Heliyon 10 (2024) e29236

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Effect of banana tree leaves ash as cementitious material on the durability of concrete against sulphate and acid attacks

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ARTICLE INFO

Keywords:
Banana tree leaves ash
Cementitious materials
Concrete
Durability properties
Sulphate attack
Acid attack

ABSTRACT

The construction industry's rapid growth poses challenges tied to raw material depletion and increased greenhouse gas emissions. To address this, alternative materials like agricultural residues are gaining prominence due to their potential to reduce carbon emissions and waste generation. In this context this research optimizes the use of banana leaves ash as a partial cement substitution, focusing on durability, and identifying the ideal cement-to-ash ratio for sustainable concrete. For this purpose, concrete mixes were prepared with BLA replacing cement partially in different proportions i.e. (0 %, 5 %, 10 %, 15 %, & 20 %) and were analyzed for their physical, mechanical and Durability (Acid and Sulphate resistance) properties. Compressive strength, acid resistance and sulphate resistance testing continued for 90 days with the intervals of 7, 28 and 90 days. The results revealed that up to 10 % incorporation of BLA improved compressive strength by 10 %, while higher BLA proportions (up to 20 %) displayed superior performance in durability tests as compared to the conventional mix. The results reveal the potentials of banana leave ash to refine the concrete matrix by formation of addition C–S–H gel which leads towards a better performance specially in terms of durability aspect. Hence, banana leaf ash (BLA) is an efficient concrete ingredient, particularly up to 10 % of the mix. Beyond this threshold, it's still suitable for applications where extreme strength isn't the primary concern, because there may be a slight reduction in compressive strength.

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https://doi.org/10.1016/j.heliyon.2024.e29236
Received 1 November 2023; Received in revised form 28 March 2024; Accepted 3 April 2024

1. Introduction

Concrete is well known for its astonishing compressive resistance and resistance to durability attack; therefore, it stands as most widely used construction material around the globe [1]. This material has its applications in the construction industry on an unmeasurable scale, and it continues to dominate any other man-made material on the earth in terms of consumption and usage [1]. Remarkably it is claimed that one cubic meter of concrete is produced per capita annually around the world, and with Portland cement being the main key ingredient [2]. However, the environmental consequences of Portland cement production are bleak. Each year a huge amount of not less than 3 billion tons of Portland cement is consumed globally and the manufacturing process of the cement is a severe environmental concern. Approximately 400 kg of carbon dioxide is produced per 600 kg of cement [3], which is a considerable contribution to man-made CO_2.

This increasing demand for concrete in the building industry has led to a massive jump in binder production, hence multiplying the amount carbon dioxide released in to the environment. Therefore, it affects the environment adversely [4–8]. To compensate these impacts, a search for alternative and sustainable binder materials has gained momentum. In the past years, detailed research studies have revealed the potentials of incorporating mineral based materials in concrete or mortars to enhance their strength and durability and also to provide a sustainable means of construction [9–16]. This exploration has involved a wide range of organic materials with pozzolanic potential, including rice husk ash, sugarcane bagasse ash [17–21], cotton stalk ash [22,23], palm oil ash [24–29], wood ash [30–32], elephant grass ash [33], crushed walnut shell [34], olive waste ash [35], cattle manure ash [36], millet husk ash [37–41] and, notably, banana leaf ash (BLA) [9,42,43].

Amongst all these materials, what makes BLA stand out as a cement replacement material is its wide availability and lack of research done on it previously. Bearing in mind the enormous cultivation of banana fruit globally, which was recorded to be spread in over 5.2 million hectares in 2020 [43], Each banana plant generally gives a 1.34 kg yield of dried leaves [9]. In 2011 a massive 9.3 million tons of dried banana leaves were collected throughout the year [9], this shows the potential of obtaining banana leaves ash considering 10 % ash yield per kg of wasted leaves [9]. The characteristics of this ash hold the potential of boosting the strength of concrete, N. Gangadhar [44]. Banana leaves ash is obtained from combustion of the dried banana leaves which is an agricultural waste. The resulting ash after combustion exhibits cementitious properties and can be used as supplementary cement replacement material in concrete. These attributes are the result of its ability to initiate pozzolanic reaction like cement in concrete - hence, increasing the performance of concrete, S. Sakthivel, [1].

Until now numerous researches have confirmed the effectiveness of banana leaves ash as a supplementary cementitious material. J. C. Tavares et al. [43] studied the result of substituting a part of cement with BLA in concrete. They replaced binder with various percentages of BLA such i.e. from 0 % to 15 %. Their findings concluded that concrete with 10 % BLA was performing better in all aspects such as compressive strength, bulk density, dry density and water absorption. So, according to their study 10 % replacement percentage is ideal for using in concrete efficiently. I. Ndubuisi [2] studied the result of replacing cement partially with banana tree leaves ash in concrete. The replacement percentages were from 0 % to 25 % with the interval of 5 %. Their findings revealed that the replacements proportions from 5 % to 15 % were showing promising results in terms of compressive strength. While the replacement proportions beyond this range showed a slight depression in compression strength graph and also showed decrement in workability and increment in water absorption. Hence it was concluded that BLA replaced with 5 %–15 % of concrete is ideal for using in construction projects. R. C. Kanning [42]. investigated the pozzolanic activity of mechanically activated Banana Leaf Ash (BLA) by varying grinding durations. They found that BLA met narrow standards with an optimal grinding time of 30 min. Furthermore, their subsequent studies explored mortar performance with BLA replacing 0 %–10 % of Portland Cement (PC) and concrete with 10 %–20 % BLA replacing PC. Particularly, concrete with 10 % and 20 % BLA showed impressive mechanical strength, surpassing reference concrete (0 % BLA) by 25 % and 40 % after 28 days. K. Madhu [3], In their study concrete's quality was assessed with BLA replacing cement in various ratios (0 %–25 %) with the interval of 5. Notably, at a 10 % cement replacement level with BLA, significant increases of up to 12 % in compressive and splitting tensile strength were monitored. In addition to that a remarkable 18 % boost in flexural strength was also observed. Moreover, Subsequent tests compared BLA-10 with conventional mixes, revealing superior acid resistance but lower sulphate resistance for BLA-10. Hence this 10 % BLA ratio proved to be the optimal cement replacement.

