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Research Article

Analyzing the Mechanical, Durability, and Microstructural Impact of Partial Cement Replacement with Pumice Powder and Bamboo Leaf Ash in Concrete

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This study explores the physiomechanical and durability properties of C-25 concrete by partially replacing cement with blends of pumice powder (PP) and bamboo leaf ash (BLA). The combined amount of major oxides SiO_2, Al_2O_3, and Fe_2O_3 in PP is 84.59%, while in BLA, it is 74.4%, classifying PP and BLA as class N and F pozzolans. Subsequently, the study examines the impact of different cement replacement percentages, emphasizing 5%, 10%, 15%, and 20% on C-25 with varying mixes of concrete: Mix-1 (100, 0, and 0), Mix-2 (90, 5, and 5), Mix-3 (85, 10, and 5), Mix-4 (85, 5, and 10), and Mix-5 (80, 10, and 10) which correspond to the proportions of OPC, VPP, and BLA used in each mix respectively and by using 1 : 2.34 : 2.68 (cement : sand : aggregate) with the water/cement ratio (w/c) of 0.491. The study's findings indicate that as the proportion of PP and BLA increases in concrete, the workability of the mixture decreases. Moreover, on the 28th day, Mix-2 with (35.84 MPa) and Mix-3 with (33.55 MPa) met the desired mean compressive strength (33.5 MPa) required for C-25 concrete per the ACI standards. Additionally, the flexural strength of concrete produced with partial replacement of Mix-2 with a flexural strength of 3.86 MPa fulfills the minimum strength requirement of 3.5 MPa specified by the C-25 ACI standards. The PP and BLA blended concrete had lower water absorption than the control mix in Mix-2. It also improved resistance to sulfuric acid attack, and Mix-3 had the least strength reduction of 9.59%. In contrast, the control mix has a 33.34% strength reduction.

1. Introduction

The construction industry plays a vital role in the global economy, encompassing the construction of buildings and infrastructure for various sectors, such as residential, transportation, education, and healthcare [1]. With the advancement of science and technology, more large-scale constructions, such as towering buildings, underground structures, and iconic buildings, are being constructed worldwide [2, 3]. Concrete is the most commonly used among the wide array of construction materials available due to its durability and strength [4, 5]. Raw materials are often used to build 13.12 billion tonnes of concrete each year to meet this demand. Natural resources are becoming scarce due to the rising demand for construction materials [6]. For centuries, concrete has relied on cement as its essential component, accounting for approximately 15% of the total weight [7]. With the construction industry experiencing significant growth worldwide [8], the demand for cement is projected to rise by 4.7% annually, resulting in substantial waste generation, high capital expenditures, energy consumption, and utilization of traditional raw materials [9, 10].

Cement production at high temperatures and with significant energy requirements leads to elevated carbon emissions and poses environmental challenges [11–13]. However, it is possible to mitigate these environmental impacts by incorporating alternative materials as partial substitutes for cement, utilizing locally available resources [14]. This approach reduces energy requirements and promotes sustainable practices in the construction sector [15]. In this regard, efforts to minimize costs and resource consumption in Portland cement production while maintaining environmental sustainability and enhancing the quality of cement and concrete have led to the exploration of pozzolans as partial cement substitutes [16, 17]. Various pozzolanic materials have been extensively studied for their potential use in the production of blended cement concrete. These materials include rice husk ash, bamboo leaf ash (BLA), burnt clay waste, sawdust ash, corn cob ash, fly ash, silica fume (SF), metakaolin, pumice powder (PP), blast furnace slag, clinoptilolite, and periwinkle shell ash [17–19].

PP found abundantly in volcanic regions and BLA, considered an agricultural waste, have shown promise as potential substitutes for cement in concrete production [15], making them exciting candidates for further investigation in the construction industry [20]. It is clear from the current review that there is a necessity for more investigation on usability of PA in concrete production. Especially, there is a significant gap in investigation based on mechanical, durability, and microstructural analysis whether the using of PA is feasible in concrete [21]. Several studies have investigated the effect of cement partial replacement with pumice in a mortar. These studies include those conducted by Adil et al. [22] and Rahman et al. [23], as well as studies exploring the impact on concrete properties by Özcan and Koç [24], Zeyad and Almalki [25], and Ulusu et al. [26]. Similarly, the use of PVC waste powder up to 15% dose as a partial replacement for cement with fixed quantities of SF is more favorable [2], and the effect of BLA on cement paste and mortar has been examined in studies conducted by Umoh and Odesola [27]. Furthermore, the impact on concrete has been investigated by Hnin et al. [28], Silva et al. [29], and Odeyemi et al. [30]. These studies have demonstrated the potential benefits of using pumice powder and BLA in cost-effective construction and agricultural waste management. However, BLA has a low percentage of alumina (5.08%) but a high percentage of silica (83.33%), which is typical for pozzolans [13, 31]. On the other hand, volcanic PP has a silica percentage of 67.05% and a relatively higher alumina level (18.57%) [32]). These differing compositions bring unique benefits to the cementitious material. A high silica pozzolan, such as BLA, tends to exhibit more pozzolanic activity, enhancing the strength and durability of concrete. Conversely, a high alumina pozzolan, like volcanic PP, provides increased resistance to acidic attack, further reinforcing the durability of the material [17, 33]. These characteristics make the combination of these materials in ternary blends particularly advantageous. However, there is still a need for further investigation into the impact of combining cement, PP, and BLA in trinary blends on concrete properties. Although there have been studies on the synergistic effects of blending ternary binders with different materials: cement, sugarcane bagasse, and BLAs [34]; cement, scoria, and pumice [35]; and cement, PP, and glass microspheres [32] have shown that the combination in ternary blended cement materials improves the compressive strength and the durability. On the other hand, there is a lack of research specifically investigating the effects of trinary blends of cement, PP, and BLA on concrete properties.

Considering that Ethiopia is a significant producer of pumice and scoria aggregates and has an abundance of bamboo leaf waste, exploring the potential of these locally available materials becomes crucial [15]. This utilization can help mitigate construction costs and pose fewer ecological challenges [36]. To advance sustainable construction practices, it is essential to understand the workability, mechanical properties, durability, microstructural characteristics, and cost implications of such a ternary blend (cement, PP, and BLA) on concrete properties, particularly for a specific strength grade like C-25 concrete. Therefore, this study aims to bridge the gap between sustainability and construction by investigating the effects of blending BLA, volcanic PP, and Portland cement in a ternary blend. The study examines the workability, mechanical properties, durability, and microstructural characteristics of C-25 concrete incorporating this ternary blend. By doing so, it aims to advance sustainable construction practices in Ethiopia and potentially other regions with similar material availability.

1.1. Aim and Objectives

1.1.1. Aim. To comprehensively analyze the impact of partial cement replacement with PP and BLA on the mechanical strength, durability, and microstructure of concrete.

1.1.2. Objectives

(i) Evaluate the influence of varying replacement percentages of PP and BLA on the compressive strength of concrete.

