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COMPRESSIVE AND FLEXURAL STRENGTH ANALYSIS OF BAMBUSA BLUMEANA FIBER REINFORCED COPPER SLAG GEOPOLYMER CONCRETE

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ABSTRACT

Concrete is a widely used material in the construction industry known for its excellent compressive strength. Despite this, conventional concrete mixtures made with Portland Cement have several limitations, including sustainability, sturdiness, and unfavorable environmental effects. Thus, researchers are exploring alternative materials that can improve sustainable building practices, specifically in the Philippines. This study focuses on the performance of bamboo fiber-reinforced copper slag-based geopolymer concrete composites in terms of their compressive and flexural strength compared to Ordinary Portland Cement concrete. Bamboo fiber improves concrete flexural strength, and copper slag geopolymer acts as partial replacement for cement. Bamboo is an abundant and renewable resource that is cultivated sustainably. Copper slag is a byproduct of copper smelting. Both materials are considered sustainable, yet there is insufficient research and implementation of such in the Philippine construction industry.

Keywords: *Bamboo fiber, Copper slag, Geopolymer, Sustainability, Concrete*

INTRODUCTION

Concrete is a widely used construction material for many infrastructure projects due to its ability to resist high compressive loads while having the flexibility to receive additional reinforcement. However, traditional concrete mixtures manufactured using Ordinary Portland Cement concrete (OPC) have concerns with sustainability. Cement production is responsible for 5% to 8% of global CO_2 emissions (Walach, 2020; Banstola et al., 2021). In the past few years, there was growing interest in exploring alternative materials and technologies to address these concerns including the incorporation of other natural and/or sustainable materials into concrete such as fibers in order to minimize the volume of cement production.

Natural fiber is a feasible alternative to synthetic fiber in the construction due to increased environmental awareness of biomaterials usage. Considering bamboo fiber as a natural fiber, it is a suitable material that can be used in concrete composites due to its higher fracture toughness and quick renewability (Ahmad et al., 2023). *Bambusa blumeana* is a species of bamboo abundant in Southeast Asia, notably in the Philippines. Despite local abundance, literature on application of *Bambusa blumeana* fibers in concrete is limited (Libre Jr. et al., 2022).
Portland Cement manufacturing consumes vast amounts of energy and raw materials, consequently emitting tons of CO_2 responsible for global warming. Studies identified that partial replacement of Portland Cement in concrete significantly decreased the amount of CO_2 emissions in the atmosphere (Walach, 2020; Banstola et al., 2021). Innovative cementitious materials called geopolymers provide several advantages including less carbon emission, high durability, and increased mechanical properties compared to traditional Portland Cement-based concrete (Singh & Middendorf, 2020).

Studies were conducted to investigate the mechanical properties of copper slag as a fine aggregate replacement in concrete and cement replacement in cementitious materials. These studies found that copper slag can increase the mechanical properties of such composites at optimal percentages, particularly in compressive strength. Despite this, there is limited research into using copper slag geopolymer as cement replacement in concrete.

Theoretical Background

The construction industry is one of the main producers of CO_2 and other gasses that are potent in destroying the environment. Although previous and ongoing studies and investigations on more sustainable alternatives to cement and concrete exist to tackle such a problem, the construction industry is reluctant to replace an existing product that is a reliable material for decades in their line of work. There is still room to provide more insight on alternatives to cement in concrete mixes. This study investigates the mechanical properties of bamboo fiber reinforcement and copper slag geopolymer in concrete composites.

Bamboo fiber is studied to improve the flexural performance of concrete, yet *Bambusa blumeana* bamboo species has limited studies into the properties of its fiber as flexural reinforcement in concrete. Copper slag is a byproduct studied to be an appropriate partial replacement for both concrete fine aggregates and mortar cement but has limited research into partial cement replacement for concrete composites.

