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RESEARCH ARTICLE

Experimental Investigation of Bamboo Leaf Ash Blended Concrete for Sustainable Construction

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Abstract: This study investigated the feasibility of using bamboo leaf ash (BLA) as a partial replacement for ordinary Portland cement in the production of sustainable concrete. The pozzolanic potential of BLA was evaluated through chemical analysis, which showed that the combined content of SiO_2, Al_2O_3, and Fe_2O_3 was 74.61%, satisfying the requirements of ASTM C618 for Class N pozzolans. Concrete mixtures were prepared with 0%, 5%, 10%, 15%, and 20% BLA replacement levels by weight of cement, targeting a characteristic compressive strength of 25 MPa. The effects of BLA incorporation on cement paste properties, workability, compressive strength, water absorption, and sulfate resistance were experimentally investigated. The results indicated that mixtures containing 5% and 10% BLA exhibited superior mechanical performance compared with the control mix. In particular, the 10% BLA mixture achieved a compressive strength of 33.5 MPa at 28 days, exceeding the target strength requirement. Furthermore, the compressive strength continued to increase at 56 days, demonstrating the contribution of the pozzolanic reaction to long-term strength development. Concrete mixtures containing 5–10% BLA also exhibited lower water absorption and improved resistance to sulfate attack. Although higher BLA contents increased the water demand and prolonged the setting times of cement paste, the overall results demonstrate that BLA can be effectively utilized as a supplementary cementitious material, with an optimum replacement level of 10% for producing durable and environmentally sustainable concrete.

Keywords: bamboo leaf ash, pozzolan, cement replacement, compressive strength, durability

1. Introduction

Concrete is the most widely used material globally. However, production rates have significantly increased demand for cement and aggregates due to urbanization and development worldwide [1, 2]. In Ethiopia, there is also a high demand for cement due to the growing construction sector. In fact, there is a great need for sustainable cement production due to the high demand for conventional cement. Traditional cement, fine and coarse aggregates, and water are the ingredients of concrete. Among these materials, cement is the most crucial material as it acts as a binder, but it is also very costly and harmful to the environment. Therefore, there is increasing interest in exploring more economically and ecologically sustainable supplementary cementitious materials (SCMs) to augment Portland cement [3, 4].

Efforts have also been made to prospect industrial by-products and agricultural waste, which have proved to be potent cementitious materials if they have pozzolanic properties. This is because these materials improve concrete properties, in addition to enabling greater cement replacement [5]. Pozzolanic products can enhance the properties of concrete and make concrete production more sustainable by reducing the cement requirement, thereby significantly improving production cost, energy use, and environmental impacts [6, 7].

Regarding a suitable material for production in the Ethiopian context, one such material is the leaves of the bamboo plant. There are large deposits of bamboo in the Ethiopian region, mostly found in the form of "lowland bamboo" species *Oxytenanthera abyssinica*, with a large proportion (64%) located within the Benishangul-Gumuz regional state of Ethiopia, but the leaves, mostly considered waste, are not yet harnessed for anything other than their most basic applications, for example, thatching and fuel. In Ethiopia, even though it is plentiful, bamboo has been looked down upon as a low-quality material, with little documentation of its economic value. Its market value has been considered lower than that of major agricultural crops such as sesame and maize [8, 9]. Nevertheless, usable industrial material could be obtained from the plant's leaves, which are normally considered waste [10]. With processing, these leaves could be made into ash. Calcined bamboo leaf ash (BLA) has been found to exhibit pozzolanic properties due to its high silicate content. As a pozzolanic material, BLA may react with calcium hydroxide, a by-product of cement hydration, to form more calcium silicate hydrate (C-S-H) gel. This improves the concrete microstructure by reducing the free lime content [11, 12].

Although preliminary studies in different parts of the world may agree on BLA's reactivity, its adaptability in an Ethiopian context using Ethiopian-sourced bamboo has been tested. Thus,

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the aim of this study is to experimentally determine the viability of using Ethiopian BLA as a replacement for cement. The primary objective of this study is to determine the viability of using Ethiopian BLA as a partial replacement for ordinary Portland cement (OPC) in concrete manufacture. Specifically, the aim of the study is to evaluate the physical and chemical properties of BLA cement paste through the determination of normal consistency, setting time, and soundness. Further, the effect of varying BLA replacement levels on workability of fresh concrete and the subsequent development of compressive strength at varying curing ages will be determined. Through these evaluations, an optimum replacement level of BLA will be determined.