(ii) Investigate the durability aspects, including resistance to chemical attacks, in concretes with different combinations of PP and BLA.

(iii) Characterize the microstructural changes in the concrete matrix through advanced imaging techniques, such as scanning electron microscopy (SEM) and X-ray diffraction (XRD).

(iv) Assess the workability and fresh properties of concrete mixes with partial cement replacement with PP and BLA to ensure practical applicability in construction.

2. Materials and Methods

2.1. Materials. This research aims to explore the utilization of locally available resources in the construction sector. The cement used in the study was OPC of Strength Class CES 28, CEM I 42.5 N, manufactured by the National cement factory and obtainable in the local market of Adama, Ethiopia. To adhere to ASTM C33/C33M-18's [37] standards, the fine aggregate and coarse aggregate were acquired from a construction site within Adama Science and Technology University (ASTU). Potable water meeting [38] standards was employed for the research. In order to obtain pumice for the study, a sample was collected from the bulk storage in Meki, East Shawa, Oromia regional state, Ethiopia, and it has a latitude and longitude of 8°9′N 38°49′E with an elevation of 1,636 m above sea level, using a sampling tube during the discharge process. The bamboo leaf utilized in this research was sourced from Kofele near Shashamne, Oromia regional state, Ethiopia, with latitude and longitude coordinates of 7.2010°N and 38.6065°E.

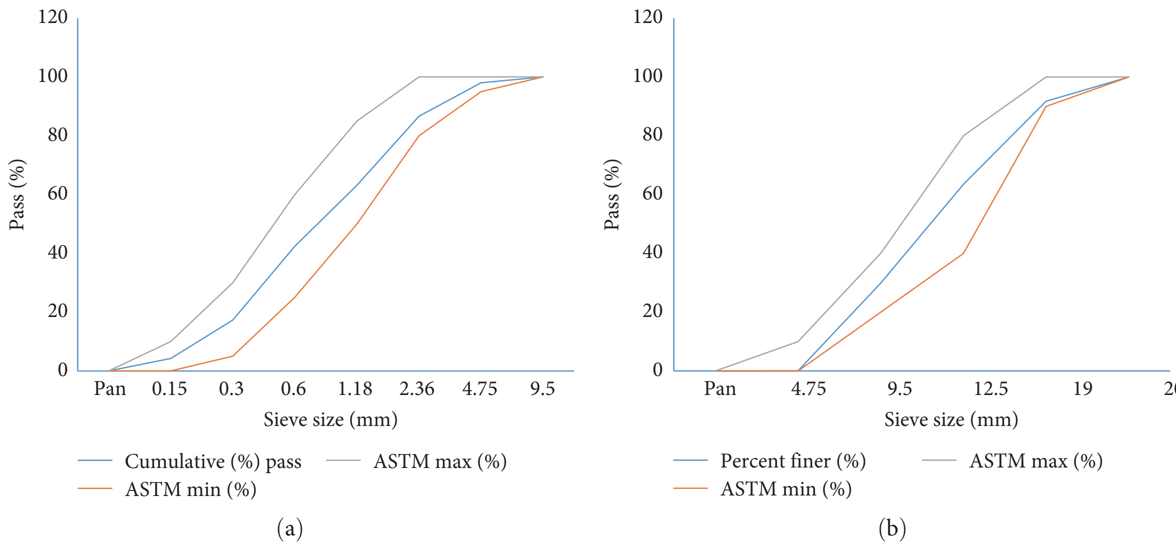


Figure 1: Gradation curve: (a) fine aggregate and (b) coarse aggregate.

3. Methods

This research employed an experimental approach to examine the impact of substituting a portion of cement with PP and BLA on concrete. To achieve the aim of the study, various laboratory tests were performed following different established procedures. The results obtained from these tests were carefully analyzed per ASTM standards. Several software tools were utilized to analyze the data, including Origin, X'pert High Score Plus, Minitab Statistic, and Excel. These software programs facilitated the analysis of the gathered data. The findings of the analysis were then presented in a clear manner through the use of tables, figures, and charts. This visual representation of the analyzed data allows for better understanding and easier interpretation by researchers and readers alike.

3.1. Characterizations of Materials. The quality of the fine aggregate in the study was evaluated through various tests. These tests included measuring the silt content [13], conducting sieve analysis [39], and determining unit weight, specific gravity, and water absorption [40]. Silt content should be at most 6% [41], and in this study, it was found to be 2.33%, meeting the requirements. The particle size distribution of the fine aggregate, as shown in Figure 1(a), also met the ASTM requirements. The fineness modulus of the fine aggregate was 2.89, falling within the range specified by ASTM C33. The specific gravity and water absorption tests, conducted according to ASTM C127, yielded results consistent with the provided codes. The bulk specific gravity of the fine aggregate was 2.76, and the water absorption was 2.04%. Additionally, the unit weight of the fine aggregate, determined by following ASTM C29, was found to be 1,515.5 kg/m^3, meeting the requirements specified by ASTM. The moisture content of the fine and coarse aggregate, calculated using ASTM C566, met the standard, with values of 1.01% and 0.98%, respectively.

Various tests were conducted according to their respective ASTM codes to ensure the coarse aggregate met the requirements. The sieve analysis results indicated that the coarse aggregate met the graduation requirement of ASTM C136 [39], as confirmed in Figure 1(b). The coarse aggregate's specific gravity and water absorption were determined following ASTM C128 [40]. The bulk specific gravity was found to be 2.83, the apparent specific gravity was 2.98, and the water absorption was 2.7%. The unit weight of the coarse aggregate was 1,650 kg/m^3, which complied with the requirements of ASTM C29. Additionally, the pH of the water used in the study was measured using ASTM C1602 [38] standard to assess its quality. The obtained pH value was 7.56, falling within the specified range of 6–8.5 set by ASTM C1602 standard [38].

The quality of cement, PP, and BLA for concrete production was assessed using various tests. These tests included sieve analysis and fineness, specific gravity, and normal consistency, which followed the respective ASTM standards. For consistency testing, the ideal water percentage needed for a cement paste was determined according to ASTM C187 [42]. The Vicat apparatus was used in this test, with different amounts of PP and BLA replacing the cement. Furthermore, the cement's chemical composition was analyzed for a comparison of the cement's composition with that of PP and BLA.

PP (Figure 2) was prepared per ASTM 311 guidelines; the top layer was removed to a depth of 200 mm (8 inches) at the discharge point into a rail car or tanker before collecting the sample. The collected sample was dried, ground into powder using a ball milling machine in the ASTU's chemical department laboratory and sifted to a size of 150 μm at the ASTU construction material laboratory.

On the other hand, the procedure for the preparation of BLA ash is shown in Figure 3. The bamboo leaf was carefully washed with potable water to eliminate dust or impurities. Subsequently, it was dried under sunlight and then ground using a Grinding machine (Wofcho). The resulting ground bamboo leaf was taken to the laboratory at the Ethiopian Defense University, where it was heated in a muffle furnace

(a) (b) (c)

Figure 2: Pumice processing: (a) oven drying of pumice, (b) grind to powder by ball milling machine, and (c) VPP.

