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Research Article

Mechanical and Microstructural Properties of Bamboo Fiber-Reinforced Concrete Containing a Blend of Waste Marble Powder and Waste Glass Powder

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Using blended supplementary cementitious materials in the production of concrete has a contribution to make in reducing cement consumption, as well as having a negative environmental impact. The main objective of this study was to investigate the mechanical and microstructural properties of bamboo fiber-reinforced concrete containing a blend of waste marble powder (WMP) and waste glass powder (WGP) as a partial replacement for cement. To achieve these objectives, the physical and chemical properties of concrete ingredients were studied. The design mix was done as per the American Concrete Institute (ACI) mixing procedure by using 5%, 10%, 15%, and 20% blended WMP and WGP as a replacement for cement and 0.75% bamboo fiber as an addition. The mechanical tests were conducted after samples were cured for 7 and 28 days in water. The microstructural properties of the hardened concrete from three different mixes were also determined for the 28-day cured specimens. The study result indicated improvement in compressive strength, shear stress, and bond stress at M2 (10%), whereas maximum splitting tensile strength was achieved at M1 (5%). Moreover, scanning electron microscopy (SEM) showed a denser microstructure, whereas X-ray diffraction (XRD) illustrated portlandite, calcium aluminum silicate, quartz, and calcium silicate hydrate as common phases of the concrete structure. Eventually, the experimental finding implied that using a 10% blend of WMP and WGP as a partial replacement for cement and 0.75% bamboo fiber improves fresh and hardened concrete properties.

1. Introduction

It is known that good quality concrete is the basic precondition for making concrete infrastructure. Good quality concrete is formed by properly mixing cement, water, and fine and coarse aggregate and incorporating admixtures if necessary to get the desired output product quality [1]. The process and production of cement have a negative impact on the environment and economy as well. Producing 1 ton of Portland cement releases around 1 ton of CO_2 into the atmosphere and the cement industry accounts for a contribution of 7%–8% of CO_2 emissions to our environment [2]. The production of cement is a cause of environmental heating, gas emissions, and noise pollution [3]. Cement is also one of the most expensive ingredients to form concrete due to the shortage of its usage of nonrenewable natural resources as raw material and energy intensive during the production process [2]. The production of cement not only affects much amount of natural resources but also contributes a huge amount of CO_2 and other greenhouse gases into the atmosphere because of the decarbonization of limestone and the combustion of fossil fuels that lead to health risks, respiratory problems, and environmental pollution [4]. Nowadays, the cement manufacturing industry is developing in Ethiopia [5]. Due to this, the negative impacts not only on emissions of CO_2 on the environment but also on the nation's gross domestic product (GDP) due to importing the rawest material from abroad [1].

Numerous benefits are available from using industrial waste as an alternative cementitious material as an addition or a substitution to concrete production, such as improved quality, acceleration or retardation of setting time, coloring, greater concrete strength, increased flow for the same water-to-cement ratio, enhanced frost and sulfate resistance, improved fire resistance, improved workability, and enhanced finish ability [1]. Replacing cement with different alternative materials has made a considerable contribution to keeping global conditions safe. There has been research on the usage of wastes such as marble, ceramic, tile, fly ash, glass, and plastic utilized as various forms of replacement to protect the environment [6]. The specific effects on concrete generally vary with the type of alternative material, chemical composition, temperature, mix proportion, and dosage. Waste marble powder (WMP) and waste glass powder (WGP) are two pozzolanic materials, which are used as cement in concrete by substituting partially. Marble dust is a waste product formed during marble production with a high CaO content [2]. Marble is one of the most significant metamorphic stones and is calcareous by nature as a limestone. Its production has increased to account for 50% of all natural stone production worldwide, among all other stones. The extraction, cutting, and polishing processes result in the production of a significant amount of waste powder [7], whereas WGP is produced from discarded glass in large quantities and has a high SiO_2 content [8]. Glass waste poses significant environmental problems since it is so difficult to control the vast amounts that are produced worldwide. These materials make up a sizable amount of landfill space due to their nonbiodegradable nature, which has had serious negative effects on the ecosystem in the form of pollution. The paucity of fresh locations for landfills is a result of the expanding populations in various nations. Reusing them is the ideal solution to fight the environmental dangers posed by waste glass. By effectively merging them to synthesize sustainable geopolymer manufacturing as a precursor material, construction technology might offer an advantageous and workable solution for the environmental effects of waste glass [9].

Additionally, concrete incorporates a reinforcement bar to provide tensile strength for the structure. Reinforcing bars provide concrete with high tensile strength, ductility, and flexural strength [5]. Using fibers as a reinforcement to improve the construction material's characteristics dates back many years [10]. After that, the modern development of fiber-reinforced concrete started around the 60s and rapidly grew throughout the building industry since contractors and homeowners started to recognize its many benefits [11]. Nowadays, fibers for concrete are available in different types, sizes, and shapes. Synthetic fibers can affect concrete's physical properties. The fibers can enhance properties such as cracking resistance, impact, bending, and durability. However, it has a high initial cost and a detrimental effect on the ecosystem [5]. On the other hand, the natural fiber that is preferable for reinforcing concrete is directly obtainable from an animal, plant, or mineral source and is readily available in developing countries [10]. Bamboo is one of the more abundant plants and about 67% of African bamboo resources and more than 7% of the world's total bamboo are found in Ethiopia. It is fast growing renewable and eco-friendly, as it consumes nitrogen, which could be a part of a huge effort to prevent air pollution. This plant can grow and reach its maximum height within a few years. The fiber of bamboo is a natural organic fiber that is incorporated into reinforced concrete and enhances the concrete's tensile strength [12]. The study's finding indicates that the bamboo's strength has a direct relationship with its age; the more aged bamboo has more strength [13]. Some factors are barriers to using bamboo and its fiber for engineering purposes. Lack of technologists, lack of awareness, lack of instruments, and frequent laboratory investigations were some of them [5]. To mitigate the stated environmental and economic problems, this research seeks to utilize alternative materials for cement in bamboo fiber-reinforced concrete (BFRC) by incorporating a blend of WMP and WGP, which can reduce CO_2 emissions to the environment, the cost of cement, and landfill problems. Hence, the main objective of this research is to investigate the mechanical and microstructural properties of BFRC containing a blend of WMP and WGP as a partial replacement for cement.

The research's significance is to investigate the potential use of alternative materials to partially replace the cement without affecting the mechanical and microstructural properties of BFRC. Likewise, it attains an eco-friendly and cost-efficient alternative pozzolanic material from industrial waste and the findings will further show how to optimize the proportioning of WMP and WGP to use as a cement substitution in concrete. In addition, this study will have importance in enhancing the concept of bamboo fiber in concrete production related to tensile cracks to the construction community as well as researchers. To investigate the mechanical and microstructural properties of concrete, the study conducted common tests such as chemical and physical characterization and mechanical tests, including compressive strength, splitting tensile strength, shear strength, and pullout (bond stress). Additionally, scanning electron microscopy (SEM) and X-ray diffraction (XRD) were performed to show the mineralogical and morphological characteristics of the microstructure.

2. Materials and Methods

In this section, the sources of materials used for the experimental study are described. Moreover, the methodologies were discussed, as were how materials were sourced and prepared for this experimental laboratory program.

2.1. Materials. The materials used in this study were cement, fine aggregate, coarse aggregate, water, WMP, WGP, and bamboo fiber.

2.1.1. Cement. Cement is the most common binding material used in concrete production. Ordinary Portland Cement (OPC) is designed for the general use of construction work throughout the world [14]. The cement used in this study was locally available Dangote OPC 42.5R, which satisfied the

Figure 1: Extraction process of bamboo fiber.

American Society for Testing and Materials (ASTM) C150 standard specification.

2.1.2. Fine Aggregate. This study used fresh and organic free river sand as fine aggregates from Alage, Oromia, Ethiopia. It was conducted laboratory tests as per ASTM standards. The physical characteristics such as specific gravity and absorption capacity as per ASTM C128-01, fineness modulus as per ASTM C33-03, permissible silt content limit as per ASTM C117-04, and moisture content as per ASTM C566-97.

2.1.3. Coarse Aggregate. This experimental study used basaltic crushed rock as per ASTM recommendations from Gorro Aggregate Production, Addis Ababa, Ethiopia. Physical properties of coarse aggregate, like specific gravity and absorption capacity as per ASTM C128, moisture content as per ASTM C566, and sieve analysis as per ASTM C136, were determined in the laboratory.

2.1.4. Water. The quality of water is important because contaminants can adversely affect the strength of concrete [14]. This study used water, which should be clean and free from substances that lead to an unnecessary chemical reaction, such as oil, acid, salt, sugar, silt, organic matter, alkali, and other elements that are detrimental to the concrete. Hence, potable tap water from Addis Ababa Science and Technology was used in this study for mixing and curing.

2.1.5. Waste Marble Powder. WMP is produced during the crushing and polishing of marble in the form of dust [2]. The waste marble dust collected for this study comes from the Tsegaye Marble and Granite Factory, which is located around Alam Gena, Oromia, Ethiopia, and is sieved through a 150-μm sieve for use as a replacement for cement.

2.1.6. Waste Glass Powder. WGP was obtained from the milling of glass chips wasted during preparation, cutting, and installation. The WGP was collected for the study from a locally available glass shop. Consequently, it was ground up to pass through a 150-μm sieve at the Geological Laboratory of Ethiopia.