This study evaluates the effectiveness of bamboo fiber as reinforcing material and copper slag as partial replacement for cement. It assesses copper slag geopolymer and bamboo fiber mixture's flexural and compressive strength in concrete. The study relies on the data obtained from testing procedures to evaluate effectiveness of copper slag geopolymer and bamboo fiber as an additive material reinforcement in concrete using specific testing standards (ASTM C39M for testing concrete compressive strength and ASTM C293 for concrete flexural strength testing) to determine its performance. The study only considers the effect of bamboo fiber and copper slag on concrete performance and mechanical composition. It does not investigate other properties of bamboo fiber and copper slag that can influence the stability and workability of concrete nor the resistance to decay of *Bambusa blumeana* fiber.

Literature Review

Tensile and Flexural Properties of Bamboo Fiber

Bamboo has similar tensile strength to steel (28,000 N/m^2). Only a small number of modern structures have utilized bamboo due to the advancing technology and the creation of concrete and steel. Compared to steel being a manufactured construction material, bamboo can only be acquired through plantation. This results in inconsistent mechanical properties of bamboo. Its properties heavily depend on its age, species, diameter, wall thickness, position of load, radial position from outside to inside, and levels of water (Manandhar et al., 2019).

Study found that there was a noticeable increase of up to 355.82% in flexural strength for bamboo fiber-reinforced fly ash-based geopolymer concrete (Libre Jr. et al., 2023). Study on the thermal and mechanical properties of bamboo fiber presented that bamboo fiber reinforced concrete with fibers treated with 10% sodium hydroxide (NaOH) concentrated solution increased the fiber's tensile strength to 319.52 MPa (Chin et al., 2019).

Compressive Properties of Bamboo Fiber as Composite Additive

Addition of bamboo fibers beyond 1% of composite weight decreases compressive strength by a minimal drop of 3.8% to 9.6%. Samples including 0.75% fiber showed more positive results. At this additive percent, fibers worked as crack arrestors, helping slow the spread of cracks, further increasing the final strength (Ahmad et al., 2023).

Incorporating bamboo fiber and fly-ash geopolymer in cementitious material with the addition of short bamboo fiber extracted from *Bambusa blumeana* enhanced mortar compressive strength. The length and loading of bamboo fiber influenced the strength of fly ash-based geopolymers. Using Unconfined Compressive Strength, there was an increase of 292.41% compressive strength when bamboo fiber was added at fiber loading of 1.4% by weight and 20 mm fiber length.

Copper Slag as Cement Replacement for Cementitious Materials

Investigation of mechanical properties of geopolymer replacement in concrete showed that the compressive strength of geopolymer cement paste was higher than OPC. Found stable at hot temperatures, making it a viable material for fire resistive composites. The replacement of copper slag in cement reports that 5% is recommended for increasing concrete flexural strength. High percent replacement of cement in cementitious materials can decrease its mechanical properties. The highest percentage of replacement allowable for copper slag geopolymer in cementitious materials was 20% to avoid reduction in compressive and flexural properties (Chaitanya & Kumar, 2021; Jin & Chen, 2022).

Slag as Cement Replacement in Concrete

Mechanical properties of concrete were analyzed when cement is replaced with ladle furnace slag and blast furnace slag at percentages of 30%, 40%, and 50%. At 30% cement replacement, blast furnace slag increased concrete compressive strength by 10%, whilst 40% replacement yielded a 7% increase, and 50% replacement yielded a 5% increase. Flexural strength for 50% cement replacement with blast furnace slag yielded the highest increase of 4%, with 40% replacement having a 3% increase, and 30% replacement having a 1% increase in flexural strength.

Compressive strength increases when cement replacement with slag is smaller, whilst flexural strength increases when the percent replacement is higher (Parron-Rubio et al., 2019). In an investigation of compressive and flexural strength of steel slag as cement replacement in M40 concrete, the most optimum percent replacement to increase mechanical properties was 10% for both compressive and flexural strength. Higher percent replacement presented a decrease in compressive and flexural strength (Pushpa & Sharma, 2021).