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

Figure 3: Bamboo leaf processing: (a) collected bamboo leaf, (b) washed by tap water, (c) dried in the Sun, (d) grinded bamboo, and (e) BLA after burned in a furnace under a controlled temperature of 600°C for 2 hr.

Table 1: Percentage replacement of cement with VPP and BLA.

Batch	Mix samples	Cement (OPC, %)	Volcanic pumice powder (VPP, %)	Bamboo leaf ash (BLA, %)
1	Mix-1 (100, 0, 0)	100	0	0
2	Mix-2 (90, 5, 5)	90	5	5
3	Mix-3 (85, 10, 5)	85	10	5
4	Mix-4 (85, 5, 10)	85	5	10
5	Mix5 (80, 10, 10)	80	10	10

at a controlled temperature of 600°C for 2 hr to eliminate excess carbon and obtain amorphous material containing amorphous silica. The ash produced from this process, after being sieved on a 45 μm (No. 325) sieve, was considered as the BLA sample, and its percentage of passing was verified according to ASTM C618 [19] specification.

3.2. Concrete Mix Proportion and Tests. This study utilized the ACI 211.1 method to design the mix proportion for a C-25 concrete grade with the desired compressive strength of 25 MPa. Based on the characteristic strength, the target mean compressive strength was determined to be 33.5 MPa. The mix proportion chosen for this study was 1 : 2.337 : 2.678 (cement : sand : aggregate), with a water/cement ratio (w/c) of 0.491, suitable for general reinforced/structural concrete.

Most studies indicate that 10% of cement replacement could be acceptable as the optimum percent for VPP [25, 32, 43] and for BLA [15, 17, 27, 33] without affecting concrete properties. Therefore, for this experimental investigation, the effect of blending these materials with cement was assessed by partial replacements of blended VPP and BLA at intervals of 5%, 10%, 15%, and 20%. In this regard, Table 1 displays the five mix samples created for this experiment, which involved combining cement, BLA, and volcanic PP. This research used the weight batching method to replace ordinary Portland cement (OPC) with CBSA at different percentages. Weight batching is preferred over volume batching due to the difficulty of accurately measuring the volume of granular materials with voids. A small automatic mixer was used at room temperature to ensure a homogeneous mix.

Three (150 mm × 150 mm × 150 mm) concrete cubes and three (500 mm × 100 mm × 100 mm) beam samples for each sample mix were cast. The water tank curing method was adopted as all the specimens were wholly submerged in a water tank for continuous water curing [32] and cured in the open tank for the 7th, 14th, and 28th. Generally, 90 concrete cube

Table 2: Number of sample preparation.

	Compressive strength			Water absorption	Acid attack	Flexural strength		
	7 days	14 days	28 days			7 days	14 days	28 days
Mix-1 (control)	3	3	3	3	6	3	3	3
Mix-2	3	3	3	3	6	3	3	3
Mix-3	3	3	3	3	6	3	3	3
Mix-4	3	3	3	3	6	3	3	3
Mix-5	3	3	3	3	6	3	3	3
Total	15	15	15	15	30	15	15	15

Table 3: Chemical requirements for pozzolans as per ASTM C 618: 2014 [19].

S./no.	Property of pozzolan	ASTM requirements (class)		
		N	F	C
I	$(SiO_2) + (Al_2O_3) + (Fe_2O_3)$ (min. %)	70	70	70
I	Sulfur trioxide (max. %)	4.5	5.0	5.0
III	Water requirement, max. percent of control	115	105	105
IV	Moisture content (max. %)	3.0	3.0	3.0
V	Loss on ignition (LOI) (max. %)	10.0	6.0	6.0

samples and 45 beam samples, as presented in Table 2, were cast for this experimental investigation.

3.3. Testing Procedure. The workability of the freshly mixed concrete was evaluated using the slump cone test, following the ASTM C143 [44] standard. The test involved washing the slump cone with water and placing it on a flat pan. The fresh concrete was poured into the cone in three layers, each layer filling around one-third of the cone's capacity and compacted with 25 tamper rod strokes evenly distributed across the cone's cross-section. Once the filling and compaction were completed, the cone was gently lifted, and the slump value was measured using a ruler for three trials to ensure accuracy. The mean value was computed for each mix-code to obtain reliable results regarding the consistency and homogeneity of the fresh concrete. According to ACI for C-25, a 2–10 cm concrete slump is recommended.

To evaluate the compressive strength of concrete samples, three cubes measuring 150 mm × 150 mm × 150 mm were cast and tested at ages 7, 14, and 28 days. This was done to assess the effects of volcanic PP and BLA replacement levels. The testing was conducted at the ASTU Construction Material Laboratory using a compressive testing machine following the ASTM C39/C39M standard. The specimens were loaded gradually at 140 kg/cm^2 per minute until failure, with a load capacity of 3,000 kN. The maximum load applied was recorded, and the compressive strength was calculated based on the average of three tests. The flexural strength of the concrete beams was determined using the ASTM D790 procedure at various curing ages (7th, 14th, and 28th day). The beams, measuring 500 mm × 10 mm × 10 mm, were tested using a two-point load flexural testing machine with standard loading rates.

The procedure outlined in ASTM C1585 was followed for the water absorption test. After 28 days of curing, the samples were taken from the curing water and dried at 105°C for 24 hr. They were weighed and immersed in curing water for 72 hr. Following this, the samples were considered again. The water absorption percentage was calculated by comparing the weight increase of the saturated surface dry concrete to the initial weight. As per ASTM C1585, the highest water absorption limit is 10%. The formula for calculating water absorption percentage is $(A - B/B) \times 100\%$, where A represents the saturated surface dry concrete's weight and B represents the oven-dry concrete's weight.

To examine the acid attack (durability) through testing the compressive strength loss, the casted concrete cubes were cured for 30 days in a water tank for 7 days. Then, the samples were soaked in 5% H_2SO_4 for 30 days. The concrete cube is cured in potable water and 5% H_2SO_4 is compared, and compressive strength losses due to acid attack are determined [15, 45]. This experiment was conducted on both the optimal and control concrete mixes.

SEM and XRD techniques were used to examine the microstructure of the concrete. After 28 days of curing, samples were taken from the control mix and the mix that yielded the maximum strength. These samples were prepared and analyzed using SEM to observe the internal morphology. Additionally, XRD analysis was conducted by taking samples from different sections of the specimens and grinding them into powder. The XRD data were then analyzed using Origin Software to generate intensity and degree of diffraction peaks. Finally, the peaks were interpreted using X'pert High Score Plus software to gain insights into the crystal formations of the concrete.