2. Literature Review

The cement industry is responsible for 7–8% anthropogenic global CO_2 emissions due to the energy-intensive production process of clinker; therefore, the need for alternative SCMs from industrial and agricultural wastes has been explored [1, 4]. The use of SCMs such as fly ash, silica fume, rice husk ash, and ground granulated blast-furnace slag has been shown to enhance the performance and sustainability of concrete while reducing its environmental impacts [6, 13].

Agricultural by-product materials with high amorphous silica content have gained increased attention due to their pozzolanic properties when properly processed [3, 8]. BLA has been found to be a promising SCM because of the high silica content of bamboo leaves and the ubiquity of bamboo in tropical and subtropical climates [13, 14]. Chemical analysis of BLA has revealed that it contains more than 60% SiO_2 after proper calcination, meeting American Society for Testing and Materials (ASTM) standards for pozzolanic materials [15, 16].

Experimental work has revealed that the partial substitution of cement with BLA at levels of 5–15% by weight of cement leads to an improvement or maintenance of compressive strength, especially at longer curing ages, because of the secondary C-S-H gel formed [13, 17, 18]. Similar improvements in split tensile and flexural strength have also been observed, which can be ascribed to the refinement of the pore structure [17, 19]. However, beyond a certain limit of substitution, the strength tends to decrease because of dilution and insufficient pozzolanic reaction [2, 20].

Properties of fresh concrete are also affected when BLA is incorporated. Research findings have shown that water demand and mix workability decrease due to the porous nature and irregular morphology of BLA particles. However, the use of chemical admixtures has proven helpful in improving the mix's workability, albeit at moderate replacement levels. Durability is one of the major aspects to consider when using BLA in concrete. Although the literature on the durability of BLA-blended concrete is scarce, findings indicate that sulfate resistance, permeability, and chloride resistance are better than in conventional concrete. The majority of existing investigations on BLA have been conducted using Asian and West African material sources, while there has been limited investigation on East African bamboo species and available production technologies [17, 19]. In addition, calcination temperature, grinding fineness, and replacement ratio were found to affect the properties of BLA, leading to inconsistent findings in existing investigations [14].

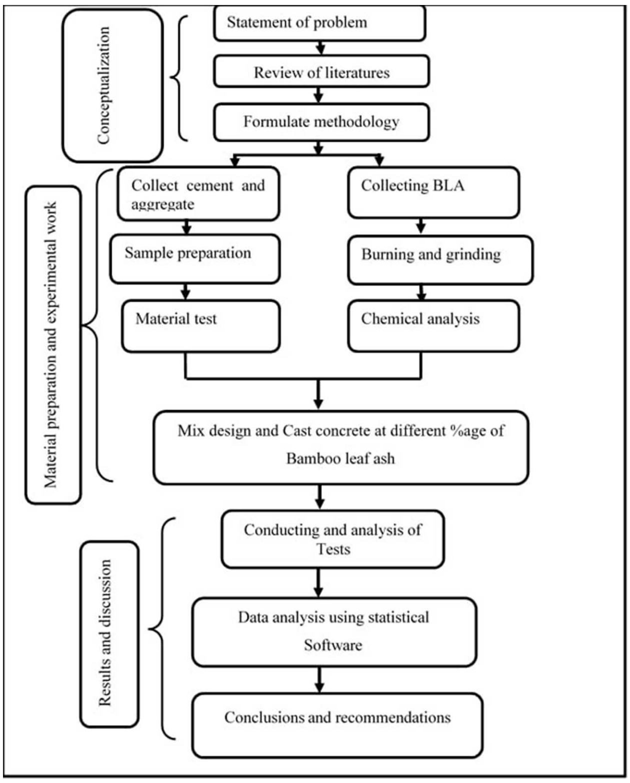
Ethiopia has one of the largest reserves of bamboo in Africa. However, the utilization of BLA in blended cements has not been adequately explored, while there is an increasing need for sustainable cements in Ethiopia due to rising cement demand [11, 10]. The utilization of BLA as a cement substitute has the potential to reduce environmental impact while increasing resource efficiency in construction activities [1, 4]. However, there has been limited experimental investigation on Ethiopian BLA-blended concrete.

Accordingly, the purpose of this research is to experimentally examine the mechanical properties of concrete incorporating locally available BLA from Ethiopia as a partial replacement for cement, thereby contributing to the development of sustainable construction materials in developing countries [21, 22].