2.1.7. Bamboo Fiber and Its Extraction. The source of bamboo used in this study was around Ambo, Oromia, Ethiopia, and it used about 3–4 years of aged bamboo after extraction to get its maximum resistance from tensile loads and avoid shrinkage due to drying. After collecting the bamboo, the fiber extraction process takes place at African bamboo around Sarbet, Addis Ababa, Ethiopia, up to the fibers reaching a diameter of 3–5 mm. Consequently, it hammered mechanically, removed the fat, and got up to 1 mm in diameter. This was taking place in Addis Ababa Science and Technology University's laboratories. The extraction process of bamboo fiber is shown in Figure 1.

2.2. Sampling. Sampling is a process in statistical analysis that helps to determine a representative number of observations from a larger population. The methodology used to take samples from a population based on the type of study and data analyzed may include techniques categorized under simple and systematic random sampling [15]. Stratified random sampling was used for the experimental program that classifies strata before taking samples randomly. It was first categorized into different compositions based on the amount of blended WMP and WGP with an optimal percentage of bamboo fiber.

2.3. Mix Design. This study examines the production of BFRC from a control mix and the partial substitution of cement by a blend of WMP and WGP. The design mix followed the American Concrete Institute, ACI-318 mixing procedure. The following techniques were relevant to this research. Three samples were cast by replacing a blended WMP and WGP partially as cement by weight for 0%, 5%, 10%, 15%, and 20% and symbolized as CM, M1, M2, M3, and M4, respectively, including the control mix for 7th- and 28th-day different strength measurements. On bamboo fiber content, all mixes have incorporated 0.75% by weight except the control mix, CM.

2.4. Test Methods

2.4.1. Tests for Physical and Chemical Properties. The study carried out tests for physical and chemical properties. Physical tests include density, moisture content, and water absorption for fine aggregate, coarse aggregate, WMP, and WGP. The specific gravity of an aggregate was considered a measure of the strength or quality of the aggregate. The specific gravity test was carried out in Addis Ababa Science and Technology University civil engineering laboratory. Likewise, water absorption as per ASTM C128 was carried out to check whether the material is porous or not.

Figure 2: Slump test.

Additionally, the study performed sieve analysis to determine the percentage of different grain sizes of aggregates and replacement material retained. This study was performed to determine the coarser, larger-sized particles, and fine aggregate distributions.

Moreover, the slump test of concrete measures the workability of fresh concrete. More specifically, it measures the consistency of the concrete in each batch [16]. This study performed a test for workability to check the fresh concrete's consistency. Consistency is a word that describes workability. The slump test is shown in Figure 2.

This study also performed a chemical composition test in the Geochemical Laboratory Directorate, Geological Survey of Ethiopia, at Addis Ababa to know the content of major and minor oxides found in the WMP and WGP based on the silicate analysis report generated after the test.

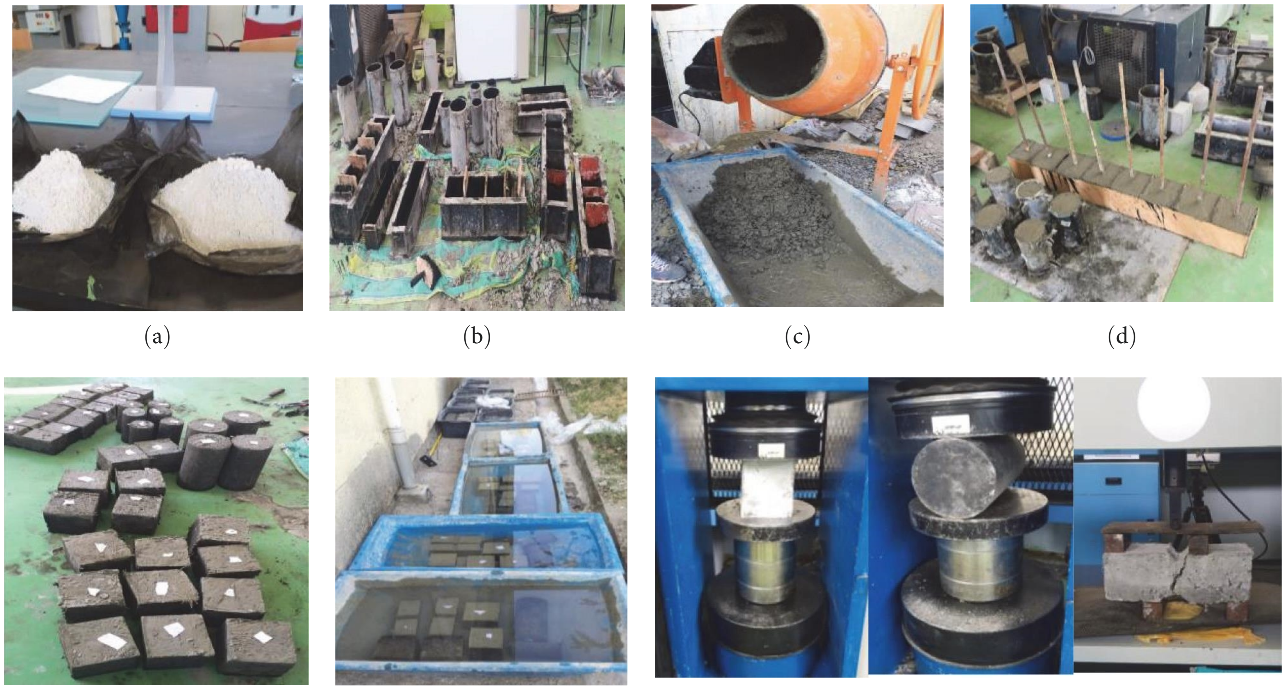
2.4.2. Tests for Mechanical Properties. This study performed a compressive strength test according to ASTM C109 to check the capacity of a material or structure under loads. This compressive test was carried out in the Addis Ababa Science and Technology University civil engineering laboratory. The 150-mm-sized cube samples were cast for each percentage replacement of WMP and WGP as cement, and those samples were soaked and cured for 7 and 28 days to check their compressive strength. After that, the results were displayed and taken on a mechanical gauge. Similarly, three 300 mm height and 150 mm $\varnothing$ cylindrical samples were cast for reinforced concrete containing bamboo fiber in 0.75% as addition and blended WMP and WGP as cement in a different composition. Consequently, those samples were soaked and cured for 28 days. Consequently, the splitting tensile test was undertaken and showed the ability to withstand tension forces. The methodologies for materials preparation and conducting mechanical tests are shown in Figure 3.

A shear test was also done in the construction material laboratory at Addis Ababa Science and Technology University to determine the shear behavior of BFRC containing blended WMP and WGP. For this purpose, double V-notched samples were prepared as recommended by ASTM standard D5379 (1993). Double V-notched shear test, also named the Iosipescu shear test, where the loads are applied in antisymmetric four-point bending, to insure a pure shear section and zero bending at the center of the samples.

Moreover, the study performed a pullout test in the construction material laboratory at Addis Ababa Science and Technology University to determine the bond strength of BFRC containing a blend of WMP and WGP as per ASTM C234. The fiber concrete samples were cast in standard cubical molds of 150 by 150 mm. Deformed steel bars have a diameter (*db*) of 14 mm and were partially embedded with a length of 120 mm along each cube taken as embedment length (*ld*) and they extend outside the concrete cube of 630 mm to allow gripping of the bars by the universal testing machine. The methodologies of test setup for determining shear stress and bond stress are shown in Figure 4.

2.4.3. Tests for Microstructural Properties. In this study, sample preparation was carried out in the construction material laboratory at Addis Ababa Science and Technology University for the microstructural investigation of hardened cement paste that was obtained immediately after conducting compressive testing. Accordingly, the cube samples were crushed, and the hardened cement in a 1 by 1 cm rectangular specimen was extracted from the inner core of the hardened concrete, which was enough for microstructure examinations. Consequently, the prepared specimens from the control and those mixes in which the compressive strengths were significantly high as compared to the other mixes M1 (5%) and M2 (10%) were placed on a benchtop SEM machine and scanned in three different resolutions: 600x, 1,100x, and 2,000x. A benchtop SEM machine is shown in Figure 5.

Besides, XRD tests were done in the Microbiology and Material Engineering laboratories at Adama Science and Technology University, Adama, Oromia, Ethiopia, to check the crystallization and mineralogical pattern of the cement, WMP, and WGP after hydration. Regarding specimen, a



(a) (b) (c) (d)

(e) (f) (g)

FIGURE 3: (a) Weighting materials, (b) oiling formwork, (c) mixing, (d) casting, (e) removing formwork, (f) curing, and (g) conducting mechanical tests.

(a) (b)

FIGURE 4: (a) Shear test setup and (b) pullout test setup.

powder prepared from the 28th-day cured and crushed samples from control, M1 (5%), and M2 (10%) was then placed on XRD apparatus model: XRD-7000 X-Ray Diffractometer. The obtained results included intensity and peak information in terms of angular position (2θ). The X-ray diffractometer is shown in Figure 5.

3. Results and Discussion

3.1. Introduction. This section presented the results, discussion, and analysis of physical, chemical, mechanical, and microstructural tests conducted in the laboratory. Test results for aggregate quality, fineness, and specific gravity for cementitious material were presented. Additionally, test results like slump, compressive, split, shear, microstructural, and pullout were discussed.