Theoretical Framework

Using ASTM guidelines for concrete compressive and flexural strength, the study establishes the objective of the BFRCS-GPC (Bamboo Fiber-Reinforced Copper Slag Geopolymer Concrete) composite meets said standards to be deduced as a feasible alternative to traditional concrete mixes (American Society for Testing Standards, 2017). Preparation and extraction of the bamboo fibers is through soaking in 10% NaOH concentrated solution (Aziz et al., 2023). Copper slag is prepared through alkali solution treatment.

Bamboo fiber and copper slag geopolymer are incorporated into a concrete mix of various mix ratios before being left to cure. ASTM testing methods are utilized to evaluate composite compressive and flexural strengths. Three separate test specimens for flexural and compressive testing include the OPC control variable, copper slag geopolymer composite of varying partial replacement for cement, and BFRCS-GPC of varying percent addition of bamboo fiber and geopolymer partial replacement for cement.

To measure compressive strength of concrete, cylindrical test specimens of 100 mm diameter by 200 mm length are cast per ASTM C39M and ASTM C293 procedures (American Society for Testing Standards, 2017; American Society for Testing Standards, 2010). To determine concrete flexural strength, a beam test specimen with dimensions of 500 mm length and 150 mm width by 150 mm depth is cast per ASTM C293 procedure. Specimens were subjected to a curing time of 28 days. Results were recorded with evaluation of collected data.

METHODOLOGY

Bambusa Blumeana Fiber Extraction

Preparation of the bamboo fiber starts with the chemical treatment of the *Bambusa blumeana* splints soaked in a 10% NaOH solution for 48 hours (Chin et al., 2019). The length of each extracted bamboo fiber is approximately 20 mm.

Design of Concrete Mix Ratios

There are two groups of composite designs used in the study: the control group consisting of OPC and design samples of BFRCS-GPC. Each percent bamboo fiber added has a percent copper slag-based geopolymer cement replacement of 20% and 40%.

Mix ratio design of 1 cement: 2 sands: 4 aggregates for OPC was used. M15 grade concrete has a nominal maximum diameter of 20 mm for coarse aggregates and a minimum water-cement ratio of 0.40. For this study, 0.50 was used (Verma et al., 2022). The composites assessed for compressive load are cast into 100 mm x 200 mm cylinder molds at room temperature subjected to 28 days of curing time, while composites assessed for flexural load are cast into a 500 mm x 150 mm surface area by 150 mm height rectangular molds.

Table 1 Mix proportions for the control group.

	Samples	Cement (kg)	Sand (kg)	Gravel (kg)	Total weight per sample (kg)
OPC-C	3	0.522	1.052	2.176	3.750
OPC-F	3	3.742	7.536	15.593	26.871

Table 2 Mix design for BFRCS-GPC.

Group	No. of samples	Bamboo Fiber (% added)	Copper Slag Geopolymer (% cement replacement)
BF1.00CS20	3	1.00	20
BF0.75CS20	3	0.75	20
BF1.00CS40	3	1.00	40
BF0.75CS40	3	0.75	40

Table 3 Mix Proportions for Design Samples.

Label	Sample	Cement (kg)	Sand (kg)	Gravel (kg)	Copper slag cement wt% replacement	Total weight per sample
BF1.00CS 20-C	3	0.418	1.052	2.176	0.104	3.750
BF0.75CS 20-C	3	0.418	1.052	2.176	0.104	3.750
BF1.00CS 40-C	3	0.313	1.052	2.176	0.209	3.750
BF0.75CS 40-C	3	0.313	1.052	2.176	0.209	3.750
BF1.00CS 20-F	3	2.994	7.536	15.593	0.748	26.871
BF0.75CS 20-F	3	2.994	7.536	15.593	0.748	26.871
BF1.00CS 40-F	3	2.245	7.536	15.593	1.497	26.871
BF0.75CS 40-F	3	2.245	7.537	15.593	1.497	26.871

The table 1-3 represent the mix proportions and design specifications for different concrete samples used in an experimental study. Specifically, they provide details on the materials and their quantities used in both the control group and the experimental group incorporating bamboo fiber and copper slag in geopolymer concrete (BFRCS-GPC).