3. Research Methodology

This chapter discusses the materials used and the experimental methods employed in this research. Coarse and fine aggregate, cement, BLA, and water were the materials used in this study. The research was conducted in western Ethiopia, specifically in the Benishangul-Gumuz Regional State, approximately 665 km from Addis Ababa. The experimental work was conducted between December 2022 and June 2023. Laboratory tests were conducted on aggregates, including normal consistency, soundness, slump, and compressive strength, as well as initial and final setting times, at the Addis Ababa Construction Materials Laboratory. An investigation into the chemical composition of BLA was carried out at the Ethiopian Geological Survey in Addis Ababa. In this research, conventional concrete with a grade designation of C-25 MPa was selected. Five series of mix proportioning based on conventional mix design techniques were used to create concrete cubes. Two mixes were selected as control mixes containing OPC without BLA. The remaining four mixes were made with BLA at weight percentages of 5%, 10%, 15%, and 20% as a partial substitute for OPC. For OPC in proportions of 5%, 10%, 15%, and 20% by weight. The main methodologies of this experimental work are shown in Figure 1.

Figure 1
The study's methodology flowchart



3.1. Materials for the research work

3.1.1. Cement

The OPC grade 32.5R was obtained from Mugher Cement Factory, Ethiopia. It met the ASTM C150 standards and had a specific gravity of 3.15.

3.1.2. Water

In this research, tap water was used in curing and mixing.

3.1.3. Fine and coarse aggregate

Crushed basaltic coarse aggregates having a maximum size of 25 mm were used, sourced from Amba 14 quarry. River sand was used as fine aggregate, which is obtained naturally from Kumuruk River. This aggregate was sieved with a 4.75 mm sieve size but retained on a 150 µm sieve size. Fineness modulus, specific gravity, and absorption of this aggregate were found to be 2.80, 2.76, and 2.77%, respectively.

3.1.4. Bamboo leaf

The leaves of the bamboo plant used in this research were obtained from Gumu Kebele in Homosha Woreda of Assosa Zone in Benishangul-Gumuz Regional State of Ethiopia. The leaves collected in this study weighed about four quintals. The leaves were dried in the sun for minimal moisture content. Then, they were crushed using a mechanical machine and a hammer. After that, they were burned in a furnace. The obtained ash had a particle size of 75 µm.

3.2. Preparation of bamboo leaf ash

The bamboo leaves needed to produce ash were obtained from the Homosha region. The process involved in creating charcoal ash involved three stages: (1) physical reduction of leaves through a hand hammer to make them burnable; (2) burning leaves in a furnace at a 600 °C temperature for 2 h, followed by 24 h of cooling in a furnace; and (3) sieving ash through a 75 µm sieve, with larger particles ground with a milling machine. This is represented in Figure 2.

3.3. Batching

The mix proportions were determined by the weight batching method. OPC was partially replaced by BLA at 5%, 10%, 15%, and 20% by weight of OPC, based on previous studies, to investigate the optimum substitution level of OPC with BLA. A control mix containing 100% OPC and 0% BLA was also used.

3.4. Concrete mix proportion

Concrete mix design/proportion involves calculating the relative amounts of cement, water, aggregates, and any chemical additives required in a batch to achieve specified performance criteria. These criteria typically include key characteristics such as workability in the fresh state, as well as strength and durability once hardened. For this research, proportions were calculated following the standard procedure laid out in ACI 211.1, the American Concrete Institute's normal-weight proportions approach.

Figure 2
End product of fine bamboo leaf ash

3.5. Concrete mixing and sample preparation

The concrete cube samples were cast using a conventional casting procedure. The materials, in their respective quantities, were weighed according to the mix design.

The aggregates and cement were first combined in a pan mixer and blended for approximately 1 minute. Afterward, water was introduced, and mixing continued for an additional 2 minutes to achieve a uniform consistency. The fresh concrete was then placed into steel cube molds measuring 150 × 150 × 150 mm, filling them in three equal-volume layers. Each layer was compacted using mechanical vibration for about 30 s to eliminate trapped air, and the top surface was leveled with a trowel.