3.2. Tests on Aggregate. This study used aggregates as per ASTM recommendations. Basaltic crushed rock from Gorro Aggregate Production, Addis Ababa, Ethiopia was used as coarse aggregate, whereas river sand from Alage, Oromia, Ethiopia was used as fine aggregate.

3.2.1. Properties of Fine Aggregate. This study presented the important physical and chemical characteristics of fine aggregate. In this section, silt content, sieve analysis, moisture content, specific gravity, and absorption capacity were included.

FIGURE 5: JCM-6000 Plus Benchtop SEM machine.

TABLE 1: Silt content of fine aggregate.

Trial no.	Volume of silt deposit, A (ml)	Volume of clean sand, B (ml)	Silt content $= \frac{A}{B} \times 100\%$
1	3.2	96	3.33
2	2.8	95	2.94
3	3.6	96	3.75
Average			3.34%

(1) *Silt Content of Fine Aggregate*. The material finer than the No. 200 (75 μm) sieve in fine aggregate is considered clay or silt particles as per ASTM C117-04. These particles must not exceed the permissible limit in fine aggregate because those particles have severe effects on the fresh and hardened properties of concrete such as workability, bond strength, and durability. Hence, this experimental study used the sand after washing and avoiding organic impurities.

As shown in Table 1, this experiment conducted a jar test by taking samples of washed and dried sand in three trials. Accordingly, 3.33%, 2.94%, and 3.75% were recorded in three consecutive trials, and 3.34% was recorded as an average value that is within the recommended limit as per ASTM standards. A 3.34% silt content is not only permissible according to ASTM; the value is also below 6%, which is permissible according to the Compulsory Ethiopian Standard (CES).

(2) *Sieve Analysis and Fineness Modulus of Fine Aggregate*. This test was performed to confirm the requirements for grading fine aggregate as per ASTM C33-03. ASTM specifies that fine aggregate shall not exceed 45% after passing any sieve and being retained on the next sieve. Moreover, it specifies FM within the range of 2.3–3.1. If fine aggregates do not fulfill the requirement, ASTM says difficulties may happen with workability, pumping, or excessive bleeding, which leads to severe effects on the strength and long-term durability of concrete. The details of the sieve analysis are shown in Table 2 and Figure 6.

$$\text{Fineness modulus (FM)} = \frac{\sum \text{Cumulative coarser}}{100}, \tag{1}$$

$$\text{FM} = \frac{300.94}{100}, \tag{2}$$

$$\text{FM} = 3.0. \tag{3}$$

As shown in Table 2 and Figure 6, the cumulative passing percentage was recorded within the permissible range recommended by ASTM C33-03 for fine aggregate. In addition to this, the fineness modulus (FM) is 3.0, which is between 2.3 and 3.1.

(3) *Specific Gravity and Absorption Capacity of Fine Aggregate*. The study performed specific gravity as oven dry and saturated surface dry of fine aggregate as per ASTM C128-01 to determine the density of a solid portion of aggregate particles and provide an average value representing the sample. Moreover, absorption was undertaken to determine the percentage increase in the mass of aggregate due to water penetrating the pores of particles.

Table 3 shows that 2.13, 2.17, and 2.22 were recorded as oven-dry specific gravity, saturated surface dry specific gravity, and apparent specific gravity during an experimental test, whereas 2.04% was recorded from the laboratory experiment as absorption capacity for the fine aggregate.

(4) *Moisture Content of Fine Aggregates*. This test was performed to obtain important information about the total moisture conditions of the stockpile aggregate, which have a severe effect on the strength, water–cement ratio, water tightness, and long-term durability of the concrete. The moisture content test result is shown in Table 4, and the experimental tests result for fine aggregate is shown in Table 5. The experiment followed the procedures recommended by ASTM C566-97. Accordingly, 2.67% was recorded as the total moisture content of fine aggregate, which can adjust water requirements during concrete mix design.

3.2.2. Properties of Coarse Aggregate. The study performed physical tests for coarse aggregate as per ASTM standard specifications. FM, moisture content, loose unit weight, dry-rodded unit weight, specific gravity, and water absorption capacity were some of the laboratory tests undertaken for this study. Accordingly, the results obtained from these tests are summarized, as shown in Table 6.

3.3. Tests on Binders

3.3.1. Chemical Property of Cementitious Materials. The study performed a chemical composition test in the Geochemical Laboratory at the Geological Survey of Ethiopia to determine which major and minor oxides existed in WMP and WGP. The obtained result showed that WGP has comparable results with standards for pozzolanic material as per ASTM C618. As for WMP concern, although it cannot meet standards set by ASTM, its chemical composition is the same as limestone, which is used as the major substitution for cement because it contains CaO. The results obtained from the geochemical laboratory are shown in Table 7.

3.4. The Effect of Blended WMP and WGP on the Mechanical Properties of BFRC

3.4.1. Compressive Strength. The experimental study was carried out under controlled laboratory conditions using

Table 2: Sieve and fineness modulus of fine aggregate.

Sieve size	Weight of sample retained (g)	Percentage retained (%)	Cumulative coarser (%)	Cumulative passing (%)	ASTM C33 limits (%)
9.5 mm	0	0	0	100	100
4.75 mm	20	4.12	4.12	95.88	95–100
2.36 mm	45	9.27	13.39	86.61	80–100
1.18 mm	85	17.52	30.91	69.09	50–85
600 μm	140	28.86	59.77	40.23	25–60
300 μm	160	33	92.77	7.23	5–30
150 μm	35	7.21	99.98	0.02	0–10
Pan					
Total	485		300.94		

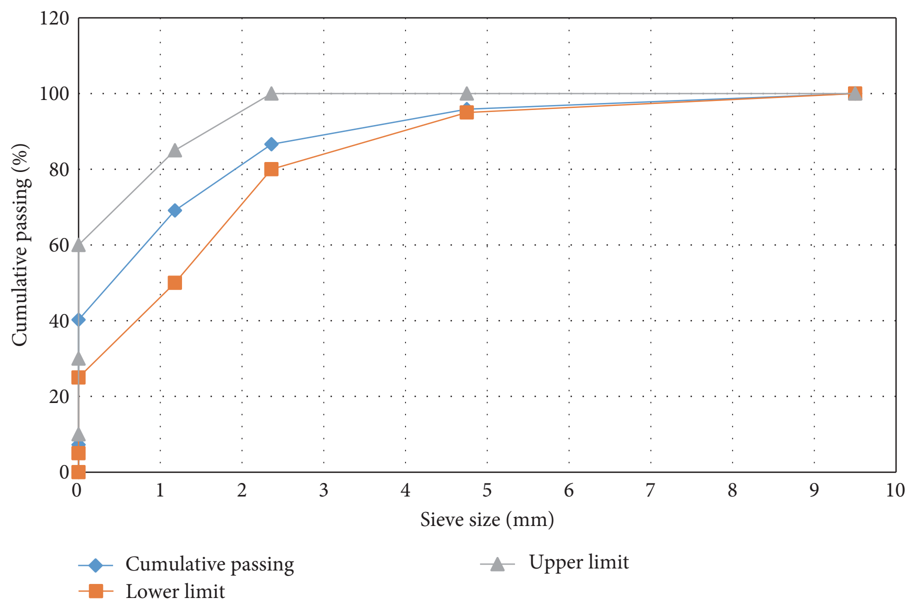


Figure 6: Sieve analysis of fine aggregate.

Table 3: Specific gravity and water absorption capacity of fine aggregate.

Description	Trial
Weight of oven dry sample (g) (D)	490
Weight of pycnometer + water (g) (B)	1,815
Weight of pycnometer + water + sample (g) (A)	2,085
Weight of saturated surface dry sample in the air (g) (C)	500
Specific gravity	
Specific gravity (OD) $= \frac{D}{C-(A-B)}$	2.13
Specific gravity (SSD) $= \frac{C}{B+C-A}$	2.17
Apparent specific gravity $= \frac{D}{D-(A-B)}$	2.22
Water absorption $= \frac{C-D}{D} \times 100\,\{\%\}$	2.04%

Table 4: Moisture content of fine aggregate.

Description	Trial
Weight of original sample (g) (A)	500
Weight of oven dry sample (g) (B)	487
Moisture content $= \frac{A-B}{B} \times 100\,\{\%\}$	2.67%

procedures as described in ASTM C109. The materials include OPC 42.5 R produced at the Dangote Cement Factory, basaltic crushed coarse aggregate from Gorro, river sand from Alage, potable water from AASTU, WMP from Tsegaye Marble and Granite Factory, WGP collected from different local shops, and milled into powder form, and aged bamboo fiber from Ambo. The test samples from a control mix and a different replacement level were cast as per ASTM Test Method C109/C109M. In replacement levels, 5%, 10%, 15%, and 20% of the weight of the cement used in the control mixture were replaced by the same weight of blended WMP and WGP.

The 150-mm-sized cube samples were cast for each percentage replacement of WMP and WGP as cement, and

Table 5: Summarized test results for fine aggregate.

Description	Test results
Fineness modulus	3.0
Moisture content (MC)	2.67%
Specific gravity	
Specific gravity (OD)	2.13
Specific gravity (SSD)	2.17
Apparent specific gravity	2.22
Water absorption	2.04%

Table 6: Summarized test results for coarse aggregate.

Description	Test results
Nominal maximum size of aggregate	20 mm
Fineness modulus	3.0
Moisture content (MC)	0.502%
Loose unit weights	1,569.3 kg/m^3
Dry-rodded unit weight	1,680 kg/m^3
Specific gravity	
Specific gravity (OD)	2.82
Specific gravity (SSD)	2.86
Apparent specific gravity	2.92
Water absorption	1.21%

Table 7: Chemical and mineralogical compositions of WMP and WGP.

