Prasad, N., Agarwal, V. K., & Sinha, S., 2016)
10	Alkaline treatment	28	58	-	(Komal et al., 2018)
20	Alkaline treatment	27	61	-	(Komal et al., 2018)

Coir fiber treated with benzene diazonium treatment exhibit optimum mechanical properties. In table 3, benzene diazonium treatment had the highest tensile strength and flexural strength (Haque et al., 2010). Benzene diazonium treatment caused effective stress transfer between coir fiber and polymer, resulting in improved fiber-polymer matrix adhesion. Sodium bicarbonate treatment does not improve the mechanical properties of fiber since it did not significantly modify the fiber surface for better fiber-polymer compatibility (Santos et al., 2019). However, sodium bicarbonate treatment displayed better impact strength and flexural strength values due to longer treatment time, which caused improvement of fiber stiffness.

The tensile strength of treated composites increased as fiber content decreased. Haque et al. (2010) tested composites with different fiber loadings, 15% being the lowest, and the results showed that 15% got the maximum values of tensile strength. Stress transfer in the composite is more effective in less fiber content. Flexural strength and impact strength of treated composites increased as fiber content increased due to the improved stiffness of the composite. This trend is also the same for untreated fibers. Naveen et al. (2013) observed the tensile strengths of untreated composites at different fiber contents. Maximum values of tensile strength are kept at the lowest fiber content (5%).

Table 3.3 *Mechanical Properties of Coir FRP composite*

Fiber content (wt.%)	Chemical treatment	Tensile strength (MPa)	Flexural strength (MPa)	Impact strength (mJ/mm^2)	Authors
15	benzene diazonium salt	30.1	56.2	5.6 x 10^{-5}	(Haque et al., 2010)
30	benzene diazonium salt	26.3	58.5	6.2 x 10^{-5}	(Haque et al., 2010)
-	Sodium bicarbonate treatment	18.77	28.37	18.03	(Santos et al., 2019)
-	Sodium bicarbonate treatment	12.53	40.44	6.38	(Santos et al., 2019)
-	Alkali treatment	23.8	40.4	-	(Yan et al., 2016)
5	-	25.2	-	-	(Naveen et al., 2013)

3.2 Tensile Strength

In figure 3.1, coir FRP has the lowest value of tensile strength. Raw coir fibers have low tensile strengths (Yan et al., 2016). This is caused by the chemical composition of coir fiber which contains low cellulose content and large micro-fibrils angle. On the other hand, raw abaca fiber (Punyamurthy, Sampathkumar, Bennehalli, Patel, et al., 2014) and raw banana fiber (Prasad et al., 2016) naturally have high tensile strengths due to their high cellulose content. Untreated banana fiber has the highest value since its fiber content is 50% which is the appropriate fiber content for banana FRP's. Figure 3.1 shows that banana untreated FRP has the highest tensile strength due to fiber's high cellulose content and proper fiber content in the composite.

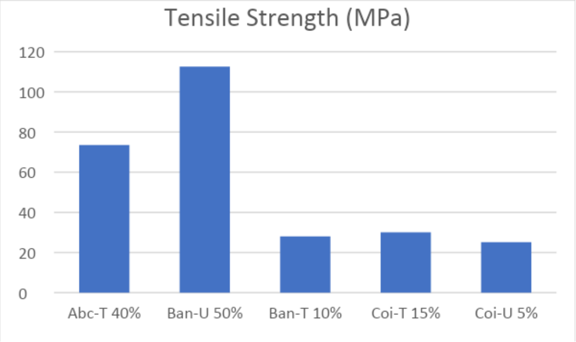

Figure 3.1 *Tensile Strength of composites*

3.3 Flexural Strength

Abaca and banana fiber FRP display better flexural strength, as seen in Figure 2. Flexural strength of abaca and banana fibers is nearer to that of glass fibers (Punyamurthy, R., Sampathkumar, D., Bennehalli, B., & Badyankal, P., 2014) (Prasad et al., 2016). Abaca FRP treated with 40% fiber content displayed the highest flexural strength. Banana FRP had the lower value since broken banana fibers are arranged perpendicular to the application of flexural loads, shown in SEM micrographs (Aswin, et al., 2014). Banana untreated displayed better flexural strength than banana treated because the fiber content of the untreated FRP is 60%.