3.4. Results and Discussion

3.5. Characterization of OPC Cement, PP, and BLA. PP and BLA qualify as pozzolans, according to ASTM C 618 [19] standards in terms of Chemical Requirements for Pozzolans as per ASTM C 618: 2014 [19], as shown in Table 3, states for any material to qualify as a pozzolan, it must satisfy the

Table 4: Oxide composition of national OPC cement, PP, and BLA.

Oxide Composition (%)	National OPC Cement	VPP (Appendix C1)	BLA (Appendix C2)
SiO_2	26.02	61.06	68.12
Al_2O_3	5.09	18.13	4.92
Fe_2O_3	3.48	5.4	1.36
CaO	60.4	2.12	6.02
MgO	1.76	0.34	1.52
Na_2O	0.34	3.9	0.66
K_2O	0.56	4.04	0.16
MnO	0.04	0.16	0.12
P_2O_5	0.1	0.32	1.46
TiO_2	0.16	0.1	0.01
H_2O	0.39	0.63	2.39
LOI	1.89	4.68	14.25
$SiO_2 + Al_2O_3 + Fe_2O_3$	—	84.59	74.4

requirements stipulated in the standards examined. $SiO_2 + Al_2O_3 + Fe_2O > 70\%$.

The complete silica analysis was conducted for PP and BLA to examine oxides present within the sample. This analysis was done through different methods such as LIBO, fusion, HF attack, gravimetric, colorimetric, and AAS. The analysis was conducted at the laboratory of the Ethiopia Geological Survey.

The chemical characterization of the materials used for the blended binders is presented in Table 4. The result indicates that the combined oxide components ($SiO_2 + Al_2O_3 + Fe_2O_3$) of BLA and VPP exceeded the 70% minimum requirement for classes F and N pozzolans, as ASTM C618-08 [46] specified. ASTM C618 [19] classified BLA as a class F pozzolan, whereas PP falls under class N. Moreover, Table 4 highlights that BLA exhibits a higher silica composition than PP, while PP possesses a greater concentration of alumina and ferrite, thus providing a superior resistance to acid attack [25, 33].

Likewise, the same standard limits the maximum loss on ignition (LOI) of classes F and N pozzolans to 6% and 10%, respectively. PP satisfied this specification since it exhibited 4.68%, which is lower than ASTM C618's maximum value of 6%, while BLA has an LOI of 14.25%, which is higher than ASTM C618's maximum value of 10%. The high LOI in BLA is due to the presence of carbon in the ash due to low combustion temperature. According to Mohan et al. [47] and Silva et al. [48], the value of LOI increases when compounds are burned at a low temperature. Furthermore, the PP was discovered to contain alkali content, such as Na_2O (3.9%) and K_2O (4.04%), signaling a high potential for the alkali–silica reaction when utilized in concrete with silica reach aggregate. As a result, combining PP with silica reach aggregate harms the long-term durability of concrete. It is recommended to handle this problem with a silica-free aggregate [48].

The chemical composition of PP (Al_2O_3 of 18.13%) for this research conforms to previous studies by Hossain [10], Kabay et al. [32], and Zeyad and Almalki [25], with higher alumina of 18.57, 16.71, and 12.90, respectively. BLA contains a higher silica content of 68.12%, which conforms with previous studies by Abebaw et al. [15], Mekonnen et al. [49], ASTM C 618 [19], and Temitope and Olubunmi [17], with silica content of 65.66%, 74.23%, and 75%, respectively. As noted by various researchers, the minor variations in the composition of PP and BLA could be due to the source location, geological factors, and processing techniques [27, 50].

The fineness of the BLA retained on 45 μm (No. 325) sieves is 30%, and 70% passed, less than the maximum value of 34% retained as specified per ASTMC 618. Increasing the fineness of BLA increases the amount of mixing water required to achieve a given consistency and reduces the amount of bleeding by the concrete [15, 33]. The fineness of the volcanic PP retained on 45 μm (No. 325) sieves is 29.3%, less than the maximum value of 34%, retained as specified per ASTMC 618.

According to ASTM standards, the specific gravity of OPC must be between 3.10 and 3.16 g/cc. The fact that the specific gravity of OPC was found to be 3.14 g/cc, which falls within this range, indicates that it meets the required ASTM standards. The specific gravity of BLA (2.24 g/cc) and volcanic PP (2.32 g/cc) are both less than the specific gravity of OPC (3.15 g/cc). BLA and PP have lower specific gravity than OPC because they contain more air voids and pores within their particles. These voids and pores reduce the density and weight of the materials but also increase their water absorption capacity [27, 51].

3.6. Influence of Cement Partial Replacement with PP and BLA on Consistency and Workability. The study evaluated the consistency of binder paste in various mixes with different levels of cement replacement using the Vicat equipment and following the ASTM C-187 standard. Each mixture had different percentages of constituents. Each mixture had different percentages of constituents. For instance, OPC Mix-1 contained 100% OPC, while Mix-2 had 90% OPC, 5% volcanic PP, and 5% BLA. Similarly, Mix-3 included 85% OPC, 10% PP, and 5% BLA, and Mix-4 had 85% OPC, 5% PP, and 10% BLA. Lastly, Mix-5 consisted of 80% OPC, 10% PP, and 10% BLA. The normal consistency of each mix was measured as a

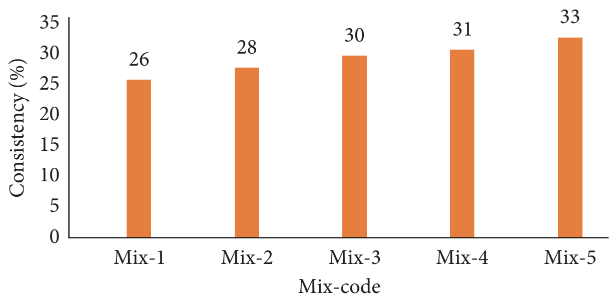


FIGURE 4: Normal consistency of blended paste.

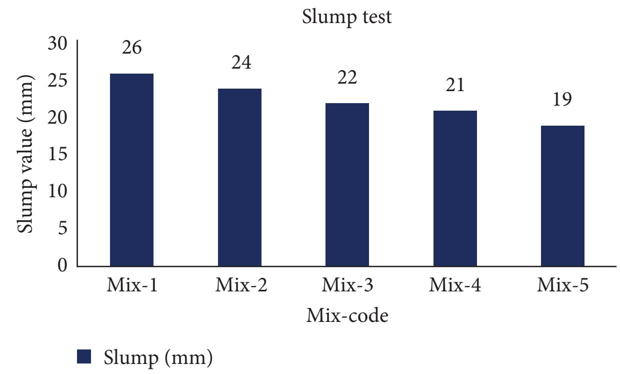


FIGURE 5: Slump value of concrete at different percentage of replacement.

percentage. OPC Mix-1 exhibited a normal consistency of 26%, while Mix-2, Mix-3, Mix-4, and Mix-5 had normal consistencies of 28%, 30%, 31%, and 33%, respectively. The results, depicted in Figure 4, illustrate how the partial replacement of constituents affects the consistency of the cement paste in different mix compositions. This improvement can be attributed to the presence of 5% BLA and 10% PP in Mix-3. The fineness of BLA and its larger specific surface area likely contributed to this effect, as finer particles require more water to wet their larger specific surface area [15].