Copper Slag Activation

Copper slag geopolymer is used as the binding agent in BFRCS-GPC. Copper slag underwent alkaline activation using sodium silicate, an industrial-grade water glass solution. In obtaining a homogenous mixture, activator was dissolved in water before mixing.

Concrete Curing

After cylinder and beam molding, samples were stored in a moisture controlled environment. Water immersion of specimens was employed to maintain moisture temperature. Concrete mixtures maintained initial curing temperatures between 16 and 27 °C for up to 48 hours. After initial curing and 30 minutes after removing the molds, specimens were cured with free water maintained on their surfaces at all times at a temperature of 23° C. Drying of surfaces of the beam was prevented between removal from water storage and testing (American Society for Testing Standards, 2019).

Control Group Testing

Perform compressive test for control groups in cylinder molds, and flexural test for beam molds. Applied forces and corresponding deformation were recorded at regular intervals during testing.

Compressive and Flexural Strength Test

Perform compressive strength tests for cylinder mold design specimens by placing the lower bearing side and centered on the upper bearing side of the test. Applied forces and corresponding deformations were recorded during the test.

Perform flexural strength test for beam mold design samples by placing it in at center of the UTM, ensuring that loading devices contact the midpoint of the specimen. Gradually apply load at the center of the specimen with a specified range until failure. Record the maximum applied load and the corresponding deflection or deformation.

Data Analysis

Application of Test of Homogeneity of Variances to investigate the variability of data sets. If the significant difference is more than 0.05, then data is tested using ANOVA. Otherwise, Welch Robust test is used (University of Southern Queensland, 2022). One-way ANOVA was used due to the presence of a single independent variable. The independent variable is the control group consisting of OPC with no added bamboo fiber and copper slag.

Tukey's Honest Significant Difference (HSD) test is used as a post-hoc test (Kenton, 2024; BioSTATS, 2020). Dunnett's Test was also used as a post-hoc test in case the variances from the data are not equal (Statistics How To, 2020). Correlational analysis is applied to determine if there is a relationship between the variables (QuestionPro, 2020).

RESULTS AND DISCUSSION

Compressive Strength

Table 4 Compressive Strength of Control and Design Samples

Label	Sample #	Maximum Load (kN)	Compressive Strength (MPa)	Average Compressive Strength (MPa)
OPC-C	1	142.50	18.10	**16.00**
	2	109.35	13.90	
	3	125.85	16.00	
BF1.00C S20-C	1	40.65	5.20	**5.33**
	2	39.35	5.00	
	3	45.40	5.80	
BF0.75C S20-C	1	46.70	5.90	**6.23**
	2	50.56	6.40	
	3	50.10	6.40	
BF1.00C S40-C	1	19.30	2.50	**2.73**
	2	22.55	2.90	
	3	21.65	2.80	
BF0.75C S40-C	1	22.20	2.80	**3.03**
	2	26.00	3.30	
	3	23.85	3.00	

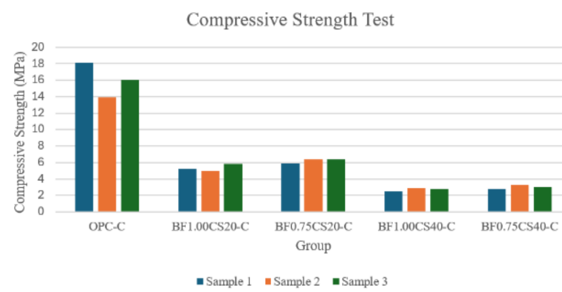

Figure 1. Compressive strength of control and design samples

Table 4 and Figure 1 present and visualize the data for the compressive strength of each control and design sample, considering the average compressive strength achieved by all three samples in each batch. Results of the control sample compressive strength test yielded an average of 16 MPa, indicating that the control sample was able to achieve the expected 15 MPa standard compressive strength for the M15 concrete mix.