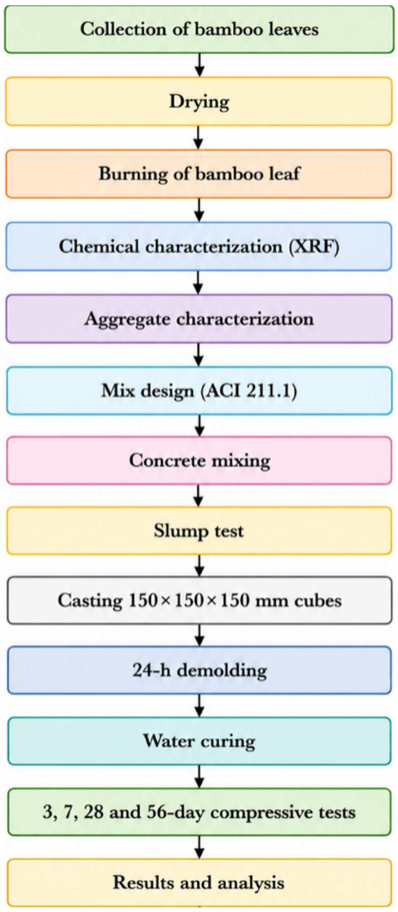
Immediately after casting, the molds were covered with plastic sheets to prevent moisture loss and kept at room temperature for 24 h. Following this initial curing period, the specimens were demolded and transferred to a water tank, where they remained submerged for continuous curing until testing.

In total, 60 cube specimens were prepared, including control samples made with OPC only. Each mix category consisted of twelve specimens.

3.6. Concrete mixing, casting, and curing procedures

Concrete samples were produced based on the standard method of concrete preparation, which involves the proportioning, mixing, and molding procedures. The amounts of materials used, such as the amount of coarse aggregate, fine aggregate, OPC, and BLA, were determined according to the proportioning ratios. First, all the dry ingredients, such as the aggregates, cement, and BLA, were thoroughly mixed in a pan mixer for about 1 minute. Then, water was gradually added to the mixture and mixed for another 2 minutes to produce a homogeneous mixture. Concrete was poured into steel cube molds of 150 × 150 × 150 mm in three layers. Each layer was compacted using a vibrating table for 30 s in order to minimize the presence of air bubbles and ensure proper compaction. Upon pouring the concrete into the mold, its surface was leveled using a trowel. Specimens were kept under plastic cover to retain moisture, and they remained undisturbed for 24 h at normal room temperature. After that, specimens were removed from the molds and soaked in a curing tank of water at a temperature of 23 ± 2 °C until the test age. The main flowchart illustrating the experimental procedure is shown in Figure 3.

Figure 3
Flowchart illustrating the experimental procedure



3.7. Test for aggregates

The coarse aggregate used in this study was crushed basaltic rock with a nominal maximum size of 25 mm. The fine aggregate consisted of natural river sand, which was graded to pass a 4.75 mm sieve and be retained on a 150 μm sieve. Impurities were removed from the coarse aggregate by thoroughly washing and then air-drying it on plastic sheets. All aggregates were tested using standard test methods to determine their physical properties for mix design. The respective specific test types, along with standard procedures adopted, are listed in Tables 1 and 2.

3.8. Test for cement and cement paste

OPC with a strength grade of 32.5R was utilized. The cement and its paste were characterized in the laboratory through the following tests: fineness, consistency, setting time, soundness, tensile strength, and chemical composition.

Table 1
Coarse aggregate testing and methodology

S. no.	Test types	Test methods
1	Gradation analysis	ASTM C136
2	Bulk density	ASTM C29
3	Relative density	ASTM C127
4	Absorption	ASTM C127
5	Moisture content	ASTM C566

Table 2
Fine aggregate testing and methodology

S. no.	Test types	Methods of testing
1	Organic content test	ASTM C40
2	Gradation	ASTM C36
3	Bulk density	ASTM C29
4	Relative density	ASTM C128
5	Absorption	ASTM C128
6	Moisture content	ASTM C566

3.9. Test for concrete

The workability of the fresh concrete was determined, and then compressive strength tests were conducted. The flexural strength tests also followed. Strength tests were carried out on 150 × 150 × 150 mm cubes after 3, 7, and 28 days using a 2000 KN capacity compressive strength testing machine in the construction materials laboratory at Addis Ababa University.

4. Experimental Work

4.1. Normal consistency of paste

The normal consistency of OPC-BLA-blended cement paste was evaluated using ASTM C-187 with a Vicat apparatus, replacing OPC with BLA at 0%, 5%, 10%, 15%, and 20% by weight.

Results in Table 3 indicate that while the control paste at 0% BLA has a normal consistency of 27%, all blended pastes with BLA require additional water to reach a higher normal consistency. All results, starting with the 27% control, are within the 26–33% normal consistency range recommended by ASTM C-143.