The current study further investigated the effects of varying percentages of PP and BLA on the workability of concrete. Slump tests were conducted on the five different mixes. Mix-1 served as the control mix and had a slump value of 26 mm. As shown in Figure 5, as the percentage replacement of cement by PP and BLA increased, the slump value decreased in all subsequent mixes (Mix-2–Mix-5). For instance, Mix-2 achieved a slump value of 24 mm, Mix-3 had 22 mm, Mix-4 had 21 mm, and Mix-5 had the lowest slump value of 19 mm. It was observed that higher rates of cement replacement resulted in higher slump values, as indicated in the study by Zeyad et al. [52]. The water–cement ratio was held constant at 0.491 for all mixes.

3.7. Influence of Cement Partial Replacement with Bamboo Leaf Ash and Pumice Powder on Compressive and Flexural Strength. The findings concerning the effects of BLA and PP on the compressive strength of blended cement concrete are shown in Table 5. It is shown in Table 6 and Figure 6 that longer curing periods generally increased the concrete strength, but higher proportions of BLA and PP resulted in reduced strength [53]. Mix-1 (control) and Mix-2 (90% OPC, 5% PP, and 5% BLA) exhibited satisfactory strength of 23.64 and 22.48 MPa after 7 days of curing. At 14 days, Mix-2 (27.44 MPa) and Mix-3 (85% OPC, 10% PP, and 5% BLA) (26.71 MPa) showed comparable strength. After 28 days, Mix-1 (34.79 MPa) exceeded the target strength, and Mix-2 (35.84 MPa) had higher strength than other replacement mixes. The decrease in strength was attributed to the high replacement levels and reduced cement content [25, 54]. Previous studies on pozzolan and cement combinations supported these findings [30, 55]. Mix-2 and Mix-3 are suitable replacements for OPC in blended cement concrete. However, none of the ternary combinations matched the strength of the control mix after 28 days, except for Mix-2. The lower compressive strength in Mix-5 may be due to its higher concentration of less reactive crystalline silica [15, 26]. From the study by Zeyad et al. [56], the compressive strength of geopolymer concrete with CKD and OPC as partial substitution by 30% weight of VPD achieved an increase of 23% and 8% at a test age of 90 days compared with the control samples. In conformity with the above, a previous study on the ternary combination of pozzolans and cement has shown that the overall percentage of cement replacement with combined pozzolans is higher than individual blending with cement [27]. A study on the ternary blend of BLA, periwinkle shell ash (PSA), and OPC in concrete found that a mix of 10% BLA and 10% PSA was suitable for standard structural concrete. This was attributed to the high lime (CaO) content in PSA, a cementitious material. Furthermore, the study demonstrated that the 28-day curing period exceeded that of the control mix. In another study, Shannag [57] examined SF and volcanic tuff, determining that both materials could replace cement in a ternary mixture up to 15% without negatively impacting compressive strength.

The flexural strength of concrete mixes containing BLA and PP as partial replacements for cement was evaluated at various curing days, and the result is shown in Table 7. At 7 days of curing, the control mix (Mix-1) exhibited the highest flexural strength, while mixes with BLA and PP replacements (Mix-2–Mix-5) showed decreasing flexural strengths. At 14 days, Mix-2 surpassed Mix-1, indicating the positive influence of BLA and PP replacements. However, Mix-3, Mix-4, and Mix-5 exhibited similar or lower flexural strengths than the control mix and Mix-2. After 28 days, Mix-1 significantly increased flexural strength, surpassing the required strength for C25 concrete. Mix-2 continued to show improvement, while Mix-3 and Mix-4 had lower strengths. Mix-5 exhibited the lowest flexural strength. The study conducted by Kumar et al. [58], also indicates that the concrete strength improved significantly with higher reinforcements of RSF till 1.5% by volume, but it declines with further substitutions of WGP above 9% after 28 days. The pozzolanic reaction between BLA, PP, and cementitious components contributed to the observed improvements in flexural strength for Mix-2, illustrated in Figure 7 and Table 8. However, higher BLA and PP replacement percentages in Mix-4 and Mix-5 negatively affected flexural strength. These reductions suggest a threshold

Table 5: Compressive strength of the concrete with different replacement percentages and age.

Curing days	Mix-code	Compressive strength			Target mean strength (MPa)	Percentage of target strength of 33.5 (MPa)
		1	2	3		
7 days	Mix-1	23.73	23.62	23.59	23.64	70.5672
	Mix-2	22.46	21.98	23.1	22.48	67.1045
	Mix-3	21.69	21.28	21.4	21.46	64.0597
	Mix-4	20.28	20.81	21.04	20.71	61.8209
	Mix-5	13.94	14.92	14.96	14.62	43.6418
14 days	Mix-1	28.5	26.86	27.83	27.73	82.7761
	Mix-2	27.99	27.54	26.79	27.44	81.9104
	Mix-3	26.32	27.2	26.65	26.71	79.7313
	Mix-4	23.87	25.47	24.3	24.57	73.3433
	Mix-5	21.8	22.24	20.42	21.28	63.5224
28 days	Mix-1	34.25	34.21	35.82	34.79	103.851
	Mix-2	36.34	35.17	36.01	35.84	106.985
	Mix-3	33.81	34.65	32.49	33.55	100.149
	Mix-4	32.12	29.98	31.26	31.12	92.8955
	Mix-5	29.18	27.19	28.74	28.36	84.6567

Table 6: Compressive strength increment/reduction (%) to Mix-1 (control).

Mix-code	Increment/reduction (%) with reference to control mix by curing days				
	Mix-1	Mix-2	Mix-3	Mix-4	Mix-5
7 days	0	−4.9	−9.22	−23.39	−38.15
14 days	0	−1.0458	−3.67	−11.39	−23.26
28 days	0	+3.01	−3.56951	−10.54	−18.48

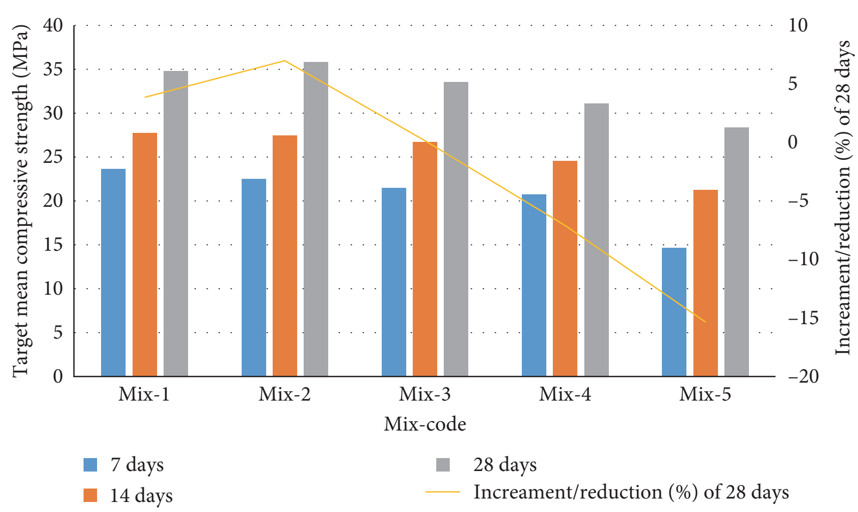


Figure 6: Compressive strength results.