Chemical name	WMP	WGP
SiO_2	5.74	70.76
Al_2O_3	0.01	0.83
Fe_2O_3	0.01	0.54
CaO	50.26	8.28
MgO	1.38	3.24
Na_2O	0.01	14.28
K_2O	0.56	1.04
MnO	0.01	0.01
P_2O_5	0.01	0.01
TiO_2	0.01	0.01
H_2O	0.2	0.18
LOI	41.26	0.21

those samples were soaked and cured for 7 and 28 days to check their compressive strength.

On experimental results, the 7th-day mean compressive strengths of CM, M1, M2, M3, and M4 were recorded as 20.71, 21.28, 23.65, 20.03, and 19.67 MPa and on the 28th-day mean compressive strengths were 32.80, 31.28, 34.67, 25.89, and 24.48 MPa, respectively. The 7th- and 28th-day mean compressive strengths of WMP- and WGP-blended BFRC were present, as shown in Figure 7.

Using blended WMP and WGP as cement replacements on BFRC enhances the compressive strength up to the optimum level. This experimental result also indicates that the 28th-day mean compressive strength increment was 5.7% when using 10% blended WMP and WGP in addition to the 0.75% optimal amount of bamboo fiber from the control mix one. Accordingly, 34.67 MPa obtained from replacing the cement by 10% achieved the expected target mean strength of the design mix of 33.5 MPa, whereas 1.1% incremental was recorded on the 7th-day mean compressive strength of M1 (10%) = 23.65 MPa, which is greater than the expected mean strength from the 7th day (22.3 MPa), and the rest 5%, 15%, and 20% blended WMP and WGP contained 0.75% bamboo fiber, giving comparable results with the control mix. Moreover, the 31.28 MPa result, as shown in Figure 7, tells us that it can achieve a comparable 28th-day result with the control mix by replacing the cement with 5% blended WMP and WGP in addition to 0.75% bamboo fiber. On the other hand, BFRC with 15% and 20% blended WMP and WGP showed a mean compressive strength reduction of 12.5% and 15.9%, respectively, compared to the control mix.

A reviewed article gives a brief overview of the results obtained from various studies. There was a study that stated that using a blend of glass and marble powder as a 10% alternative substitution material for cement resulted in an enhancement of mechanical strength. If the replacement level exceeds 10%, there is a bondage problem due to WMP needing cement paste for the surroundings [7]. The concluded optimum replacement level is 10% for marble powder and 5%–10% for glass powder [17]. To support this result, another study done on the partial replacement of cement by MWP in concrete production in Benishangul-Gumuz, Ethiopia, showed that the compressive strength increases up to 10% replacement and decreases if the replacement level exceeds 10%. Accordingly, a 10% replacement of WMP resulted in 46.77 MPa compressive strength, whereas the reference mix recorded 45.7 MPa, which shows a 10% replacement enhances the strength by 1.07 MPa as compared to the control mix for C25 grade of concrete [18].

Although there were not many experimental investigations on using blended WMP and WGP, similar feasible records were achieved by replacing the cement with one of each individually, up to 20%. Accordingly, a 10% glass powder replacement amount gave the optimum compressive strength [19, 20]. The same was reported by Manikandan et al. [21], in ternary blended geopolymer concrete mixes containing 10% metakaolin and incorporating WGP as a ground granulated blast furnace slag (GGBS) substitution, a gradual increase in compressive strength was recorded at a substitution level of 25%–35% due to the SiO_2 high reactive capability. On the other hand, it recorded gradual declines in compressive strength when the WGP had a substitution level of 25%–40% and incorporated fly ash as 10% instead of metakaolin due to its inclusion of supplementary silica fraction, which leads to increases in the silica/alumina ratios, which is the cause of the decrease in compressive strength. Similar findings were recorded by Manikandan and Vasugi [22], using WGP as a 20%–30% substitution level in geopolymer concrete incorporating aluminosilicate source materials (fly ash, GGBS, metakaolin, etc.), which improves the compressive strength characteristics. However, with the

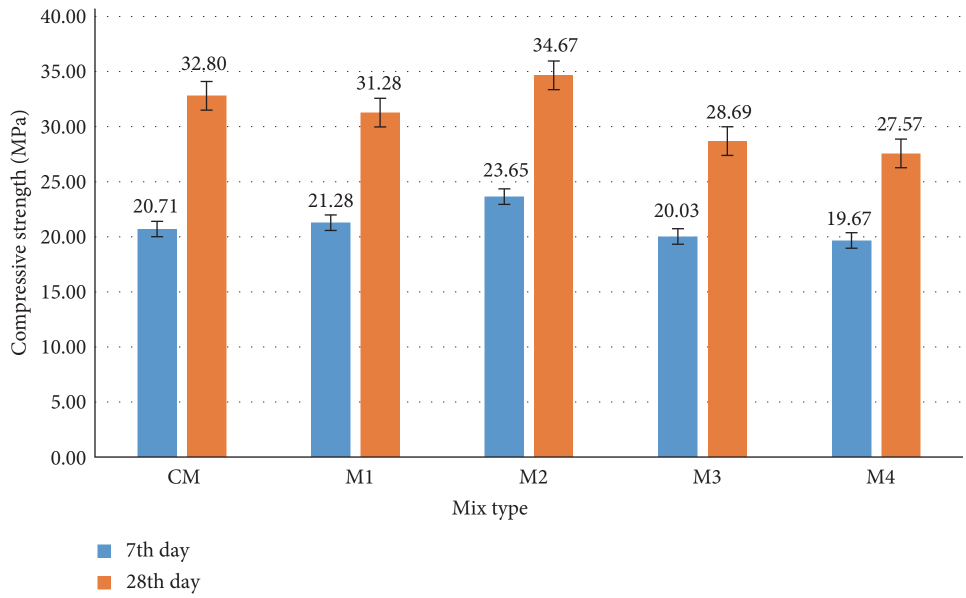


Figure 7: A 7th- and 28th-day mean compressive strength test results.

usage of WGP beyond the above stated limit, the compressive strength declines due to the brittle nature, high volume alkali formation, and lower reactivity. To add to this, it was observed that using WGP as a partial replacement up to 35% in ternary geopolymer concrete improves the compressive strength due to alumina and silica's higher dissolution capacities [23]. Moreover, the geopolymer concrete incorporating coarse aggregate, fine aggregate, and NaOH showed that as the fly ash to WGP ratio level in the mixture changed from 0% to 10%, by taking the percentage of NaOH constant 11, it was noticed that the rate of change in compressive strength reduced as 19%. Consequently, as the fly ash to WGP ratio level changes to 20%, 30%, and 40%, the compressive strength declined by 40.5%, 56%, and 76%, respectively, and the study recommended 10% of WGP as optimum [9].

The results obtained by Cagin and Artir [24] showed that the most optimal replacement level of marble powder is 5%–10%. On the other hand, another researcher [25] used a marble powder blended with tile powder for an experimental study and obtained the maximum results in compressive strength, which was enhanced by about 0.6% and 8.9% on the 2.5% marble powder and 2.5% tile powder, while it was reduced by about 17.9% and 8.95% on the 10% marble powder and 10% tile powder, for 7 and 28 days, respectively. But, a lot of research indicates that a 10%–15% replacement level of cement with marble powder gives better concrete compressive strength [18].

On the other hand, previous research, including [11], agrees that the addition of bamboo fiber at 0.75% for mix proportions has an enhancement in compressive strength. Accordingly, in this study, as shown in Figure 7, M1 and M2 recorded comparable and better results as compared to the control mix (no fiber). Although the study used an optimal 0.75% of bamboo fiber in all mix proportions except the control mix, the experimental results showed that M3 and M4 recorded mean compressive strengths of 20, 19, 27, and 28 MPa, which are lower values as compared to the control mix for the 7th and 28th days, respectively. This implied that the variation was due to the filler effect.

Another study conducted on concrete incorporating foam contents of 40 and 80 kg/m^3 with a combined 10% rice husk ash as a cement substitution and 50% WMP as a sand substitution achieved a better compressive strength as compared to the reference mix for both mixes containing 40 and 80 kg/m^3 of foam. Hence, it was concluded that using 10% rice husk ash as a cement replacement and 50% WMP as a sand replacement give the optimum level of replacement, especially at 90 days with a 40-kg/m^3 foam content [26].

As concerns fiber usage, a study done on the effect of jute fiber on the strength of C30 concrete showed a relative compressive strength loss and gain range of 4.57%–33.14% in incorporating jute fibers of different volumes into the concrete having a 5-mm length, respectively. 34.29% and 33.14% relative compressive strength loss and gain are recorded when adding jute fibers of different lengths to the concrete with 0.5% fiber volume, respectively. Thus, improvement in compressive strength can be achieved by the presence of jute fibers in the concrete [27]. Similarly, 41 N/mm^2 was recorded in the compressive strength of reinforced concrete containing 1% bamboo fiber, and the strength was incremental by 25% as compared to the strength achieved by the control mix 32.8 N/mm^2 [28].