Table 3
Standard consistency of ordinary cement paste and BLA-blended cement paste

S. no.	Designation code	Consistency % (ASTM C187)
1	BLA0	27
2	BLA5	28
3	BLA10	30
4	BLA15	32
5	BLA20	33

Table 4
Summary of initial and final setting times of ordinary cement and BLA-blended cement paste

		Setting time in minutes as per ASTM (C191)	
No	Assigned code	Initial set time	Final set time
1	BLA0	125	270
2	BLA5	150	300
3	BLA10	173	326
4	BLA15	175	328
5	BLA20	180	332

4.2. Setting time of paste

Setting times of control cement paste and cement paste blended with BLA were evaluated in accordance with ASTM C-191. The results, as indicated in Table 4, revealed that all the cement pastes met Ethiopian standards for setting, with the initial setting time at least 45 min and the final setting not exceeding 10 h. Adding large amounts of BLA prolongs the setting period because less cement is available for hydration, and some water is absorbed by the particles.

4.3. The soundness of cement—BLA mix

Tests on cement soundness were carried out in accordance with the ASTM C-151 specification, and results were obtained using Le Chatelier's apparatus.

From Table 5, it is evident that the expansion of all pastes is below 10 mm as specified by the Ethiopian standard on cement, indicating that the pastes are acceptable for use in making concrete.

Table 5
Soundness of cement and BLA-blended cement paste

S. no	Designation code	Expansion (mm)
1	Control OPC	1.6
2	5% substitution	2.1
3	10% substitution	1.9
4	15% substitution	1.9
5	20% substitution	2.1

4.4. Chemical properties of bamboo leaf ash

The elemental composition of the BLA was established by laboratory testing conducted at the Geological Survey of Ethiopia. According to the data summarized in Table 6, the combined proportion of SiO_2, Al_2O_3, and Fe_2O_3 equals 74.61%, which is well over the 70% required by ASTM C618 and qualifies BLA as a Class N pozzolan.

4.5. Silt content

To determine the strength of the concrete, the percentage of silt in the river sand was tested in accordance with Ethiopian standards. The result was 2.96%, below the 6% maximum limit and therefore suitable for use.

Table 6
Chemical composition of BLA

S. no.	Oxide	Bamboo leaf ash (%)
1	SiO_2	74.16
2	Cao	5.64
3	Al_2O_3	<0.01
4	Fe_2O_3	0.44
7	K_2O	2.88
9	P_2O_5	0.32
5	MgO	4.24
6	Na_2O	<0.01
8	MnO	0.06
10	TiO_2	<0.01
11	H_2O	1.59
12	LOI	10.5

4.6. Gradation of fine aggregate

A sieve analysis (ASTM C136) was conducted to determine the variation in grain sizes and grading characteristics of fine aggregates. Figure 4 illustrates the complete particle size distribution, and the fineness modulus was calculated to quantify the sand's overall fineness.

Figure 4
Particle size distribution curve of the fine aggregate

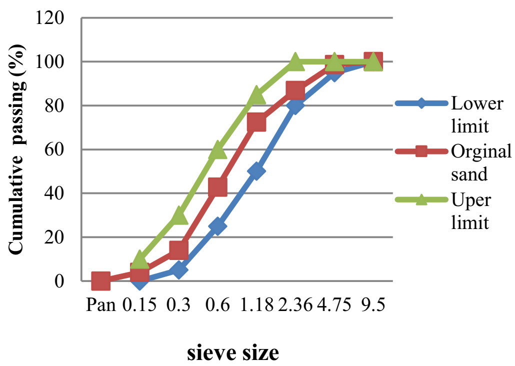


Table 7
Summary of fine aggregate physical properties

No	Test types	Method of test	Experiment outcome	ASTM standard limit
1	Fineness modulus	ASTM C136	2.80	2.3–3.1
2	Bulk density	ASTM C29	1819 kg/m^3	1280–1920 kg/m^3
3	Specific gravity	ASTM C128	2.76	2.6–2.8
4	Absorption capacity	ASTM C128	2.77%	0.2–4%
5	Moisture	ASTM C566	1.62%	–

4.7. Bulk density, relative density, and absorption of fine aggregate

The bulk density of the fine aggregate was measured at 1819 kg/m^3, in accordance with ASTM C29, which falls within the typical range of 1280–1920 kg/m^3. The specific gravity and water absorption were evaluated in accordance with ASTM C128.