In spite of extensive research into the utilization of agricultural residues for eco-friendly concrete, the practical application of these alternatives within the construction sector remains challenging. Industry apathy toward novel materials J. C. Tavares [33], B. A. Tayeh [35,45], limited contemporary research on and utilization of agricultural waste in diverse concrete formulations M. Amin [23], along with the pressing need for comprehensive guidelines, interdisciplinary collaboration, training, and real-world implementation, collectively impede the global adoption of environmentally friendly concrete S. Luhar [46]. While it is acknowledged that BLA has been utilized by numerous researchers in prior studies, this research introduces a novel dimension by focusing extensively on the durability properties of BLA-concrete compositions. Unlike the majority of existing literature, which predominantly centers around mechanical properties such as compressive strength, workability, water absorption, and tensile strength, our study explores into the durability and dives deeper into understanding how well it holds up under tough conditions.

Along with the basic strength parameters, this research specifically investigates the acid resistance and sulphate resistance of concrete incorporating BLA, providing a comprehensive understanding of its performance under challenging environmental conditions. Furthermore, this research taps into an unexplored area by measuring the elongation/expansion, shedding light on the material's behavior in terms of crystal formation—a parameter rarely addressed in previous research on BLA.

This investigation aims to take the assessment of the banana leaves ash as a cement replacement material to a further detailed insight by focusing mainly on its durability implications along with physical and mechanical performance. Ordinary Portland cement was substituted with various levels (0 %, 5 %, 10 %, 15 %, and 20 %) of Banana tree leaves ash, thus altering concrete properties. Additionally, it endeavors to promote the use of low-value agricultural waste to contribute to a more sustainable environment, facilitating the production of concrete with a reduced carbon footprint. Therefore, this meticulous exploration of BLA's durability aspects, particularly in the context of acid and sulphate resistance, along with the measurement of expansion elongation, constitutes a unique and significant contribution to the literature.

2. Materials

2.1. Banana leaves ash (BLA)

In this research, the source of Banana tree leaves ash was Al-hayee Rashidi farms in the Shaheed Benazirabad district of Sindh province in Pakistan. The leaves were carefully collected, air-dried for approximately 30 days, and subsequently crushed. The dried banana leaves were then subjected to controlled combustion in a Muffle Furnace, operating at a temperature of 600 °C for a duration of 5 h in order to develop reactive silica, as illustrated in Fig. 1(a). The resulting ash was allowed to cool down at room temperature as can be seen in Fig. 1(b) collected in air-tight plastic bags and subsequently passed through a #325 sieve with 45-μm openings, conforming to ASTM C-618 [47] standards for Fly Ash used in concrete applications. This sieving process allowed the resulting ash to be fine enough to be used effectively in concrete as a partial cement replacement material. The specific gravity of the Banana Leaves Ash (BLA) was determined according to the ASTM C188 [47] guidelines, employing the Le-Chatelier flask method and was found to be 2.67 g/cm3.

2.1.1. X-ray fluorescence Spectroscopy (XRF) analysis of banana leaves ash

The chemical composition of Banana Leaves Ash (BLA) was tested through X-ray Fluorescence (XRF). The results of this test as shown in Table 1 portrays a significant insight to the composition of BLA. It enlightens its use as a potential cement replacement material. The XRF analysis revealed the presence of Silicon oxide (SiO_2), over 48 % in content, and Calcium oxide (CaO), exceeding 24 %. This high silica content is of particular interest, as it suggests the presence of cementitious properties within BLA Because silica is essential for starting the pozzolanic reaction and forming C–S–H gel in concrete, which subsequently interacts with calcium hydroxide generated during cement hydration, silica makes BLA a valuable substitute for cement in building materials. Additional chemical examination showed the presence of alkalis such as magnesium oxide (MgO), sodium oxide (Na2 O), and potassium oxide (K2O), as well as trace levels of iron (Fe2O3) and alumina (Al2O3) oxides. These findings are most likely the result of the use of fertilizers to increase plant output. Thoroughly characterizing the chemical makeup of BLA is an essential first step in assessing its suitability for various applications, particularly in the construction industry. In accordance with the classification defined by the American Society for Testing and Materials (ASTM) under C-618 standards [47], BLA falls into the category of Class C fly ash. This classification is predicated on the summation of the percentages of Silicon oxide (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3). In the case of BLA, the collective percentage of these three oxides stands at 52 %, unequivocally placing it within the Class C classification.