beyond which higher proportions of pozzolanic materials hinder flexural strength development. BLA and PP's particle sizes, shapes, and chemical compositions can influence the packing density and hydration process, affecting flexural strength. Studies by Charitha et al. [59] and Özcan and Koç [24] supported these findings. A study by Malhotra and Mehta [60] highlighted that incorporating pozzolanic materials can delay the hydration process and affect the formation of C—S—H gel, resulting in reduced flexural strength. Concrete mixes were prepared by utilizing fly ash (FA) at 0%, 15%, and 30% replacement levels, which are coupled with SF in varying percentages of 0%, 6%, 12%, and 18% by mass substitutions of cement and subjected to a curing duration of 28 days. Results reported that an optimum mix of 15% FA, 12% SF, and 1% inclusion of steel

Table 7: Mean flexural strength of the concrete with different replacement percentages and age.

Mix-code	7 days Samples	Mean	14 days Samples	Mean	28 days Samples	Mean	28 days increment/reduction (%)
	3.178	—	3.267	—	3.87	—	—
Mix-1	3.219	3.078	3.31	3.163	3.597	3.684	0
	2.837	—	2.912	—	3.584	—	—
	2.702	—	3.106	—	3.917	—	—
Mix-2	2.917	2.897	3.452	3.229	3.968	3.868	4.99
	3.082	—	3.129	—	3.723	—	—
	2.65	—	3.436	—	3.504	—	—
Mix-3	2.793	2.696	3.382	3.102	3.747	3.604	−2.17
	2.646	—	3.238	—	3.581	—	—
	2.48	—	2.97	—	3.248	—	—
Mix-4	2.631	2.63	3.17	3.087	3.28	3.249	−11.80
	2.78	—	3.1	—	3.34	—	—
	2.518	—	2.86	—	2.761	—	—
Mix-5	2.462	2.562	3.1	2.82	3.355	3.108	−15.65
	2.78	—	2.51	—	3.208	—	—

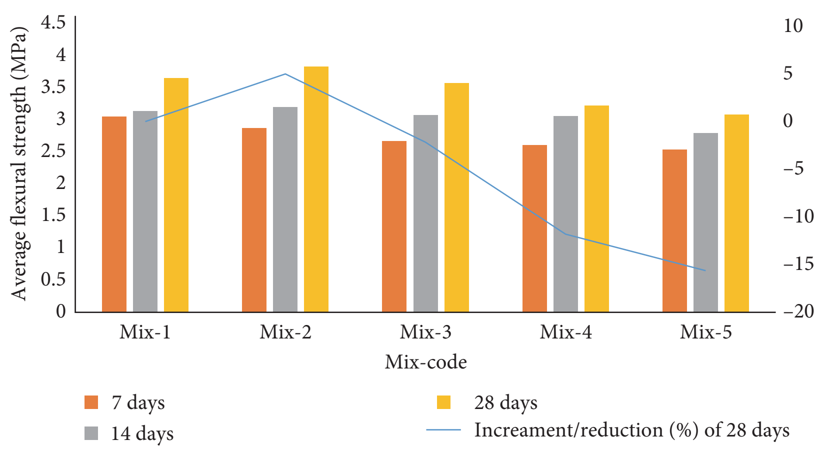


Figure 7: Flexural strength results.

Table 8: Flexural strength increment/reduction (%) to Mix-1 (Control).

Curing day	Mix-1	Mix-2	Mix-3	Mix-4	Mix-5
	Flexural strength increment/reduction (%) to Mix-1 (control) by different curing age				
7 days	0	−5.88	−12.41	−14.55	−16.76
14 days	0	−2.08	−1.92	−2.4	−10.84
28 days	0	+ 4.99	−2.17	−11.8	−15.63

fibers achieved higher compressive strength by 5.89% and showed a remarkable performance in terms of the flexural and split tensile strength [61, 62], which conform with the above study.

3.8. Influence of Cement Partial Replacement with Bamboo Leaf Ash and Pumice Powder on Water Absorption and Acid Resistance. Table 9 depicts the water absorption percentages after 28 days of curing for five different concrete mixes, identified as Mix-1 (control mix) to Mix-5 at different percentages of replacement.

Moving on to Mix-2, it is noteworthy that it exhibits a slightly lower water absorption percentage of 3.84% compared to other mixes. This suggests that it has a relatively lower tendency to absorb water, which can be attributed to the preliminary filling of gaps by PP and BLA concretes, which act as a barrier against water penetration. Mix-5 stands out among the listed mixes with the highest water

Table 9: Percentage of water absorption of VPP and BLA blended cement concrete.

Mix-code	Average water absorption @28 curing days		
	Weight of oven-dry (kg)	Weight submerged in water (kg)	Water absorption (%)
Mix-1	7.85	8.165	4.01
Mix-2	7.675	7.97	3.84
Mix-3	7.675	8.145	6.12
Mix-4	7.715	8.295	7.51
Mix-5	7.61	8.38	10.11

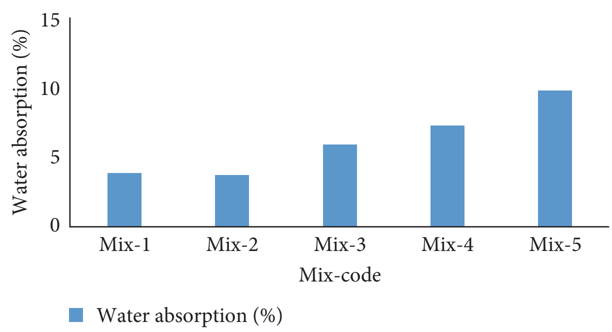


Figure 8: Water absorption at 28 curing days of different replacement levels.

Table 10: Compressive strength for concrete exposed to 0% and 5% of H_2SO_4.