The obtained relative density values, 2.76 and 2.77, lie within the standard range of 2.60–2.83, while the absorption value remained below the 4% upper limit. These outcomes indicate that the aggregates comply with the relevant specification requirements. The results are presented in Table 7.

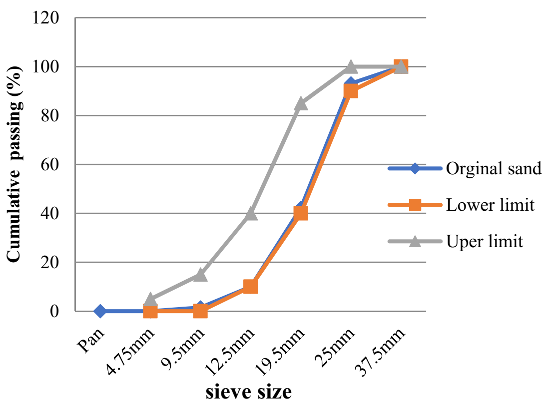
4.8. Moisture content of fine aggregate

The amount of moisture contained within fine aggregate, including pore and surface water, was determined based on the standard method of test for total water content present in fine aggregate, as specified in ASTM C566. The total moisture content of fine aggregate was 1.62% after drying at 110 °C for 24 h. The free moisture can be calculated by subtracting the aggregate's absorption capacity. The results are presented in Table 7.

4.9. Particle size distribution of coarse aggregate

The sieve analysis was performed according to ASTM C136 to determine the coarse aggregate gradation, as with the fine aggregate. The particle size distribution was determined using a set of ASTM standard sieves with openings of 37.5, 25, 19, 12.5, 9.5, and 4.75 mm. The outcomes of the sieve analysis are summarized and illustrated by the plotted curve presented in Figure 5.

Figure 5
Summary of physical properties of coarse aggregate



4.10. Bulk density, relative density, and absorption of coarse aggregate

Testing of the coarse aggregate indicated that its properties satisfied the required specifications. The measured bulk density was 1605 kg/m^3, which falls within the ASTM acceptable interval of 1280–1920 kg/m^3.

In addition, evaluation in accordance with ASTM C-127 gave a relative density value of 2.76 and a water absorption of 2.1%. The detailed outcomes are summarized in Table 8.

4.11. Moisture content of coarse aggregate

The water content of the coarse aggregate was determined using the same procedure as for the fine aggregate, following the ASTM C566 method, yielding a value of 0.65%. The physical properties are summarized in Table 8.

4.12. Mix proportion of concrete

The design of the concrete mix was carried out in accordance with the ACI 211.1 standard. As earlier stated, 60 cubes were cast for the experiment, and they were categorized into five unique mix series.

Series I was the control mix and used 100% OPC. Series II, III, IV, and V used BLA as a partial substituent for OPC. A uniform water-to-cement proportion of 0.49 was maintained throughout every mixture. The mix design is shown in Table 9.

5. Results and Discussion

5.1. Fresh properties of concrete

5.1.1. Slump test

Workability, a key property of freshly prepared concrete, was evaluated for each mixture using a slump test. As shown in Table 10, the slump test results showed a uniform decrease with increasing quantities of BLA, indicating reduced workability. This is due to the higher fineness of BLA, which has a Blaine specific surface area of 3236 cm^2/g compared to 2750 cm^2/g for OPC. The higher surface area results in higher water demand.

Additionally, the lower specific gravity of BLA implies that a unit weight of the material occupies a higher volume than cement, thus requiring a higher water demand. However, all slump values for replacement levels up to 15% BLA were within the acceptable limits, as shown in Table 10. The slump decreased as the BLA content increased, under a uniform water-cement ratio of 0.49.

Table 8
Summary of physical properties of coarse aggregate

No	Types of tests	Test method	Test result	ASTM limit
1	Nominal maximum size of aggregate	ASTM C33	25 mm	4.5–90MM
2	Bulk density	ASTM C29	1605 kg/m^3	1280–1920 kg/m^3
3	Relative density	ASTM C127	2.76	2.4-3-6+
4	Absorption capacity	ASTM C127	2.1%	0.2–4%
5	Moisture content	ASTM C566	1.62%	–

Table 9
Summary of mix proportion

Batch mix code	Quantity of materials per cubic meter (kg/m^3)					W/C ratio
	Cement	BLA	Water	Fine agg.	Coarse agg.	
OPC	360	–	204	843	1087	0.49
BLA 5%	342	18	204	841	1087	0.49
BLA 10%	324	36	204	832	1087	0.49
BLA 15%	306	54	204	824	1087	0.49
BLA 20%	288	72	204	820	1087	0.49