The reported result from bamboo fiber-reinforced self-compacting concrete containing limestone powder revealed that an increment in compressive strength was recorded initially when the limestone content was 10%. The limestone powder has a filler nature that fills up the pore spaces in the concrete, making the concrete denser by reducing the number of honeycomb pores and improving the concrete's strength. The maximum compressive strength was achieved at bamboo fiber-reinforced self-compacted concrete (BFRSCC) 3, which contains 0.75% bamboo fiber and 10%

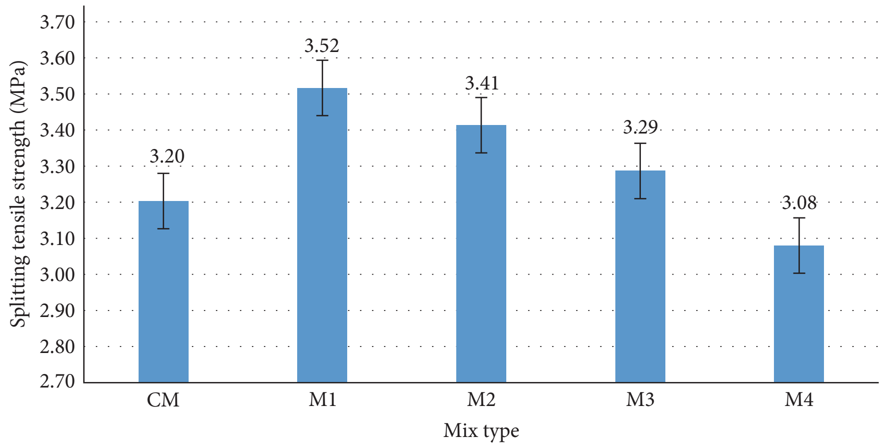


Figure 8: A 28th-day mean splitting tensile strength test results.

limestone powder content. This resulted in an enhancement of 17.4% and 4.4% as compared to SCC1 and SCC2, respectively [11].

As the results obtained from Bayraktar et al. [29] indicate, 79.4% and 41.79% incremental increases in 7th- and 28th-day compressive strength were recorded on concrete incorporating 50 kg/m^3 of foaming agent, WMP as fine aggregate, and basalt fiber at 0% and 30%, respectively. The improvement becomes slightly reduced when it incorporates GGBS as a cement substitution and basalt fiber as an addition at 7 days.

3.4.2. Splitting Tensile Strength. Three hundred millimeter height and 150 mm Ø cylindrical samples were cast for reinforced concrete containing bamboo fiber in 0.75% as addition and blended WMP and WGP as cement in different compositions. Consequently, those samples were soaked and cured for 28 days to check their splitting tensile test. On the 28th day, the mean splitting tensile strengths of WMP- and WGP-blended BFRC were present, as shown in Figure 8.

The mean splitting tensile strength of blended WMP and WGP concrete with 0.75% addition of bamboo fiber by weight of concrete showed an increment by a different percentage compared to the control mix but not the mix M4 (20%), which gives 3.08 MPa and recorded as a reduction of 3.75% compared to the control mix. The test result indicates that M1 (5%), M2 (10%), and M3 (15%) have recorded 3.52, 3.41, and 3.29 MPa, respectively, in splitting tensile strength. Accordingly, it showed an incremental value of 10%, 6.5%, and 2.8%, respectively, compared to the control mix. The maximum strength was recorded on M1, which contains blended WMP and WGP in 5% with 0.75% bamboo fiber. The incremental value recorded by three mixes, M1, M2, and M3, showed us the bamboo fiber contribution for better tensile strength.

As per the study done on the partial replacement of cement by waste marble dust in concrete production in Benishangul-Gumuz, Ethiopia, the split tensile strength increases as the level of replacement of marble dust powder increases up to 10%. But beyond that level, the split tensile strength showed a reduction. In the control mix, 2.91 MPa was recorded as the 28th-day split tensile strength. At 10% waste marble dust substitution, the split tensile strength of the sample becomes 3.24 MPa, which is a 38.26% increment. The results also showed a reduction with a 2.64-MPa split tensile strength recorded at 20% waste marble dust [18]. Similarly, Majeed et al. [7] concluded that a 10% WMP replacement level helps to enhance the average 7th- and 28th-day compressive strengths. Regarding WGP inclusion, a progressive increment was recorded in split tensile strength in ternary-blended geopolymer concrete mixes containing 10% metakaolin incorporating WGP as a GGBS substitution due to the filling capability and pozzolanic nature of WGP, which helps to make the bond between the binders and aggregates stronger. The split tensile strength declines when the WGP replacement level is beyond 40% due to its brittle characteristics. The study concluded the optimum replacement levels of WGP in ternary geopolymer concrete for a better split tensile strength to be 25% and 35% for 10% fly ash and 10% metakaolin, respectively [21]. Similarly, Manikandan and Vasugi [23] recommended 35% as the optimum replacement level of WGP to achieve enhanced splitting tensile strength for geopolymer concrete. Another finding in a study by Manikandan and Vasugi [22], concerning the effect of WGP on the splitting tensile strength of geopolymer concrete, stated that the inclusion of WGP with other source materials in a proportion of 0%–15% enhances the splitting tensile property and significantly decreases it if the replacement level exceeds 15% due to the high silica content of WGP and its brittle characteristics [9]. Also, recorded were supporting findings from the geopolymer concrete containing coarse aggregate, fine aggregate, and NaOH. Accordingly, as the fly ash to WGP ratio level in the mixture changed from 0 to 10%, 20%, 30%, and 40% by taking the percentage of NaOH to 11%, the splitting tensile strength declined from 3.57 to 3.47, 3.09, 2.64, and 2.18 MPa, respectively, and this study concluded that using 10% of WGP is optimal.

Research indicates that a significant property of concrete, tensile strength, can be improved by incorporating different fibers. Again, this study ascertains that adding bamboo fiber

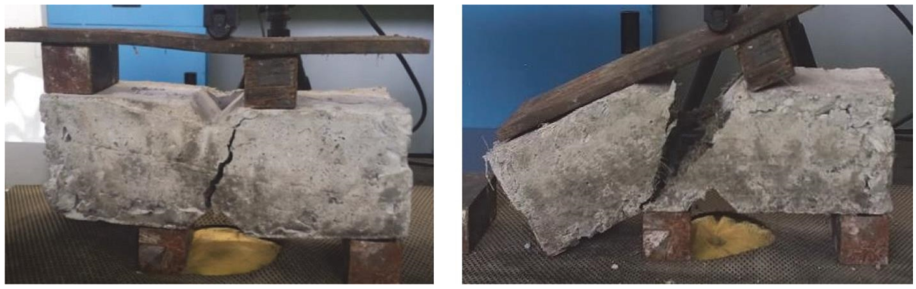


Figure 9: Crack pattern on specimens subjected to shear load.

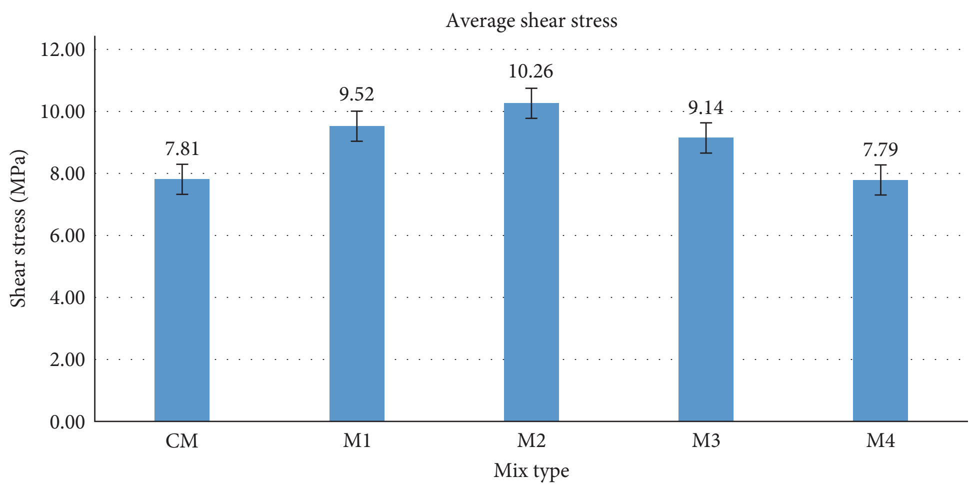


Figure 10: A 28th-day mean shear stress results.

at 0.75% of the mix proportion makes the concrete highly resistant to tensile stress. As shown in Figure 8, the recorded split tensile strengths of the other mixes (3.52, 3.41, and 3.29 MPa) are greater as compared to the control mix's 3.20 MPa. Meanwhile, a decrease in the tensile strength was noted at M4 = 3.08 MPa. This implies that a 20% blend of WMP and WGP used in M4 leads to lower tensile stress. Similarly, Ede et al. [11] supported the idea that using 0.5% bamboo fiber gave the concrete optimal tensile strength.

According to a study by Ede et al. [11], after 7, 14, and 28 days of curing, BFRSCC2, which contains 0.5% bamboo fiber and 10% limestone powder content, has shown improvement in tensile strength. The incremental split tensile strength recorded by the BFRSCC2 mix is 18.11% and 32.5% as compared to BFRSCC1 and the control SCC mix, respectively. Again, the tensile strength property of the SCC mix helps to improve filler action and density caused by the addition of limestone powder and treated bamboo fiber. Meanwhile, a reduction in tensile strength was noticed when the fiber content exceeded 0.5%. Similarly, 4.8 N/mm^2 was recorded in splitting tensile strength of reinforced concrete that incorporates 1% of bamboo fiber, and a reduction was noted when the fiber content exceeded 1% [28].