2.1.2. X-ray diffraction (XRD) analysis banana leaves ash

The mineralogical composition of Banana Leaves Ash (BLA) was revealed using X-ray Diffraction (XRD) investigation, as illustrated

(a) Burning Process (b) BLA after Calcination

Fig. 1. Process of obtaining banana leaves ash.

Table 1
Chemical composition of BLA.

Oxides	SiO2	CaO	Al_2O3	Fe_2O3	MgO	K2O	SO3	Na2O
Percentage	48.12	24.48	3.23	1.43	6.98	6.12	2.36	2.02

in Fig. 2. This graphical depiction offers a thorough grasp of the crystalline phases and structural features present in the ash, which advances our knowledge of its possible uses.

Among the discovered crystalline phases, the XRD diffractogram showed peaks that could be identified as silica (SiO2) and lime (CaO). Despite their small size, these peaks highlight the existence of these crystalline non-reactive components. Their creation is explained by the gradual cooling that occurs after calcination. Notably, the frequency of these phases is consistent with the results of the X-ray fluorescence (XRF) investigation, supporting the thorough characterization of BLA. In addition, the XRD study revealed the presence of several alkali elements, most notably potassium oxide (K2O). It is possible to trace the existence of these alkalis to outside influences, such as the use of fertilizers in banana tree agriculture. This discovery validates the precision and coherence of the chemical composition findings obtained from XRF analysis. The identification of amorphous silica, which appears in the 20 θ to 30 θ range, in the XRD examination is crucial. The existence of amorphous silica is significant because it has the innate capacity to start pozzolanic reactions, which is essential for improving the performance of cementitious materials in concrete matrices. This ability to participate in pozzolanic processes enhances the strength and longevity of concrete and highlights the promise of BLA as an environmentally acceptable and sustainable cement substitute.

2.2. Cement

Lucky Cement is a well-known company that provided the cement used in this study. It is easily available locally and well recognized for following the ASTM C150-22 [48] standards. The specific gravity of this cement was determined to be 3.15 g/cm3 and the fineness was found to be 3950 cm^2/g by Blaine's air permeability method. Detailed chemical composition analysis of the Ordinary Portland Cement (OPC) is provided in Table 2.

2.3. Aggregates

The coarse aggregate employed in the study were having maximum size not more than 20 mm and exhibited a specific gravity of 2.54, with a modest water absorption of 1.35 %. Its density measures at 1563 kg/m^3. On the other hand, the fine aggregate possesses a specific gravity of 2.64, with a slightly higher water absorption rate at 1.42 %. It boasts a density of 1767 kg/^{3} and a minimal silt

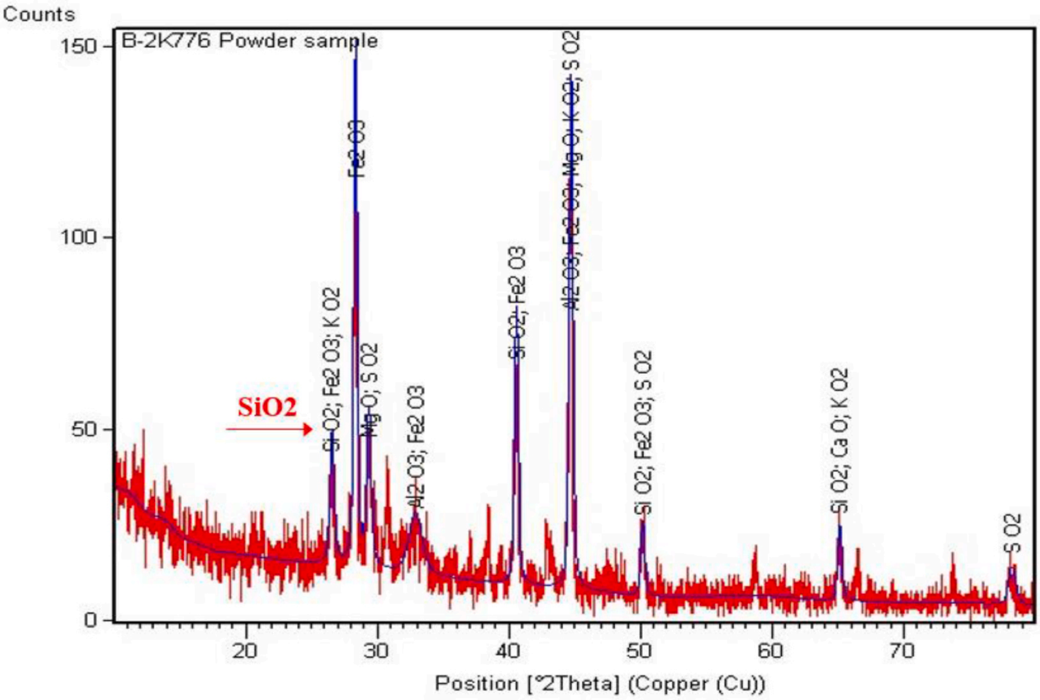

Fig. 2. X-ray diffraction (XRD) test of BLA.

Table 2
Chemical composition of OPC.

Oxides	Lime (CaO)	Silica (SiO2)	Alumina (Al_2O3)	Ferrous Oxide (Fe_2O3)	Magnesium Oxide (MgO)	Alkalies (K_2Na_2O)	Sulphur di-Oxide (SO2)
Percentage %	64.30 %	18 %	3.80 %	0.56 %	0.13 %	0.40 %	1.34 %

content of 3.79 %. The particle size distribution curve of aggregates is shown in Fig. 3.