Table 10
Slump test results

No	Mix code	Slump result	W/C ratio
1	BLA0	30	0.49
2	BLA5	28	0.49
3	BLA10	28	0.49
4	BLA15	26	0.49
5	BLA20	24	0.49

5.2. Hardened properties of concrete

5.2.1. Compressive strength of concrete

Compressive strength is a critical mechanical property of hardened concrete. For each mix, this strength was determined at multiple ages by testing cubes in a compression machine at 3, 7, 28, and 56 days. The reported strength for each mix represents the average of identical cube specimens; the full results are provided in Table 11. The 28-day strength data show that both the control mix (OPC) and mixes containing up to 10% BLA as a cement replacement attained a target mean strength of 33.5 MPa. In contrast, mixes with 15% and 20% BLA replacement exhibited significant strength reductions of 24.3% and 17.92%, respectively, relative to the control.

This indicates a clear decline in 28-day compressive strength when BLA content exceeds 10%. The primary cause is likely a dilution effect, in which higher replacement levels of a less reactive pozzolan reduce the cementitious content per unit volume, thereby slowing the hydration process.

However, the trend in strength gain beyond 28 days was reversed. From 28 to 56 days, the reference mix experienced only a slight increase in strength, amounting to about 1.62%. In

Table 11
Results obtained from compressive strength testing of cube concrete specimens

Mix code	Mean values of compressive strength							
	3rd day		7th day		28th day		56th day	
	Result		Result		Result		Result	
	Load (KN)	(Mpa)	Load (KN)	(Mpa)	Load (KN)	(Mpa)	Load (KN)	(Mpa)
Control BLA 0%	381.4	16.9	642.4	28.6	814.7	36.2	828.5	36.8
BLA 5%	359.1	15.9	615.4	27.4	766.1	34.1	792.0	35.2
BLA 10%	351.2	15.6	586.5	26.1	756.5	33.6	782.3	34.8
BLA 15%	333.9	14.8	562.1	24.9	745.4	33.1	776.9	34.5
BLA 20%	323.5	14.4	511.7	22.7	688.7	29.7	719.3	32.0

Table 12
Hardened BLA concrete density

OPC (%) replacement level	BLA 0%	BLA 5%	BLA 10%	BLA 15%	BLA 20%
Density (kg/m^3)	2373	2362	2361	2328	2326
Density reduction (%)	0.00	0.46	0.51	1.89	1.98

Table 13
Analysis of variance test on the impact of independent variables

Source	Sums of squares of type III	DF	Average square	*F*	Significance
Corrected model	1432.199a	23	62.173	222.383	.000
Intercept	17045.873	1	17045.873	21351.445	.000
BLA	114.701	5	22.940	28.735	.000
Age	1305.613	3	435.204	545.131	.000
BLA × AGE	11.957	15	.789	1.34	.000
Error	.00	0			
Total	18488.262	24			
Corrected total	1431.829	23			

comparison, the BLA mixes exhibited progressively greater strength gains as BLA content increased, suggesting continued pozzolanic activity at later ages.

5.2.2. Density of hardened concrete

The bulk density of each concrete cube was calculated as the ratio of its mass to its volume, and the measurements were taken prior to conducting the 28-day compressive strength test. The results are summarized in Table 12.

The data indicate a consistent reduction in bulk density as the proportion of BLA in the mix increases. This behavior occurs because BLA has a lower specific gravity (2.15) than OPC (3.15). Consequently, replacing part of the cement with BLA decreases the overall mass per unit volume of the concrete.

5.3. Statistical analysis

5.3.1. Analysis of variance (ANOVA)

A two-way ANOVA was used to examine the impact of two independent variables—the curing age and the percentage replacement of BLA—on the dependent variable, compressive strength. A statistical analysis that can account for both the individual main effects and their interaction, describing the combined effect of the factors on the outcome. The results are shown in Table 13.