BF1.00CS20-C achieved an average compressive strength of 5.33 MPa, showing an estimated 70% reduction in concrete compressive strength. BF0.75CS20-C samples achieved an average compressive strength of 6.23 MPa, showing an estimated 60% reduction in concrete compressive strength. BF1.00CS40-C samples achieved an average compressive strength of 2.73 MPa, showing an estimated 80% reduction in concrete compressive strength. BF0.75CS40-C samples achieved an average compressive strength of 3.03 MPa, showing an estimated 80% reduction in concrete compressive strength.

Design sample of 0.75% bamboo fiber added reinforcement and 20% copper slag cement replacement exhibited the smallest reduction in concrete compressive strength of 60% whilst both samples of 1% and 0.75% bamboo fiber added reinforcement with 40% copper slag cement replacement exhibited the highest reduction of concrete compressive strength of 80%.

Table 5 ANOVA Test on compressive strength

		Sum of Squares	df	Mean Square	F	Sig.
Compressive Strength (MPa)	Between Groups	353.247	4	88.312	92.505	**<.001**
	Within Groups	9.547	10	.955		
	Total	362.793	14			

Table 5 Presents the results of the ANOVA test on the concrete samples' compressive strength. Significance level is shown to be less than 0.05, indicating a significant difference among the five groups.

Table 6 Post Hoc Tukey's HSD test on compressive strengths of design groups against a control group

Control Concrete Group	Design Concrete Group	Mean Difference	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1	2	10.666666666666668	.797774682754752	**<.001**	8.0411246074768	13.2922086772588
	3	9.766666666666666	.797774682754752	**<.001**	7.1411246074766	12.3922086772586
	4	13.266666666666667	.797774682754752	**<.001**	10.6411246074767	15.8922086772588
	5	12.966666666666667	.797774682754752	**<.001**	10.3411246074767	15.5922086772587

Table 6 presents Tukey's Honest Significant Difference test on the mean compressive strength of design groups against the control group. Results show a significant difference with design samples to the control sample.

Addition of bamboo fiber and cement replacement of copper slag in the design groups had a significant effect on concrete compressive strength in terms of strength reduction. The high partial replacement of cement, 0.5 cement ratio, and addition of bamboo fiber affected the composition of the concrete sample, making it rough and brittle in appearance after the curing stage. Bamboo fiber has a high absorption rate of water and past studies found that water absorption rises linearly with the addition of bamboo fiber. This is because the inclusion of bamboo fiber in the matrix increases the material's space and cavity.

The added bamboo fiber also contributed to the decrease in compressive strength due to potential voids created when the fibers were incorporated, lowering the binding tension between cement and aggregate (Ahmad et al., 2023). Therefore, incorporating bamboo fiber and copper slag in concrete has no significant performance as a replacement for OPC in terms of compressive strength.

Data from the compressive strength tests show that the experimental group failed to match or surpass the compressive strength of the control group. By analyzing each group individually, different mix ratios of bamboo fiber and copper slag geopolymer affected the percentage of decrease in the sample's compressive strength. At 40% copper slag geopolymer cement replacement, the samples achieved an 80% strength reduction, regardless of the amount of bamboo fibers added.

Table 7 Correlational Analysis of Compressive Strength Variables

Variables	Pearson's R	Qualitative	P-Value (N=12)	Significance (α=0.05)
Bamboo Fiber – Compressive Strength	-0.1989	Very Weak Negative Correlation	0.53523	**Not Significant Correlation**
Copper Slag – Compressive Strength	-0.9612	Very Strong Negative Correlation	0.00001	**Significant Correlation**

Result of Pearson's correlation coefficient in Table 7 for bamboo fiber-compressive strength shows a negative correlation (-0.1989). As the addition of bamboo fibers increases, the compressive strength decreases. Implying that compressive strength of concrete will lessen if more bamboo fiber is added. This correlation between bamboo fiber and compressive strength was very weak, implying that addition of bamboo fiber to the mixture will not affect the concrete compressive strength at a significant value. Pearson's correlation coefficient suggests that no amount of bamboo fiber reinforcement replacing cement will exhibit a statistically significant correlation with the concrete's compressive strength. There is no clear linear relationship between bamboo fiber addition and reduction of concrete strength.