2.4. Sulphuric acid (H_2SO_4) and Sodium Sulphate (NA_2SO_4)

A solution of water and Sulphuric acid was prepared as per guidelines provided by ASTM C267-20 [49] in order to check the concrete its Acid resistance ability. The desired acidic solution was formulated by adding 3 % concentrated Sulphuric acid (H_2SO_4) to water by its volume and thus a solution with 2 pH was achieved. For Sulphate Resistance evaluation a solution was prepared by adding 50 gm of Sodium Sulphate (NA2SO4) per 1 L of water as per instruction provided by ASTM C1012M [50].

3. Experimental programs

3.1. Casting of concrete

Concrete cubes measuring (100 mm × 100 mm x 100 mm) were precisely casted with a ratio of 1: 1.5: 3 with a (w/c) ratio of 0.5, to measure compressive strength, acid resistance and sulphate resistance. Additionally, mortar prisms (25 mm × 25 mm x 285 mm) were also prepared with a cement to sand ratio of 1: 2.75 keeping w/c ratio as 0.485 to investigate length changes induced by sulphate attacks as specified by ASTM 1012 [50]. Cement was Replaced with Banana leaves ash partially by its weight and the replacing percentages were 5 %, 10 %, 15 % and 20 %. The mix proportions of concrete incorporated with banana leaves ash can be seen in Table 3.

3.2. Curing of concrete

Following the casting process, the samples were kept under the water for curing at room temperature in a curing tank. Subsequently, for the compressive strength the total duration of curing was 90 days with intermediate testing after 7 days, 28 days and 90 days of curing. However, in compliance with ASTM C267 [49], for Acid resistance and sulphate resistance the specimens were cured for duration of 28 days in water, after that they were submerged to their respective solutions i.e. acidic solution and sulphate solution. The specimens were then tested for change in compressive strength, change in weight, and physical appearance after 7 days, 28 days and 90 days of Acid and Sulphate exposure period.

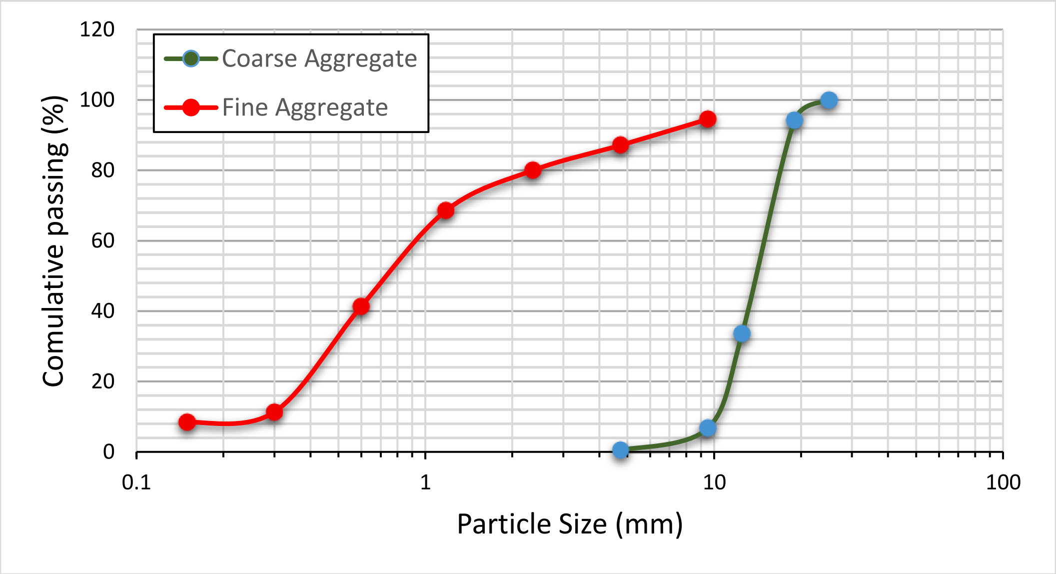

Fig. 3. Particle size distribution curve of aggregates.

Table 3
Mix proportions of concrete specimen (kg/m^3).

Mix id	Cement	BLA	Fine Aggregate	Coarse Aggregate	Water	W/C Ratio
BL-0	430	0	649	1311	211	0.49
BL-5	408.5	21.5	649	1311	211	0.49
BL-10	387.0	43.0	649	1311	211	0.49
BL-15	365.5	64.5	649	1311	211	0.49
BL-20	344.0	86.0	649	1311	211	0.49

3.3. Testing methods

3.3.1. Workability

Workability of fresh Concrete was determined using Slump cone method immediately after mixing. This test was conducted by following ASTM C-143 [48] regulations. Slump test was conducted on each mix with different cement to BLA ratio in order to understand the varying consistency of the concrete with incorporated of BLA. No super plasticizers were used to enhance the slump.