5.4. Discussion

The above results show that BLA influences the properties of concrete through particle fineness, pozzolanic reaction, and cement dilution effect. The reduction of workability with an increase in BLA content is due to the high specific surface area and particle irregularity of the material, leading to a high water requirement, hence less slump. Such behavior is also observed in other agricultural ash-based supplementary cementing materials. The results of compressive strength indicate that a low BLA replacement ratio gives adequate strength, whereas high BLA replacement ratios lead to a reduction in strength due to the dilution effect caused by a lower amount of cement. But BLA-blended concrete mixes have shown an increase in compressive strength at higher curing age as compared to control mixes. This is because of a secondary pozzolanic reaction where silica in BLA reacts with calcium hydroxide to produce additional C-S-H gel. Hence, there is an improvement in concrete structure. The slight decrease in density with an increase in BLA content is attributed to the lower specific gravity of BLA as compared to cement.

5.4.1. Comparison with previous works

The results obtained from this study are in agreement with the results from previous literature reviews conducted on the use of BLA as SCMs. The sum of silica dioxide (SiO_2), alumina trioxide (Al_2O_3), and iron oxide (Fe_2O_3) of 74.61% indicates the pozzolanic characteristic of BLA in Ethiopia and fulfills ASTM C618 requirements, which is consistent with the studies conducted by Debnath et al. [13] and Silva et al. [16]. Like previous literature [13, 21], workability decreased with an increase in BLA due to the smaller particles and high demand for water. The optimum replacement of BLA is at 10%, giving a 28-day compressive strength of 33.6 MPa, which agrees with the previous study carried out by Ikumapayi et al. [18] and Mirzaei et al. [21]. Continuous improvement in strength at 56 days is consistent with the study carried out by by Huang et al. [17] and Villar-Cociña et al. [22].

6. Conclusions

This research examined the potential of BLA as a partial substitute for OPC in concrete, focusing on its chemical characteristics and its influence on fresh and hardened concrete properties. The chemical analysis showed that BLA contains a high proportion of Iron oxide, alumina, and silica, with a combined content of 74.61%, which meets the requirements for ASTM Class N pozzolanic materials specified in ASTM C618. This indicates that BLA possesses adequate pozzolanic activity and can participate in secondary reactions that contribute to strength development. With respect to fresh concrete behavior, it was observed that workability steadily dropped as the BLA proportion rose. The control mixture exhibited the highest slump, while mixes containing higher amounts of BLA became progressively stiffer. This trend can be linked to the finer particle size and higher absorption capacity of BLA, which tend to increase water demand and reduce the quantity of free water AVAILABLE for lubrication in the mixture. The compressive strength results further revealed that replacing cement with BLA up to 10% produced concrete that met the target mean strength at 28 days of curing, demonstrating that this replacement level can be safely adopted without compromising structural performance. However, when the replacement amount was raised to 15% and 20%, the compressive strength fell below the target mean value, suggesting that excessive substitution reduces the amount of cementitious material available for hydration and limits the effectiveness of the pozzolanic reaction. In addition, a gradual decrease in the concrete's unit weight was recorded as the proportion of BLA increased. This behavior is mainly attributed to the lower specific gravity of BLA (2.15) compared with that of OPC (3.15), and a maximum unit weight reduction of about 1.98% was observed at 20% replacement. Although this reduction is relatively small, it indicates a potential benefit in producing slightly lighter concrete. Overall, the study's findings indicate that bamboo can be successfully utilized as an SCM in concrete at replacement levels up to 10%, offering an environmentally friendly option that reduces cement consumption, promotes the beneficial use of agricultural waste, and supports sustainable construction practices while maintaining acceptable performance.

7. Recommendations

According to this study's findings, it is recommended that BLA be adopted as an SCM in concrete at replacement levels of up to 10% of OPC. At this proportion, BLA provides satisfactory performance while helping reduce cement consumption. The utilization of BLA sourced from the local environment offers several important benefits. It can help reduce the continuous extraction of natural raw materials required for cement production, thereby minimizing environmental degradation and preserving the local landscape. In addition, the use of BLA presents a practical and environmentally responsible option for managing agricultural waste that would otherwise be discarded. These combined advantages support the inclusion of BLA as part of a broader strategy toward more sustainable concrete production. To enhance the practical implementation of this material, further collaborative efforts are encouraged among researchers, concrete producers, and relevant government agencies to investigate large-scale processing, quality control measures, and standardization of BLA. Moreover, additional studies focusing on long-term durability, performance under different environmental conditions, and economic feasibility are recommended to strengthen confidence in the widespread application of BLA in the construction industry.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data are available on request from the corresponding author upon reasonable request.

Author Contribution Statement

Chekol Menberu Teshome: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **Habtamu Diress Yizengaw:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **Shegaw Alemu Shitie:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration.

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