Results of Pearson's correlation coefficient for copper slag and compressive strength yielded a negative correlation (-0.9612), which in hand means that the more copper slag is added to the mixture, the compressive strength of the concrete will decrease. In this relationship, a very strong negative correlation was also observed with a P-value of 0.00001 which means that when the copper slag is added to the mixture, the compressive strength of the concrete decreases. Therefore, what can be inferred from this observation is that the addition of copper slags into the mixture is correlated to the decrease in the compressive strength of the concrete.

Previous studies stated that 1% bamboo fiber additive was the maximum %wt addition to concrete before a noticeable reduction in compressive strength. A 0.75% bamboo fiber addition to concrete was favorable in increasing compressive strength (Ahmad et al., 2023; Chin et al., 2019). Bamboo fiber has properties that contribute to increasing the strength of concrete such as low density, high impact resistance, high flexibility, low specific gravity, and less abrasiveness. Though it should be worth noting that bamboo has high water absorption that could affect the concrete's mechanical strength, this can be mitigated through chemical and physical treatment as was done through soaking in 10% NaOH solution and performing compression extraction (Aziz et al., 2023).

Previous studies have concluded that a high copper slag percentage lowers the compressive strength significantly, and lower percentages yield a much better result (Jin & Chen, 2022; Edwin et al., 2019). Using more than 20% slag replacement can negatively impact early-age strength development, confirming that 20% copper slag cement replacement is the maximum amount before a noticeable decrease in compressive strength occurs. Replacing a significant proportion with inert material like slag dilutes the amount of cement available to react and form the strong binding phases responsible for early strength. Despite other types of slag geopolymer having observed an increase in compressive strength beyond the 20% replacement level (Chaitanya & Kumar, 2021; Parron-Rubio et al., 2019; Shoaib et al., 2023), this is not the case for copper slag-based geopolymers.

Flexural Strength

Table 8 Flexural strength of control and design samples

Label	Sample #	Maximum Load (kN)	Flexural Strength (MPa)	Average Flexural Strength (MPa)
OPC-F	1	18.55	2.70	
	2	20.55	3.00	**2.97**
	3	21.30	3.20	
BF1.00 CS20-F	1	18.70	2.80	
	2	19.75	2.90	**2.80**
	3	18.15	2.70	
BF0.75 CS20-F	1	15.00	2.20	
	2	15.80	2.30	**2.57**
	3	21.90	3.20	
BF1.00 CS40-F	1	14.55	2.20	
	2	15.85	2.30	**2.27**
	3	15.65	2.30	
BF0.75 CS40-F	1	18.10	2.70	
	2	15.75	2.30	**2.57**
	3	18.55	2.70	

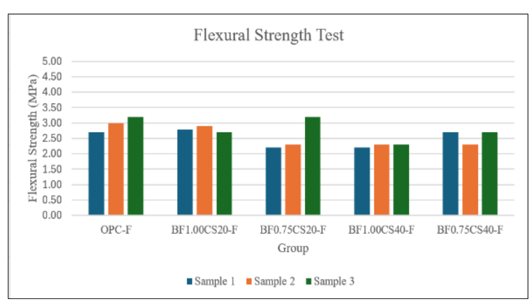

Figure 2. Flexural strength of control and design samples

Table 8 and Figure 2 present and visualize the data for the flexural strength of each control and design sample, considering the average flexural strength achieved by all three samples in each batch.

Results of the flexural strength test for the control sample yielded an average flexural strength of 2.97 MPa as seen in Table 4.4. This indicates that the control sample nearly achieved the expected strength of 3 MPa, the standard flexural strength of M15 grade concrete mix after 28 days.