Another study conducted on concrete incorporating foaming agent contents of 50 and 100 kg/m^3 with 1% and 2% basalt fiber and WMP as sand substitution achieved a splitting tensile strength of 2.67 and 3.12 MPa, which are increments of 15.32% and 51.61%, respectively, as compared to the reference mix. On the other side, the reduction in splitting tensile strength was recorded when replacing 30% and 60% of cement with slag and keeping the proportion of foaming agents at 0% and 1% [29].

3.4.3. Shear Stress. The study conducted a shear test in a construction material laboratory at Addis Ababa Science and Technology University to determine the shear behavior of BFRC containing blended WMP and WGP. For this purpose, double V-notched samples were prepared as recommended by ASTM standard D5379 (1993). Double V-notched shear test, also named the Iosipescu shear test, where the loads are applied in antisymmetric four-point bending, to insure a pure shear section and zero bending at the center of the samples. Figure 9 shows how shear failure occurs when BFRC specimens are subjected to a shear load.

This type of geometry was adopted to assure a uniform shear stress distribution in the pure shear section. As shown in Figure 9, the samples consist of a depth between two notch roots (h_0), an angle of the notch root (α), and a notch radius (r). The 28th day's average shear stress value of BFRC blended with WMP and WGP is shown in Figure 10.

As shown in Figure 10, an average 28th-day shear stress was recorded as 7.81, 9.52, 10.26, 9.14, and 7.79 MPa for CM, M1, M2, M3, and M4, respectively. Accordingly, M2, which contains blended WMP and WGP of 10% and 0.75%

Table 8: A 28th-day average bond stress results.

No.	Mix type	Nominal bar diameter (mm)	Embedment length (mm)	Maximum axial load, $P_{\max}$ (KN)	28th-day average bond stress, τ (MPa)
1	CM	14	120	48.48	9.01
2	M1	14	120	52.46	9.85
3	M2	14	120	56.64	10.61
4	M3	14	120	52.41	9.80
5	M4	14	120	51.72	9.65

bamboo fiber, achieves the maximum value for shear stress of 10.26 MPa. It can be seen that also M2 and M3 recorded 28th-day shear stress results higher than the control mix proportion CM by 21.9% and 17.03%, respectively. On the other hand, using 20% blended WMP and WGP on BFRC reduces the shear stress value by 0.25% as compared to the control mix.

Although it is not using the V-notch method, researchers have tested the shear strength of the material and structure by using different methods. Accordingly, Santamaría et al. [30] studied a three-point loading on a $4,400 \times 300 \times 200$ mm beam cast by an electric arc furnace as aggregate and 3.5 and 0.55 mm Ø steel fiber and obtained a shear stress of 11 MPa. Even if the results obtained were comparable, this study used a test setup geometry that could create a pure shear section and give an accurate relative shear force transfer across a crack.

A study done on jute fiber-reinforced concrete showed that it behaves as a homogeneous material, and the random distribution and high surface-to-volume ratio of the fibers result in a better crack-arresting method by enhancing the ductility of the concrete matrix and its resistance to post-cracking. When the fiber content is 0%–2% by volume, the strain at which the matrix cracks differs by a little as compared to the control. Once the specimen is cracked, the fibers act as crack arresters and absorb significant energy as they are pulled out of the matrix without breaking [27].

As shown in Figure 10, the variation in shear resistance varies with mix type. This is due to the enhancement of shear stress caused not only by bamboo fiber but also by the binding material, which is a blend of WMP and WGP.

3.4.4. Bond Stress (Pullout). The study performed a pullout test in the construction material laboratory at Addis Ababa Science and Technology University to determine the bond strength of BFRC containing blended WMP and WGP as per ASTM C234. The experiment consisted of testing 10 samples for a different proportion of blended WMP and WGP and contained bamboo fiber at an optimal 0.75% for assessing the effect of adding fibers to reinforced concrete on the reinforcement bar embedment length and bond strength. The specimens were cast in a 150 by 150 mm cubical mold, and 14 diameters (d_b) of deformed steel bars were partially embedded with a length of 120 mm along each cube taken as embedment length (l_d) and they extended outside the concrete cube of 630 mm to allow gripping of the bars by the universal testing machine. Consequently, a 100-KN universal testing machine was used to perform pullout tests and evaluate the bond-slip behavior of the samples by enclosing the cubical concrete samples in a custom-made plate as a loading base to fix securely on the bottom plate of the testing machine.

The 28th-day average value of bond stress of BFRC containing blended WMP and WGP is shown in Table 8.

As shown in Table 8, an average bond stress value was recorded as 9.01, 9.85, 10.61, 9.80, and 9.65 MPa for CM, M1, M2, M3, and M4, respectively. Although all mix proportions of concrete contained bamboo fiber content as an optimal percentage of 0.75 by weight of concrete. A mix of M2 required the highest ultimate load to slip the reinforcement bar, which was embedded in the concrete cube. It means that not only adding bamboo fibers have effects on the bond stress of concrete, but also using a blended WMP and WGP in different proportions as a replacement for cement affects the bond stress of concrete. Accordingly, all concrete mixes achieved a better value of bond stress as compared to the control mix CM and M2 achieved the highest value of bond stress at 10.61 MPa with 10% blended WMP and WGP and an optimal 0.75% of bamboo fiber. Generally, the results showed that there was no significant variation among different mix proportions; rather, it was comparable, and it indicated that bond strength increases with increased compressive strength. Figure 11 illustrates the failure behavior of the specimens when tension force is applied to embedded reinforcement.

In the same manner, the results obtained by Almatrudi et al. [31] showed that using hybrid steel, propylene, and fiber at 0.1% and 0.2% lead to an average 28th-day bond stress of 8 up to 13 MPa. Moreover, the recorded results showed that using bamboo fiber on blended WMP and WGP had contributed to bond strength as compared to the control mix and an improvement in postcracking characteristics. On the other hand, the research by Annapoorna and Suresh [32] used steel fiber and recorded that an average bond stress value varies between 8.54 and 14.31 MPa, concluding that there was no improvement in concrete bond stress due to fiber but not in postcracking characteristics.

A pullout test conducted on high-strength concrete containing a blend of expired hardened cement and ground granulated blast furnace slag shows an improvement in bond stress of up to 20%. When the percentage of blended content increases to 25% and 30% at the 28 days, bond stress is reduced. Hence, 9.54% and 15.94% of enhancement in bond strength were recorded at 15% and 20%, respectively. On the other hand, the reduction in bond strength was

Figure 11: Different failure behavior of specimens.

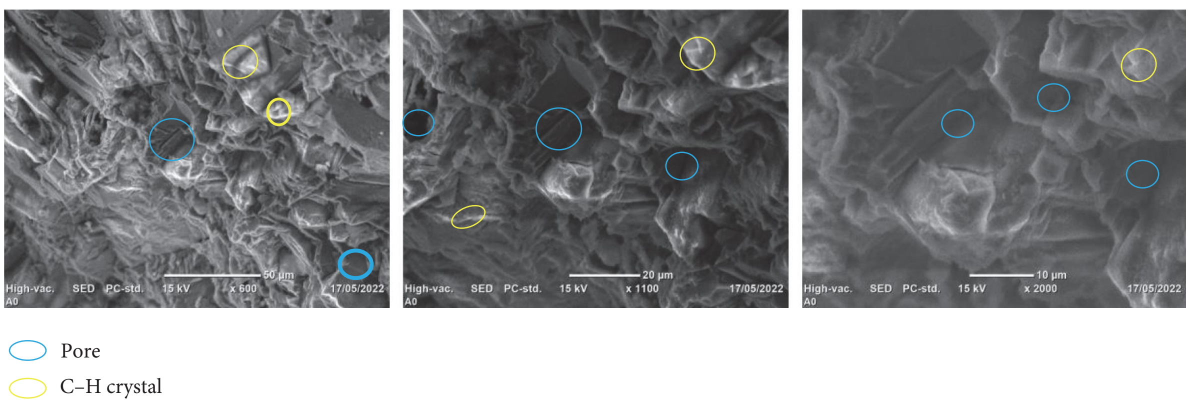


Figure 12: SEM image of control mix in different resolutions.

recorded at 25% and 30% of expired hardened cement (EHC) blended with GGBS, with negative percent reductions of 0.82% and 2.99%, respectively [33].

Regarding failure behavior, all the embedded reinforcement bars were slipped from the concrete sample when the test was conducted. This indicates that the resulting tensile stress is lower than the rebar's yield strength.

3.5. The Effect of Blended WMP and WGP on the Microstructural Properties of BFRC

3.5.1. Scanning Electron Microscopy. SEM studies were done in the Microbiology and Material Engineering laboratories at Adama Science and Technology University to analyze the microstructures of different compositions. It showed us the arrangement and morphology of calcium–silicate–hydrate (C–S–H), CH crystals, and pore structures. It was performed on the control and those samples in which the compressive strengths were significantly higher as compared to the other mixes. Two mix samples having 5% M1 and 10% M2 blended WMP and WGP with 0.75% bamboo fiber were selected for the SEM analysis.

Figure 12 shows SEM images of concrete samples of control CM, whereas Figures 13 and 14 show SEM images of 5% M1 and 10% M2, respectively, which achieve better results in compressive strength. All the figures show the pore structure, hydrated particles, and CH crystals. As shown in Figure 12, the pore structures are large. As shown in Figure 13, the pores are smaller, and C–S–H and CH crystals are shown explicitly. On the other hand, as shown in Figure 14, C–S–H particles are shown in the dominant area due to the pore structure becoming smaller.