Mix-code	Cured for 37 days in water with 0% H_2SO_4		Cured for 30 days in 5% H_2SO_4	
	Compressive strength (N/mm)	Strength deterioration factor (%)	Compressive strength (N/mm)	Strength deterioration factor (%)
Mix-1	36.64	0	23.89	33.34
Mix-2	34.99	0	25.55	26.55
Mix-3	32.75	0	30.33	9.59
Mix-4	31.82	0	27.66	11.12
Mix-5	29.36	0	24.6	13.2

absorption percentage of 10.11%. This suggests that the concrete in Mix-5 has a relatively higher tendency to absorb water compared to the other mixes. This increase in water absorption of PP and BLA mixtures refers to the increase in the porous volume of mortar mixtures and at higher levels of substitution. This finding supports previous research by Umoh and Odesola [27] and Kumar et al. [63]. However, it is important to note that as the proportion of PP and BLA used for cement replacement increases, the water absorption percentage also increases. This trend is evident from Figure 8. The increased porous volume in the mixtures can explain the increase in water absorption at higher substitution levels. At these higher levels, insufficient calcium hydroxide is available to react with the excess PP and BLA. This results in the formation of pores within the mixture, leading to higher water absorption. These findings align with previous studies, such as the research conducted by Asha et al. [64]. To address durability difficulties like as crack formation, manual examination and repair, such as impregnation of cracks with cement or epoxy-based or other synthetic fillers, are frequently utilized [65].

Interestingly, the performance can be improved by reducing the water absorption at an optimal replacement level of 20%. This optimization results in a dense microstructure in blended concrete, as Charitha et al. [59] reported. This denser microstructure reduces the presence of pores and enhances the water-resistance properties of the concrete.

Table 10 shows the compressive strength of PP and BLA mixed cement concrete when subjected to a 5% concentration of sulfuric acid H_2SO_4. The decrease in compressive strength was evaluated using the strength deterioration factor [66] by comparing it to a controlled exposure containing 0% H_2SO_4. Sulfuric acid has a strong and damaging effect on concrete, exhibiting two different forms of behavior. First, as an acid, it corrodes the calcium hydroxide and calcium silicate hydrate products present in concrete [50]. Second, it acts as a sulfate that attacks the calcium aluminate hydrate component [50, 67]. Five percentage sulfuric acid concentration had the maximal effect on the blended cement concrete. At 30 days of exposure, the control replacement suffered the greatest strength reduction of 33.34%, while replacement Mix-3 had the least strength reduction of 9.59%.

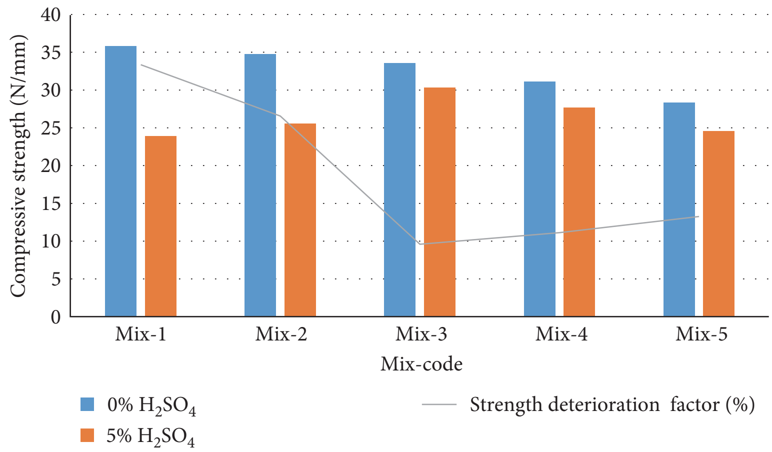
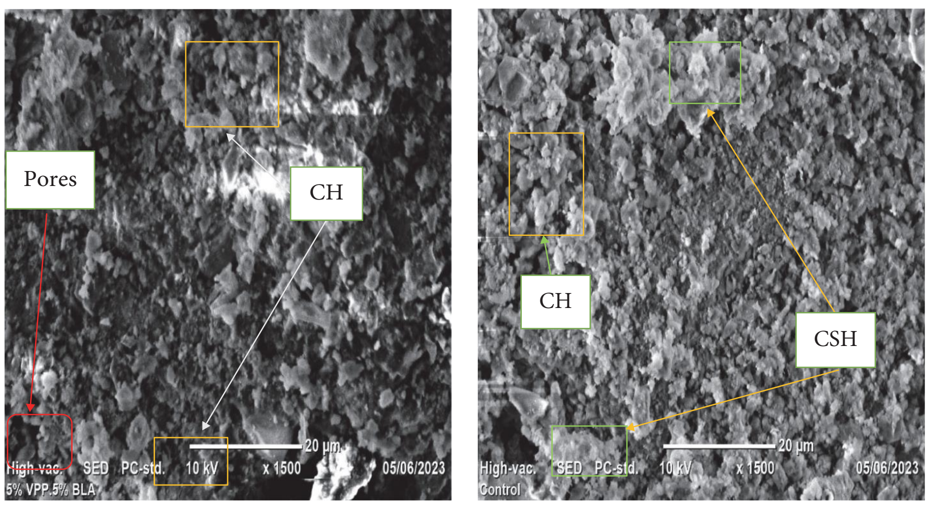


FIGURE 9: Variation of compressive strength with exposure period of concrete exposed to 0% and 5% H_2SO_4.



(a) (b)

FIGURE 10: SEM images of at 1,500 magnification: (a) control mix and (b) Mix-2 (90, 5, and 5).

Replacement Mix-2, -4, and -5 had percentage strength reductions of 26.55%, 11.12%, and 13.2%, respectively. The study conducted by Kumar et al. [68] conformed with the above result by observing that the water absorption percentage decreased with the rise in the amount of steel fibers and porosity decreased with the increase in curing period but increased with the rise in the amount of steel fibers.

Figure 9 shows the resistance of each replacement level to sulfuric acid attack for 5% acid concentration increases with the percentage replacement of PP and BLA. Replacement Mix-3 performed best with strength reduction of 9.59%, and replacement Mix-2 (26.55%), -4 (11.12%), and -5 (13.2%) provided better resistance than the control (33.34%). Hence, it is suggested that when concrete is subjected to extreme acid or sulfate conditions, using Mix-3 (85% cement, 10% PP, 5% BLA) as a replacement for OPC can improve durability. The compressive strength of the concrete cubes was increasing. With the increase in compressive strength of the concrete cubes, the deleterious ettringite generated by the sulfuric acid reaction continued to occupy the available pores within the cubes [13, 69]. The samples' ability to resist acid attack was improved because pumice, through its pozzolanic action, consumed calcium hydroxide, and formed stable products (CSH, CAH). These products effectively resisted the corrosive effects of the acid. Additionally, the acid leached out the calcium hydroxide, as shown in Figure 9, which would have otherwise contributed to the deterioration of the sample's structure. However, since the calcium hydroxide had already been consumed during the pozzolanic action, its absence did not contribute to further degradation [23]. With the increase in compressive strength of the concrete cubes, the deleterious ettringite generated by the sulfuric acid reaction continued to occupy the available pores within the cubes [13, 69].