BF1.00CS20-F achieved an average flexural strength of 2.80 MPa, showing minimal reduction in concrete flexural strength. Both BF0.75CS20-F and BF0.75CS40-F samples achieved an average flexural strength of 2.57 MPa, showing an estimated 15% reduction in concrete flexural strength. BF1.00CS40-F samples achieved an average flexural strength of 2.27 MPa, showing an estimated 25% reduction in concrete flexural strength.

Table 9 Welch Robust test on flexural strength

		Statistic	df1	df2	Sig.
Flexural Strength (MPa)	Welch	13.875	4	4.539	**.009**

Table 9 shows the results from the Welch Robust test on flexural strength among the five groups, indicating that there is a significant difference among all groups.

Table 10 Post Hoc Dunnett's test on mean flexural strength of design groups against the control group

Control Concrete Group	Design Concrete Group	Mean Difference	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1	2	.16666666666667	.1347191994114	**.914**	-.850027032337857	1.1833603671192
	3	.40000000000000	.349602949390051	**.890**	-1.7408291661613	2.5408291661612
	4	.70000000000000	.149071198499986	**.136**	-.441998105557905	1.841998105557905
	5	.40000000000000	.197202659436654	**.496**	-.5537891431040	1.3537891431040

Table 10 presents the results of Dunnett's test on the mean flexural strength of design groups against the control group. The mean difference is significant at 0.05 level. Upon individual analysis of each group, results from the Post Hoc test suggest that none of the experimental groups surpassed the flexural strength of the control group. Lack of significant difference implies that, on average, experimental samples performed similarly to control samples. This suggests that despite cement reduction in the beam, the presence of bamboo fiber was able to compensate for the reduced binding material by acting as additional flexural reinforcement in the concrete. When bamboo fibers are added to concrete, it helps avoid brittle failure (Abdalla et al., 2023).

Previous studies suggest that when bamboo fiber is added to concrete mix, there is an increase in flexural strength at additions of 0.5%, 1%, and 1.5%, enhancing concrete resistance to bending. However, at a bamboo fiber addition of 2.5%, there is a decrease in flexural strength compared to other bamboo fiber ratios (Kumarasamy et al., 2020). Therefore, incorporating bamboo fiber and copper slag in concrete has significant performance in terms of flexural strength.

Design mix containing 1% bamboo fiber reinforcement and 20% copper slag replacing cement achieved the best balance of flexural strength among the tested groups. This mix performed closer to the control samples than the other experimental groups.

Previous studies supported the idea that bamboo fibers possess high tensile strength due to their unique cellulose structure (J. S. V. & Wongkean, 2021). This strength helps to restrain cracks in the concrete mix, enhancing its overall flexural strength. In addition, bamboo fibers act as links that stretch across cracks, stopping them from spreading further (Ahmad et al., 2023).

Table 11 Correlational Analysis of Flexural Strength Variables

Variables	Pearson's R	Qualitative	P-Value (N=12)	Significance (α=0.05)
Bamboo Fiber – Flexural Strength	-0.0534	Very Weak Negative Correlation	0.87006	**Not Significant Correlation**
Copper Slag – Flexural Strength	-0.4270	Moderate Negative Correlation	0.16623	**Not Significant Correlation**

Table 11 shows that the negative values in Pearson's correlation coefficient indicate a negative correlation (-0.0534), in which the values of one variable increase, and the value of the other variable tends to decrease. There is a very weak negative correlation between the bamboo fiber content and flexural strength. This indicates a slight tendency for flexural strength to decrease as the amount of bamboo fiber increases. This correlation is so weak that the reduction is negligible. The high significance level suggests this correlation is not statistically significant. On the other hand, there is a moderate negative correlation (-0.4270) between the copper slag content and flexural strength. This is a stronger association compared to bamboo fiber, suggesting a more noticeable decrease in flexural strength as copper slag content increases. However, the significance level for this correlation is also not significant.

Therefore, Pearson's correlation coefficient suggests that neither the amount of bamboo fiber additive nor the level of copper slag replacing cement exhibits a statistically significant correlation with the final concrete's flexural strength. This means that there is no clear linear relationship between these factors and the reduction of concrete strength.