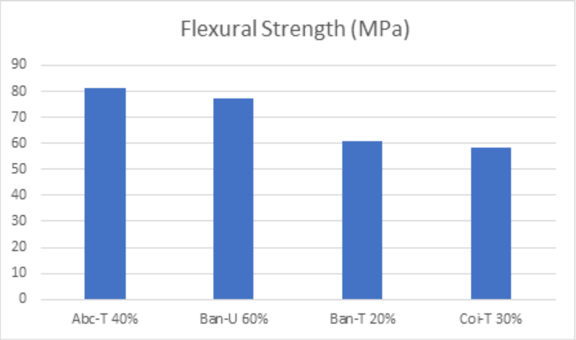

Figure 3.2 *Flexural Strength of composites*

3.4 Impact Strength

In figure 3, treated coir FRP showed the highest impact strength. SEM micrographs show that low impact strength is associated with better fiber-matrix adhesion and gives rise to fiber fracture, reduced fiber pull-out, and low energy dissipation (Santos et al., 2019). Hence, coir treated FRP is the most optimum because its chemical treatment, sodium bicarbonate, causes poor fiber-matrix adhesion. Abaca treated FRP displayed the lowest impact strength since its chemical treatment, benzene diazonium, is the most effective treatment for fiber-matrix adhesion, and it causes reduced fiber pull-out (Rahman et al., 2009). More fiber content requires more fiber-pullout force, thus improving impact strength (Haque et al., 2010). For this reason, 60% untreated banana FRP displayed better impact strength compared to 40% treated abaca FRP. Prasad et al. (2016) showed that impact strengths of untreated banana fibers increase from fiber contents of 15%-30%. Thus, 60% treated banana FRP has a slightly lower impact strength value than 25% untreated banana FRP.

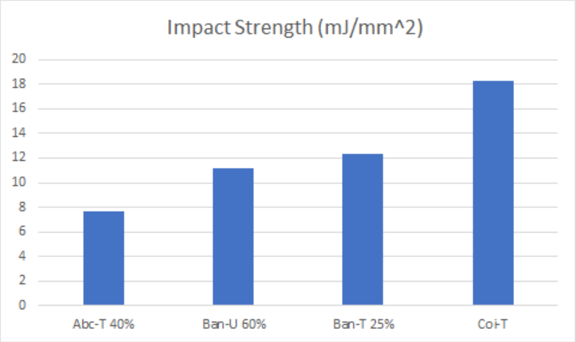

Figure 3.3 *Impact Strength of composites*

4. CONCLUSIONS

Researchers concluded that the type of chemical treatment and fiber content are different among the three NFRP composites from the studies collected. Abaca FRP composite is most optimum at 40% fiber content, benzene diazonium treatment. Banana FRP composite is most optimum at 50% fiber content, alkaline treatment. Coir FRP composite is most optimum at 15% fiber content, benzene diazonium treatment.

Comparing the mechanical properties among the three NFRP, abaca FRP had the highest flexural strength (81.2 MPa), banana FRP had the highest tensile strength (112.58 MPa), and coir FRP had the highest impact strength (18.03 mJ/mm2).

The study has the potential to exceed the objectives of the study. Modifying variables, specifically the NFRP composites with other local or hybrid NFRP's, is highly recommended to observe improvements in results. Also, other properties of composites such as thermal properties and energy & moisture absorption may be discussed to examine other factors further. Considering other chemical treatments is also encouraged. Use of more established data collection and analysis methods shall be conducted depending on the objectives. Lastly, exploring other natural fibers and renewable sources must be done to promote the optimization of such resources.

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