3.3.2. Water absorption

Water absorption is a crucial factor in determining the durability of concrete as it pertains to the presence of capillary pores formed during cement hydration. These pores serve as pathways for fluid penetration. The assessment of water absorption in concrete was carried out using three cube specimens in accordance with the guidelines stipulated in ASTM C 642-21 [51]. Initially, the weight of three oven-dried cubes (measuring 100 mm each) was recorded as W1. Subsequently, these cubes were submerged in a water bath for a period of 48 h. After the water had drained off, the specimens were gently dried with a cloth, and their final weight, denoted as W2, was promptly measured. The percentage of water absorption was then computed utilizing the following formula.

$$\text{Water Absorption} = \frac{W2 - W1}{W1} x100$$

3.3.3. Compressive strength

The compressive strength of Concrete cubes was conducted at different curing periods which were 7, 28 and 90 days. The evaluation was done as per the guidelines of ASTM C-29 [52] keeping the force uniformly distributed on the area of specimen with constant loading rate. Each specimen was subjected to the loading until it failed to resist, Hence the best mix was determined which outperformed all other specimen with different BLA mix percentages.

3.3.4. Acid resistance and sulphate resistance

The Acid and Sulphate resistance of concrete was determined by following ASTM C267 [49] according to which the specimen under the exposure should be tested for its visual appearance, Change in weight and change in Compressive strength. The test medium was a solution with 3 % Sulphuric acid for simulating Acid attack and 5 % solution of Sodium sulphate for Sulphate attack. The dry specimens were first weighted and submerged in Sulphuric acid for total duration of 90 days. In order to have detailed insights on the effects of different durations Acid and sulphate attacks on BLA incorporated Concrete, the specimens were taken out of the solution and were tested for its compressive strength and weight periodically. The testing intervals were 7, 28 and 90 days. The Compressive strength tested after each exposure duration was compared to the original strength of respective samples when cured in water for 28 days.

3.3.5. Length change of mortar bars

Length change of Mortar bars was measured following the stipulations of ASTM C1012 [50]. Metal Studs were fitted on both ends of the bars so that the it can be fitter in the test rig assembly. A testing assembly consist of a metal frame along with a measuring device attached to it. The measuring device was a LVDT (Linear variable differential transformer) which is capable of measuring 0.001 mm accurately hence any changes in length due to expansion of crystal inside the mortar were noticed. The mortar bars were submerged in the same solution of Sodium sulphate in the air-tight container for the duration of 90 days. The expansion was recorded at the interval of 7, 28 and 90 days of exposure. For this the specimen were taken of out the container and rinsed under running tap water followed by wiping the surface with a damp towel. Later the specimens were set in to the assemble and the reading were recorded and compared with the initial reading before the exposure.

3.3.6. SEM analysis

Along with above mentioned tests, a Scanning Electron Microscope (SEM) analysis was conducted to provide a detailed insight of the internal structure of concrete specimens. This analysis involved magnifying the fractured surface of concrete fragments at an electron microscopic level. By employing SEM, the interface between the cement paste and aggregates was scrutinized and evaluated. SEM offers the advantage of revealing fine-scale details and detecting any potential microstructural changes resulting from the incorporation of banana leaf ash (BLA) into the concrete. The SEM analysis provided invaluable insights into the material's microstructure, providing a better understanding on the impact of BLA on the concrete's composition.

4. Results and discussions

4.1. Workability and bulk density

Fig. 4 illustrates the workability of BLA incorporated concrete. Notably, as the incorporation of BLA increased, workability exhibited a consistent reduction. This phenomenon can be attributed to the higher specific surface area which has tendency to use more water thus some of the water required for mixing and cement to be hydrated completely was taken by BLA particles. Additionally, the reduced spacing between BLA particles, resulting from their filling effect, and the irregular particle shape collectively contributed to resistance against flow [21,43], leading to reduced workability. Consequently, a greater amount of water was required to attain desired flow characteristics in concrete.

The bulk density of fresh concrete was analyzed to investigate the impact of BLA incorporation. Notably, in Fig. 5 it can be seen that at 5 % replacement of cement with BLA, an increase in concrete's fresh density was observed. At this stage, the BLA fills micro-pores within the concrete due to the formation of additional C–S–H gel, enhancing compaction and leading to improved density [43,53].

However, as the percentage of BLA replacement exceeded 5 %, a linear reduction in bulk density was noted. This reduction can be attributed to the combined effects of the reduction in cement content and the lower specific gravity of BLA compared to ordinary Portland cement. The influence of these factors overcomes the initial pore-filling effect and improved compaction, thus leading to the linear decrease in density. Consequently, concrete mixtures with BLA percentages higher than 5 % exhibited lower density. In this context, if we take into account that the overall density of the concrete is determined by adding up the specific masses of its individual ingredients, then it makes sense that mixtures containing more BLA would result in a lower density when compared to concrete that doesn't include BLA.

The observed trends in workability and bulk density align with the findings of previous studies by Seyed Alireza Zareeri et al. [21] Jennef C. Tavares et al. [43], and Darweesh (2023) [53] which demonstrated that an increase in the substitution content led to decreased workability and density. This behavior can be related to the lower specific gravity of BLA as compared to ordinary portland cement.

4.2. Water absorption test

Table 4 shows the relation between replacement proportion of cement with banana leaves ash and the water absorption of concrete. The results shows that concrete's water absorption is reduced as the BLA replacement proportions is increased.

This positive performance can be due to the micropore filling abilities of banana leaves ash which fill up these pores inside the concrete matrix and reducing the infiltration of water. As the consequences the concrete exhibited a better resistance to water absorption ultimately an improve durability.