Accordingly, the samples M1 with the replacement of blended WMP and WGP at 5% indicate the microstructure is denser than the control mix CM, and the samples M2 with the replacement of blended WMP and WGP at 10% indicate the microstructure has a dense matrix relative to the CM and M1. As can be seen from the image, when the matrix is tight, it reduces the pores and enhances the contact between the aggregates. Due to their fines, materials like WMP and WGP can easily occupy the void spaces, which can reduce the pores and the probability of the formation of microcracks. Similarly, the pore diameter becomes reduced, which leads to the lower permeability of high glass powder paste [34, 35].

In the other research, Seghir et al. [36] analyzed the SEM image and found that replacing marble powder with cement in concrete causes higher porosity. This is due to water accumulating around marble powder particles, which leads to a reduction in the required water amount for the hydration process, resulting in a higher porosity. Similarly, the SEM image on concrete specimens containing 15% glass powder and 30% quartzite powder replacement revealed a relatively small amount of pore structure as compared to the specimens

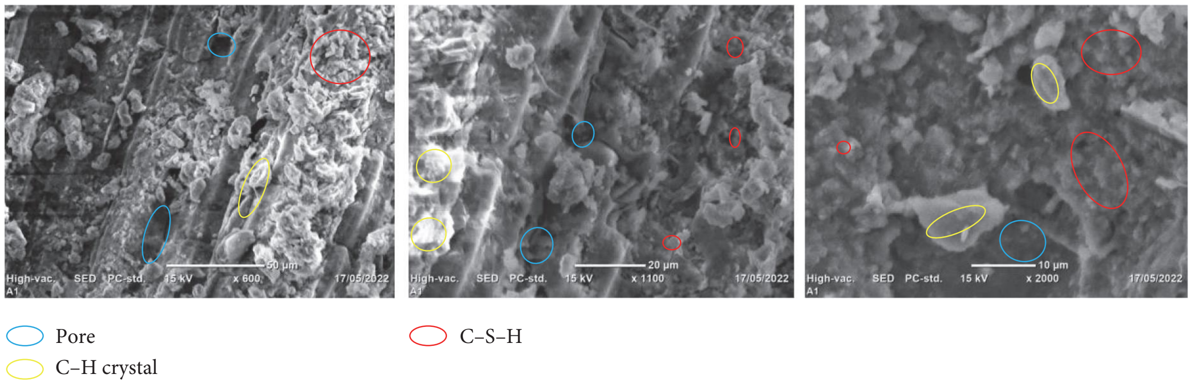


Figure 13: SEM image of M1 (5%) in different resolutions.

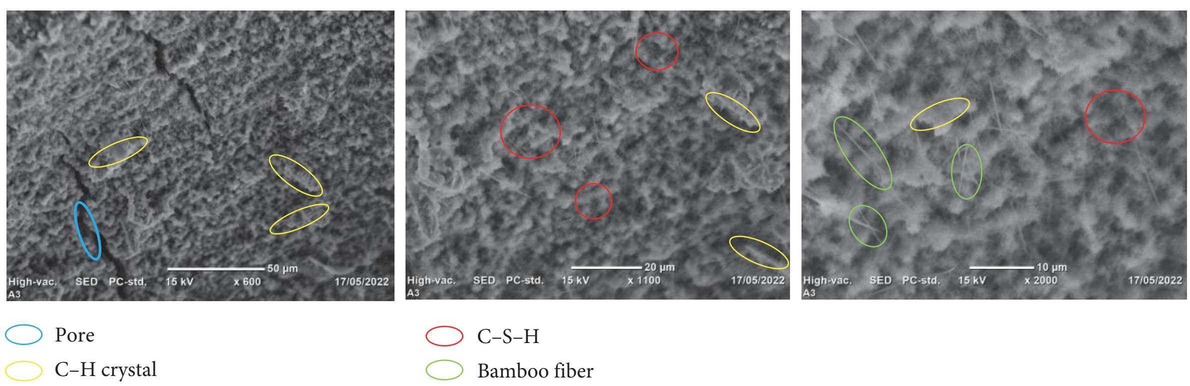


Figure 14: SEM image of M2 (10%) in different resolutions.

with no glass and quartz powder. This causes impermeability enhancement due to additional C–S–H formation [37].

As concerns the incorporation of fiber, the SEM image of BFRSCC showed a tight pore structure and well-formed interfaces when it incorporated limestone powder. The particle size distribution and pore structure influence the strength development of the self-compacting concrete. Contrarily, the same image of BFRSCC contained increments in the pore structures [11].

The SEM analysis performed on foam concrete incorporating WMP addition shows that better macrostructure is due to the fineness of C–S–H particles, and the whiskers of the crystalline phase are increased due to the addition of rice husk ash. Similarly, a larger crystalline phase is created when it uses a combination of rice husk ash and WMP as cement and sand replacements, respectively. Consequently, they dispersed homogeneously, leading to additional C–S–H formations [26]. Similarly, the SEM image conducted on fractured surfaces from 90-day aged and exposed 900°C specimens incorporating foam, WMP as a replacement of sand, and GGBS as a cement substitution showed that a dense microstructural pattern due to admixture components in foam concrete provides good bonding property with the C–S–H crystalline phase after counting 90 days and formation of additional C–S–H particles due to WMP and slag those dispersed in foam [29]. On the other hand, the SEM image of a geopolymer concrete sample incorporating 55% GGBS, 35% WGP, and 10% metakaolin showed that a considerable amount of unreacted WGP and GGBS particles exists due to the formation of semihomogeneous gel [21].

The effects of blended WMP and WGP replacement in both long-term strength and durability are commonly attributed to the pozzolanic reaction in which $Ca(OH)_2$ is burned to produce additional C–S–H and C–A–H reaction products. The pozzolanic reaction formation results in infilling of the porosity and reduction of the pore size distribution or pore structure. Similarly, another study conducted on high-strength concrete containing a blend of expired hardened cement and GGBS shows the microstructure of the control sample is denser with a few pore structures. As a result, in the mix with a 20% blend of EHC and GGBS, the extent of the void is lower as compared to the control mix, and this shows that the incorporation of blended EHC and GGBS in concrete fills the void between hydrated particles and helps for densification of the microstructure. This leads to a higher density in the concrete [33].

3.5.2. X-Ray Diffraction (XRD). XRD tests were carried out in the Microbiology and Material Engineering laboratories at Adama Science and Technology University to identify and analyze the material's crystalline phase characterization and mineralogical composition. The powder was extracted from the 28th day of cured and hydrated concrete. In the same manner as SEM, it was carried out for control samples and

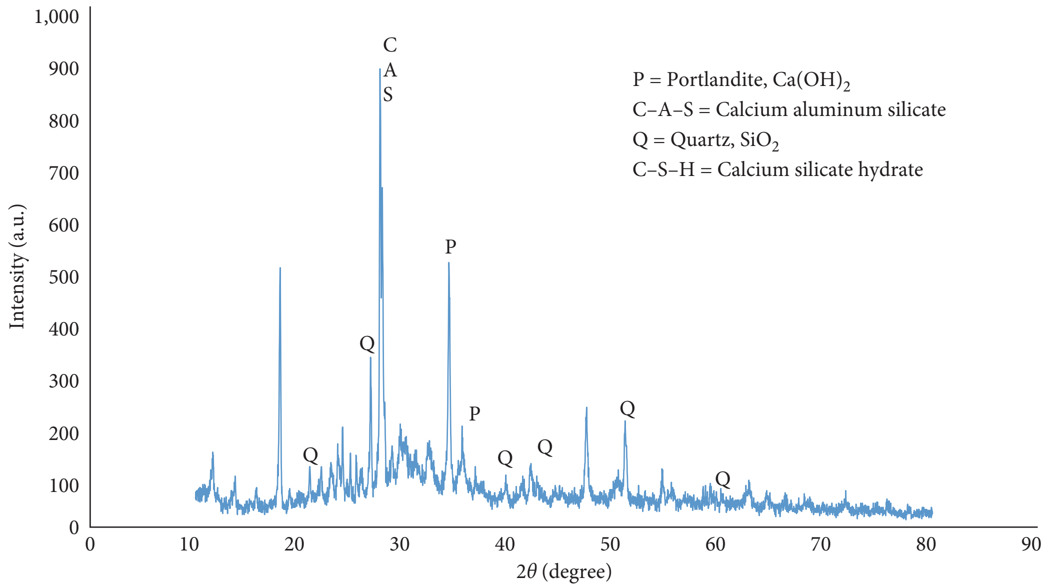


Figure 15: XRD pattern of control mix.

those samples in which the compressive strengths were significantly higher as compared to the other mixes. Accordingly, two mix samples having 5% M1 and 10% M2 blended WMP and WGP with 0.75% bamboo fiber were selected for the XRD analysis.

This study presented the mineralogical results on the *x*–*y* axis of the coordinates, as shown below. The *x*-axis represented the diffraction angle in degrees, while the *y*-axis represented the X-ray intensity. The results obtained showed that $Ca(OH)_2$ (portlandite), $Al_3Ca0_5Si_3O_{11}$ (calcium aluminum silicate), SiO_2 (quartz), and C–S–H were most of the crystalline phases identified during the test. Figure 15 illustrates the XRD result of the control mix, CM.