Copper slag as cement replacement in cementitious materials was observed to have a decrease in flexural strength at higher levels of cement replacement similarly to compressive strength. A study on different slag geopolymers showed an increase in flexural strength at lower replacement levels, unlike its compressive strength (Chaitanya & Kumar, 2021; Parron-Rubio et al., 2019). This may not be the case for BFRCS-GPC showing influence in decreasing concrete flexural strength. Yet it is worth noting that this decrease did not significantly reduce the flexural strength of the concrete composite.

Copper slag with high calcium oxide content can be a beneficial additive for concrete. This is because calcium oxide reacts with water to form additional cementitious hydrates. These hydrates fill the gaps within the concrete, making it denser and stronger. This strongly suggests that despite flexural strength reduction, copper slag-based geopolymer has such chemical properties that improve the mechanical strength of concrete, reducing its effect on flexural strength reduction.

CONCLUSION

Studies highlighted the unique cellulose structure of bamboo fibers as a key factor in its strong tensile strength (Aziz et al., 2023). This property allows bamboo fibers to effectively restrain cracks within the concrete mix. By mitigating crack formation, bamboo fibers can significantly enhance the overall flexural and compressive strength of concrete (Ahmad et al., 2023). The design samples experienced a slow decline in the maximum load it can carry after failure due to the crack restraining properties of bamboo fiber, whilst OPC experienced an immediate drop once it reached its maximum load. This translates to improved performance in structures subjected to bending forces, leading to greater durability and potentially longer lifespans.

Among the four design mix ratios, incorporating 0.75% and 1% bamboo fiber addition, and 20% and 40% copper slag geopolymer cement replacement in concrete decreases its compressive strength by 60% to 80% compared to OPC. High absorption rate of bamboo fiber and the high percent reduction of cement with copper slag geopolymer contributed to this outcome. The combined effect of bamboo fiber and copper slag on flexural strength nearly achieved the flexural strength of OPC samples. Addition of 1% bamboo fiber and 20% copper slag cement replacement presented the highest value of flexural strength amongst the design group. In comparison among the four design setups, adding bamboo fiber at an optimal percentage of 0.75% and 1% can help the concrete composites perform similarly to OPC in terms of flexural strength among the four design groups. Influence of copper slag on flexural strength can vary. There is a decrease in higher replacements of copper slag, potentially due to weaker interfacial bond between copper slag particles and cement paste, compromising the concrete's overall integrity under bending stress.

Performance of BFRCS-GPC was investigated through correlational analysis. Results show that bamboo fiber has a very weak negative correlation between compressive and flexural strength. Statistical analysis show that the correlation is not significant as there is no linear relationship between bamboo fiber addition and reduction of compressive and flexural strength. On the other hand, copper slag geopolymer attained a very strong and moderate negative correlation in terms of compressive and flexural strength, respectively. The moderate negative correlation was insignificant as there is no linear relationship between the addition of copper slag and the decrease in flexural strength. The very strong negative correlation is significant as it displays that adding more copper slag to the concrete mix will decrease composite compressive strength.

Copper slag geopolymer showed mixed results in strength development when used among the four design mix ratios. Incorporating both bamboo fiber and copper slag geopolymer in the design mix decreases compressive strength by 60% to 80% compared to OPC. While these alternatives offer environmental benefits, they can negatively impact compressive strength, especially when combined. Data assessment and statistical analysis of the flexural strength of design samples indicate that all the samples in the experimental samples have similar values to OPC. The 1% bamboo fiber and 20% copper slag replacement exhibit the highest value of flexural strength among the four design mix ratios. Beyond optimal levels of bamboo fiber addition, there's a negative effect on flexural strength due to air voids created by excess fibers. Higher levels of copper slag replacement weaken the interfacial bond with cement paste, reducing concrete integrity under bending stress. Therefore, incorporating bamboo fiber and copper slag in concrete has no significant performance as a replacement for OPC for compressive strength., but has significant performance as a replacement for OPC for flexural strength.

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