This trend is in synchronization with the study by Le Ha Thanh and Horst Michael (2016) [54] that mineral admixtures like BLA refines the pores in the matrix of concrete which improves its durability against water absorption. Darweesh (2023) [53] also concluded this in their study which further promotes the potential use of BLA as a supplementary cement substitution material in concrete.

4.3. Compressive strength analysis

Various specimen with different concrete mixes containing different proportions of BLA were tested for compressive strength test. The testing was done at different intervals of curing such as after 7 days, 28 days, 90 days as shown in Fig. 6.

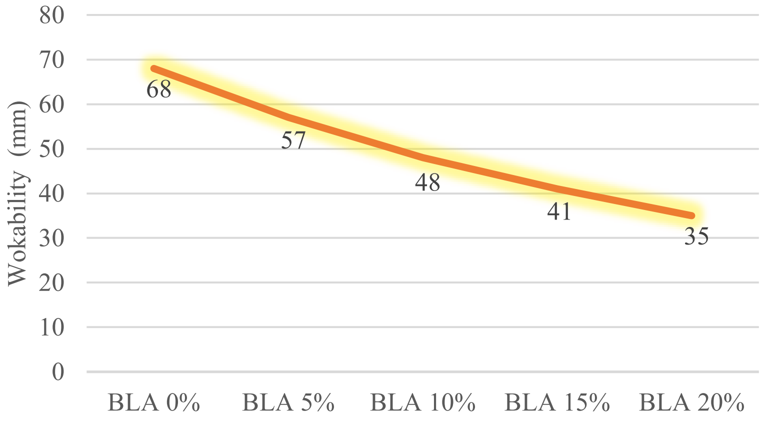

Fig. 4. Workability of concrete.

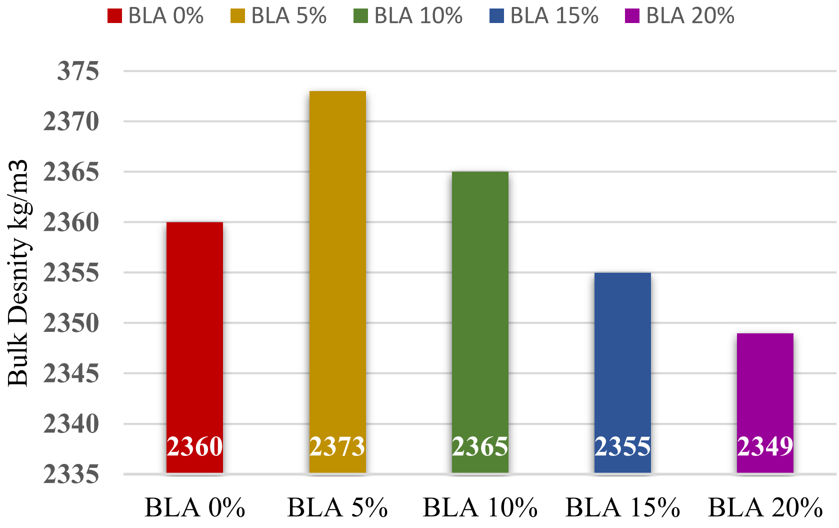

Fig. 5. Bulk density of concrete.

Table 4
Water absorption of concrete.

Mix id	BLA 0 %	BLA 5 %	BLA 10 %	BLA 15 %	BLA 20 %
Water absorption %	6.1	4.51	3.65	3.59	3.53

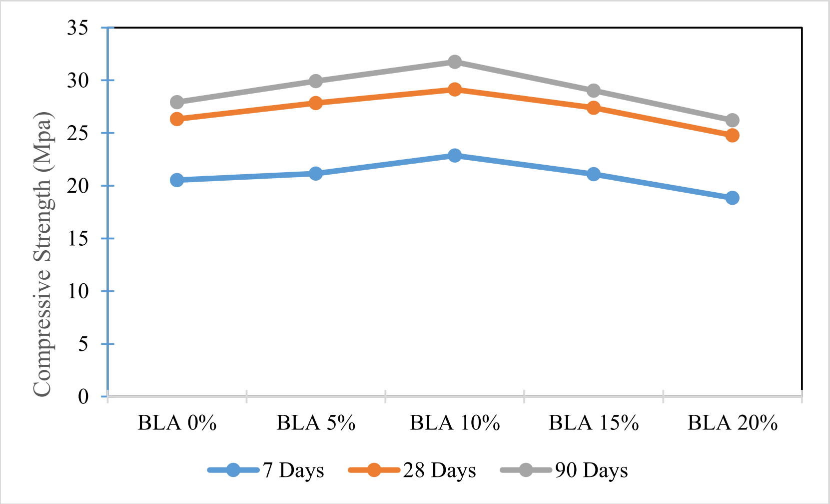

Fig. 6. Compressive strength (MPa).

The compressive strength graph provides valuable insights into how the inclusion of BLA impacts concrete strength. Initially, it was observed that as BLA was incorporated into the mix, the compressive strength of the concrete improved, especially up to a 10 % replacement of cement. This improvement can be attributed to the amorphous nature and reactivity of BLA, as determined by the XRD test. Due to this amorphous nature of BLA the pozzolanic reaction takes place, which facilitates the formation of additional calcium silicate hydrate gel (C–S–H), which is a main cause of strength in concrete.