The portlandite phase in concrete showed the degree of hydration, and it is the mineral name for calcium hydroxide. As can be seen from the results, it exists in the control mix sample, as well as in other samples containing blended WMP and WGP in different proportions. On the other hand, silicon oxide, or quartz (SiO_2), is found in sand, and its contribution to the creation of calcium silicates leads to better compressive strength because of its high heat of hydration. Moreover, the C–S–H gel is produced from the reaction of silica in the glass powder with calcium hydrate in cement and marble powder. It provides additional binding properties and enhances the compressive strength of hardened concrete. In addition to the above, calcium aluminum silicate was found as a mineral in the control mix and mix-1 (5%). It is produced by mixing calcium carbonate and aluminum silicate together and heating them.

On the experimental result, XRD analysis showed that the three strongest peak values were recorded at $2\theta = 27.5°$, 27.7°, and 34° with intensities of 560, 392, and 311, respectively. The diffraction peaks of quartz, calcium aluminum silicate, and portlandite were obtained at 27.5°, 27.7°, and 34°. While the portlandite was produced from the hydration of $CaSiO_2$ and CaO from cement, the quartz was present in SiO_2 from cement powder. Figure 16 illustrates the XRD result of mix-1.

XRD analysis showed that the three strongest peak values were recorded at $2\theta = 27.5°$, 27.7°, and 34° with intensities of 560, 392, and 311, respectively. The diffraction peaks of quartz, calcium aluminum silicate, and portlandite were obtained at 27.5°, 27.7°, and 34°. While the portlandite was produced from the hydration of $CaSiO_2$ and CaO from cement, the quartz was present in SiO_2 from cement powder.

As shown in Figure 16, calcium aluminum silicate, portlandite, and C–S–H were recorded as the strongest peak values of diffraction, and their 2θ angle and corresponding intensity were $27.8° = 454$, $34.15° = 360$, and $29.4° = 226$, respectively. As compared to the control mix, mix-1 contained $Ca(OH)_2$ in most of its phases. This implied that additional $CaSiO_2$ and CaO were brought from WGP and WMP, respectively, and could hydrate more. Again, C–S–H existed at $2\theta = 29.5°$ and $2\theta = 32.36°$, but not in the control mix since a WGP could give additional silica that can react with CH and result in C–S–H. Figure 17 illustrates the XRD result of the mix-2.

The XRD analysis results, as shown in Figure 17, implied that C–S–H existed more in mix-2 as compared to mix-1. This is due to the increasing proportion of blended WGP and WMP as cement, which results in additional silica that reacts with CH. The XRD analysis done on concrete specimens containing 15% glass powder and 30% quartzite powder replacement showed SiO_2, C_2S, and $Ca_2.SiO_4.H_2O$, and $CaCO_3$ as major compounds that are formed from the reaction of glass and quartzite powder with other materials present in concrete. Calcium silicates help concrete gain strength early, whereas dicalcium silicates contribute to the maximum strength of concrete after 7 days [37]. Another study was conducted on a geopolymer concrete sample incorporating 55% GGBS, 35% WGP, and 10% metakaolin, and the XRD

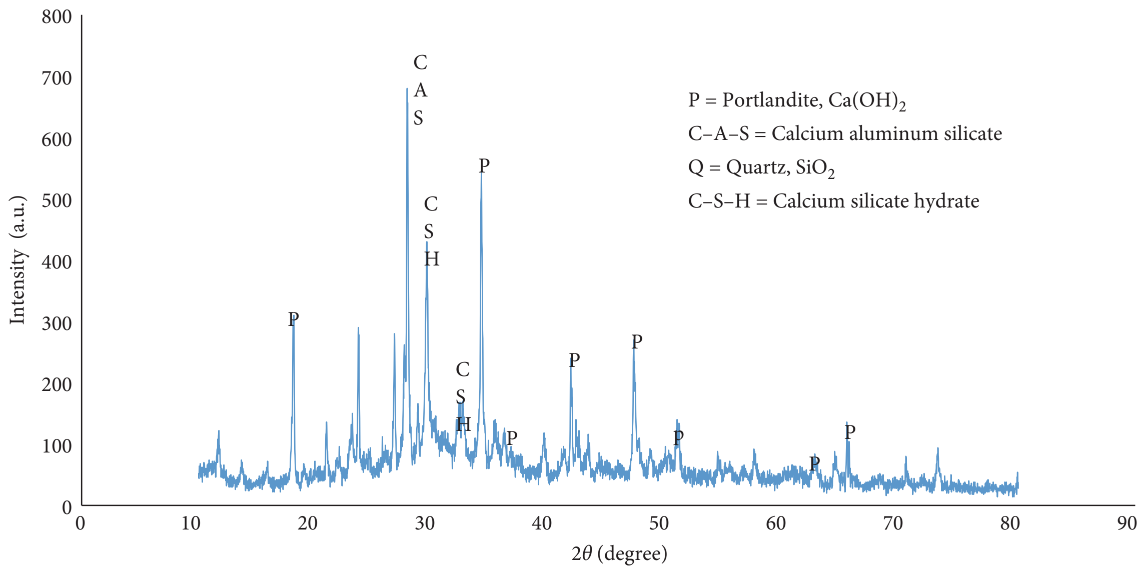


Figure 16: XRD pattern of mix-1 (5%).

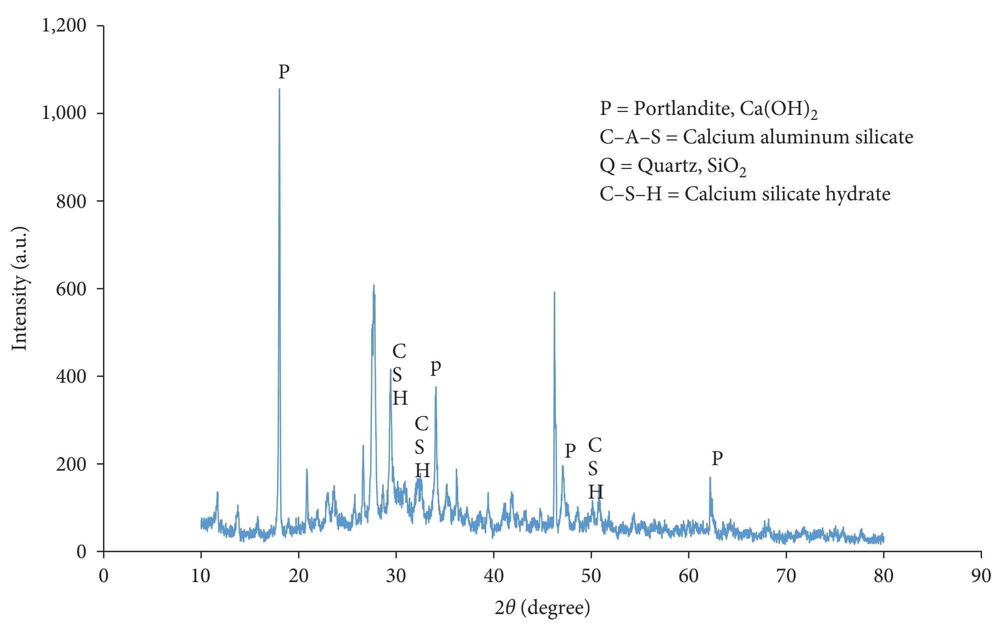


Figure 17: XRD pattern of mix-2 (10%).

pattern of the sample displays quartz, calcite, the calcium-based compound gismondine and C–S–H gel. A study concluded that the C–S–H gel contributes to the strength development in the geopolymer matrix, as indicated by the rise in peak levels ranging from 37° to 43° along (2θ) for the sample [21].

4. Conclusions

The following conclusions were drawn from the experimental results of a blend of WMP and WGP properties and their effects on the mechanical and microstructural properties of BFRC.

(1) There is an improvement in the mechanical properties of BFRC. The test results recorded an incremental increase of about 14.19% and 5.7% on the 7th- and 28th-day average compressive strengths at M2 (10%), respectively, as compared to the control mix. Moreover, at a 10% replacement level, average 28th-day shear stress was enhanced by about 31.37% and 17.7%, respectively, over the control mix. With regard to split tensile strength, the 28th-day maximum mean strength was recorded at M1 (5%), which is a 10% increment over the control mix. Results achieved by M2 and M3 also showed an improvement of 6.5% and 2.8%, respectively, as compared to

the control mix. This implied that bamboo fiber has contributed to the enhancement of tensile strength.

(2) SEM showed a denser microstructure at M2 (10%) relative to CM and M1. At M2, the image showed more area covered by C–S–H particles and a small pore structure. The reduction of pores created a tight matrix, which enhanced the contact between the aggregates, whereas XRD illustrated portlandite, calcium aluminum silicate, quartz, and calcium silicate hydrate as common phases of the concrete structure. While portlandite was produced from the hydration of $CaSiO_2$ and CaO from cement, quartz existed in SiO_2 from cement powder. The results concluded that C–S–H existed more in M2 as compared to M1 due to an increasing percentage proportion of using blended WGP and WMP as cement, resulting in additional silica that reacts with CH.

(3) Hence, the study concluded that using a 10% blend of WGP and WMP, as a partial replacement of cement, was the optimum value because it enhanced the compressive strength, shear strength, bond stress, and microstructural properties of BFRC.

Data Availability

Anyone who wants to find the main and supplementary data, which were used as input for the study, can kindly get them via a correspondence email address.

Conflicts of Interest

There are no conflicts of interest concerning this study.

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