3.9. Influence of Cement Partial Replacement with Bamboo Leaf Ash and Pumice Powder on Concrete Microstructure. SEM analysis of the concrete mixes revealed distinct microstructural characteristics. It can be observed in Figure 10 that the control mix exhibited a narrow and bright structure with crystalline formations, possibly representing calcium hydroxide (CH) [70]. In the control mix, a narrow and bright structure

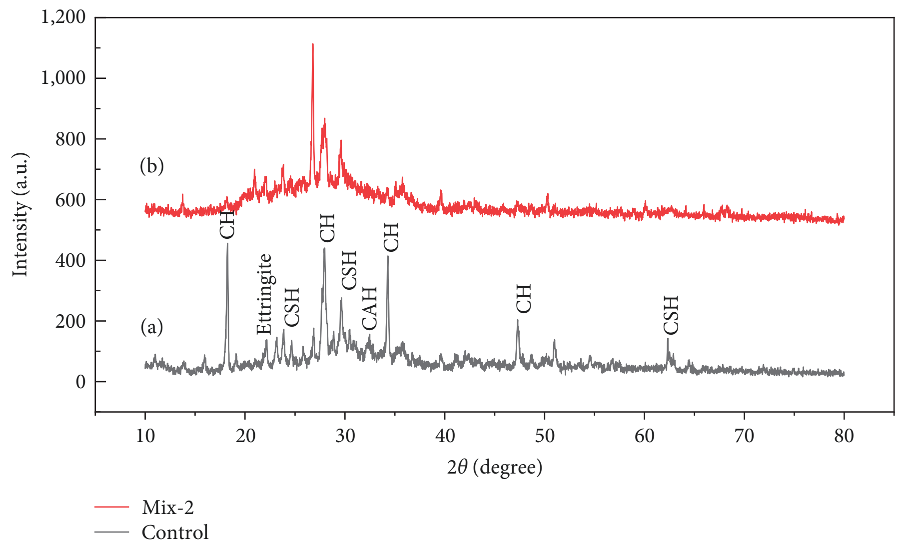


Figure 11: XRD pattern: (a) conventional concrete and (b) Mix-2 (90% cement, 5% VPP, and 5% BLA).

with crystalline formation was observed that could be CH, as shown in the Figure 10(a). Meanwhile, PP and BLAs pore structure is becoming more refined, it is still dense at Mix-2 (90, 5, 5) replacement, as shown in Figure 10(b). Mix-2, with its 90% PPC replacement by 5% PP and 5% BLA, displayed a refined but dense pore structure, voids indicating improved hydration, and a higher occurrence of calcium silica hydrate (C—S—H) gels. Ray et al. [71] studied the effect of RCA on AASC with various temperatures and found that RCA increases the properties of concrete with temperature. These observations support the blended materials' positive effects on the concrete's compressive strength and microstructure.

Similar peaks are observed from Figure 11(a) in the concrete samples with BLA and PP as partial replacements for cement, albeit with lower intensities [72]. This suggests a lower amount of calcium–silicate–hydrate (C—S—H) formation due to the dilution effect of the supplementary cementitious materials (SCMs) [73]. However, Figure 11(b) indicates additional peaks emerge at $2\theta = 26.6°$ and 31.8°, corresponding to calcium aluminate hydrate (C—A—H) and ettringite, respectively [74]. Similarly the study conducted by Sheeba et al. [75] shows two visible peaks at 15.3° (1 1 0) and 22.92° (0 0 2), which are typical plant fiber peaks. Indicating that the benzoyl chloride solution penetrated the fiber and dissolved the low molecular weight materials like hemicelluloses, wax, and lignin from the fiber's surface, revealing the cellulose, the peak (22.92°) of benzoyl-treated APFs was magnified more than the peaks of untreated APFs. These peaks indicate that the SCMs have reacted with the cement and water, resulting in the formation of supplementary hydration products that can enhance the strength and durability of the concrete [32]. Study conducted by Velusamy et al. [76] showes SEM analysis, the following compounds are present in the waste inert sample such as carbon, oxygen, magnesium, aluminum, silicon, sulfur, potassium, calcium, iron, titanium, and copper. The abovementioned characteristic test results indicate good strength and there is no harmful substances in the inert concrete so it may be applicable for dead load structures like partition walls, dividers, compound walls, etc. [77].

4. Conclusions

The study yields several key conclusions from its findings. PP and BLA both fulfill ASTM C 618 [19] standards as pozzolans, with BLA classified as a class F and PP as a class N pozzolan, affirming their suitability for the intended purpose. However, their inclusion in blended cement concrete led to reduced workability, requiring more water to maintain consistency, notably higher for BLA than PP. On the 28th day, Mix-2 and Mix-3, incorporating PP and BLA, achieved the target compressive strength of 33.5 MPa, with Mix-2 surpassing all others, including the control mix. Beyond Mix-3, further cement replacement resulted in diminished strength. Furthermore, regarding flexural strength, concrete with partial cement replacement by PP and BLA exhibited superior values, meeting required strength standards. Water absorption in blended concrete was lower in Mix-2 but higher in replacement levels, attributed to PP's porous structure and BLA's finer particles. Incorporating PP and BLA notably enhanced resistance to sulfuric acid attack, with Mix-3 displaying the least strength reduction. The XRD peaks indicated that SCMs reacted with cement and water, forming additional hydration products and improving concrete strength and durability. The distinctive features in Mix-2, including improved hydration and a high occurrence of calcium silica hydrate gels on the surface, explain the maximum compressive strength achieved at this replacement level.

The study will contribute a new knowledge area on the effect of using blended PP and BLA to be added as a partial replacement of cement in C-25 concrete production. It will aid in reducing natural resource depletion, CO_2 emissions, and cement costs. Furthermore, this research will significantly reduce ecological crises and health problems due to the disposal of bamboo leaves. Additionally, this investigation will open the way for utilizing the local cheap and available volcanic pumice and bamboo leaf material. Finally, blending VPP and BLA with cement will improve the properties of fresh concrete and the durability and strength of hardened concrete, and it will provide primary data for researchers to conduct further investigations.

Certain tests, such as ultrasonic testing and spline tensile strength assessments, were not conducted due to financial constraints. These limitations impact the comprehensive evaluation of the subject.

4.1. Future Scope of the Study

(1) Explore the commercial viability of utilizing PP and BLA as pozzolans for concrete production, aiming to reduce reliance on OPC and realize potential cost savings.

(2) Investigate the potential of BLA and PP in achieving chemical-resistant concrete. Evaluate the effectiveness of Mix-3 (85% cement, 10% PP, and 5% BLA) in replacing OPC for enhanced durability in concrete exposed to severe acid/sulfate environments while maintaining comparable strength.

(3) Conduct petrographic analyses to assess the alkali–silica characteristics of aggregates containing PP due to their high alkali content, ensuring a comprehensive understanding before incorporating it into concrete.

(4) Extend the study to examine additional durability parameters and strength properties, such as tensile and shear strength, for the ternary combination of BLA, PP, and OPC in concrete, providing a more comprehensive evaluation of their performance.

Data Availability

All materials and data are available in the hands of the authors.

Conflicts of Interest

The authors affirm no conflicting interests about the publication.

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