However, as the BLA replacement percentage exceeded 10 %, particularly at 15 % and 20 %, a decline in compressive strength became evident [42]. Various reasons can be the cause of this reduction. Firstly, the higher BLA content tends to cause particle agglomeration due to the larger specific surface area of its particles. This agglomeration has an adverse effect on the structural integrity of the concrete [43]. Secondly, the decrease in cement content in mixtures with higher BLA content limits the formation of primary hydration products and reduces the availability of calcium hydroxide, which is essential for initiating the pozzolanic reaction with BLA and, consequently, leads to a decrease in strength [43].

Therefore, the results indicate that the optimal replacement limit of cement with BLA is 10 %, as percentages higher than this threshold result in a loss of compressive strength due to above mentioned reasons.

These findings align with the study conducted by Tavares et al. (2022) [43] and Darweesh (2023) [53] on the use of banana leaf ash as a partial replacement for cement in eco-friendly concrete. Their study also demonstrated an initial increase in compressive strength with BLA replacement, followed by a decrease at higher BLA percentages (15 % and 20 %). In addition to that Rodrigo C. Kanning et al. (2014) [42] also confirms in their study the increment of strength with the use of BLA substituting cement partially in their study.

In general, the incorporation of BLA up to 10 % replacement of cement enhances compressive strength due to pozzolanic reactions, while higher replacement percentages result in reduced strength, primarily due to particle agglomeration and reduced cement content.

4.4. Resistance to acid attack

4.4.1. Change in weight due to acid attack

Fig. 7 illustrates the changes in weight of concrete mixes over time, particularly during exposure periods of 7 days, 28 days, and 90 days. Initially, all concrete mixes exhibited an increase in weight at the 7-day and 28-day exposure periods. This weight gain can be attributed to the absorption of liquid and the formation of compounds such as ettringite and gypsum. However, a noteworthy trend emerged after the 90-day exposure period, where a decrease in weight was observed. This decrease can be attributed to the deterioration of the concrete surface, as evident in Fig. 8. The disintegration of the cement paste can be attributed to the action of harmful aggressive ions present in the acid attack environment.

It is important to note that the specimen with 0 % BLA, serving as the control, exhibited the maximum change in weight. Conversely, specimens with increasing percentages of BLA replacement demonstrated reduced changes in weight, indicating better performance in terms of weight stability during acid attack.

This improved acid resistance which concrete exhibits with the incorporation of BLA can be the result of the pore filling ability of the BLA in the concrete. In addition to that the BLA promotes the formation of supplementary C–S–H inside the concrete matrix. This additional C–S–H gel not only densify the matrix but also limits the permeability of concrete. So the penetration of aggressive ions inside the concrete is limited and constrained therefore, leading to an improved performance against Acid attack. This proves that BLA showed a positive performance in making concrete more durable and also this could increase the service life of structures which are susceptible corrosion.

In summary, the use of BLA in concrete help to resist the weight change during acid attack, as shown in Fig. 7 below. This enhancement in the resistance characteristics of concrete can be attributed to the pore filling ability of BLA and also developing the additional C–S–H gel as a result of the pozzolanic reaction.

4.4.2. Change in compressive strength due to acid attack

The acid resistance test of concrete, specially highlighting the change in compressive strength provides a meaningful insight in the material's durability characteristics against aggressive atmosphere.

As shown in Fig. 9, the variation in compressive strength displays an intriguing behavior. Initially all the specimen with different mixes showed an increment in compressive strength at the 7 days' exposure period to the acid. This increment in compressive strength can be the result of formation of compounds inside the concrete such as ettringite and gypsum. These compounds fill the pores within the concrete, resulting in a denser and more tightly packed matrix, which, in turn, leads to a slight improvement in compressive strength.

However, the situation changes as the exposure period to acid is extended to 28 days and 90 days. At these longer exposure periods,

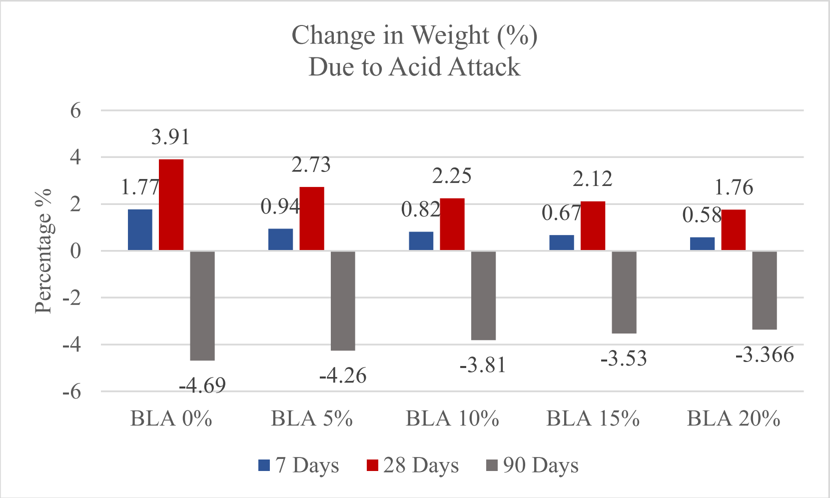

Fig. 7. Change in weight due to acid attack (%).

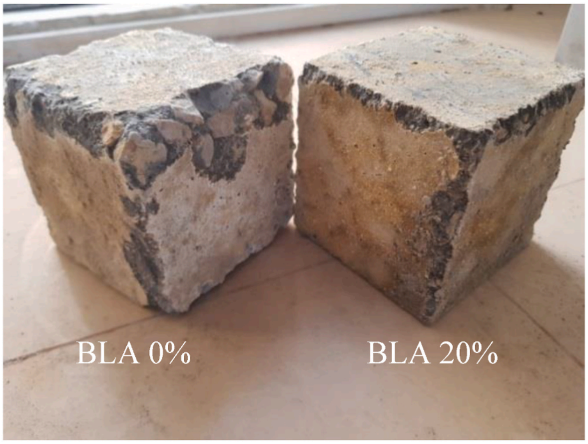

Fig. 8. Surface deterioration due to acid attack after 90 days of exposure period.

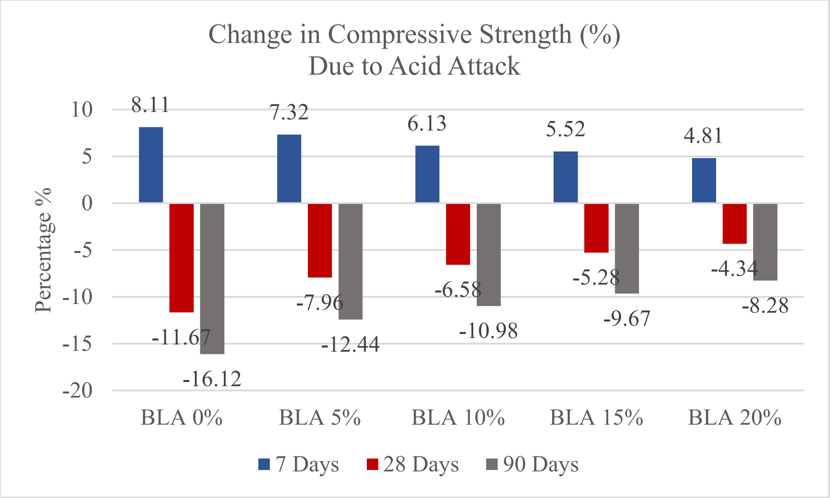

Fig. 9. Change in compressive strength due to acid attack (%).

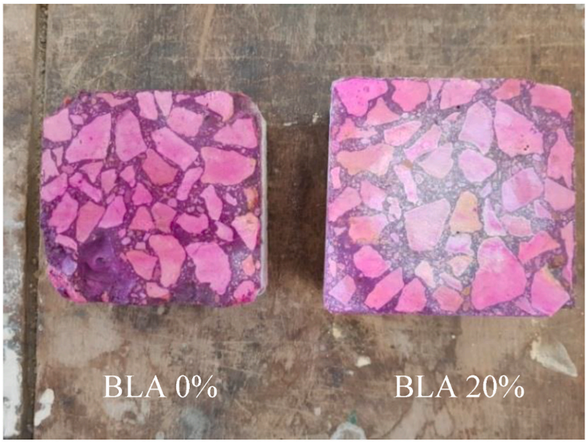

Fig. 10. Cross sectional view of Specimen with acid indicator.

a decline in compressive strength is observed across all concrete mixes. This decline can be attributed to the expansive nature of the products formed (ettringite and gypsum). These products require additional volume to expand, generating internal stresses within the concrete matrix. Consequently, micro cracks develop, which can lead to the deterioration of the concrete from within. Additionally, these micro cracks provide pathways for aggressive ions to penetrate the concrete, which damages the matrix from inside and reducing compressive strength.

Notably, the concrete mix with 0 % BLA, characterized by increased porosity [43], exhibited the maximum change in compressive strength. The higher porosity allowed a greater number of products to form within the mix, resulting in the generation of stresses greater than those observed in concrete mixes containing BLA.

In contrast, concrete mixes incorporating increasing percentages of BLA demonstrated improved performance. The presence of BLA reduced the permeability of the concrete due to the filling action of secondary calcium silicate hydrate gel (C–S–H) within the pores. This reduction in permeability minimized the formation of the expansive products, resulting in less volumetric expansion and, consequently, less deterioration. This ultimately led to an enhancement in compressive strength.

Fig. 10 visually represents the penetration of acid inside the concrete by used of Acid indicator on the cross section of the specimen. This lower permeability which is seen in the mix with 20 % BLA can be justified by this visual representation which is based on the coloration. It can be seen that the specimen has not turned pink from the center, this clearly shows that acid has not fully penetrated all the way to the core of the specimen.

In summary, the effects of BLA on concrete's compressive strength during acid attack shows a complex behavior. Where the strength is initially gained which can be due to the pore filling products, while long term exposure leads to expansive stresses generated by the formed products inside and results in micro cracking. The mixes with increasing proportion of BLA performed significantly well due to lowered permeability which results in less volumetric expansion and overall improvement in compressive strength.

Similar findings were stated by Dhage et al. (2020) [55] their research evaluated the use of banana leaves ash BLA as a cement replacement material and by Vinod tanwar et al. (2021) [56]. in their study they tested the numerous aspects of performance of concrete including acid resistance and sulphate resistance along with other mechanical properties.

The findings of their observations in their study of concrete with BLA incorporated illustrated the improved resistance to both acid an sulphate attacks. The research concluded that banana leaves ash can be efficiently used in concrete as a partial cement replacement material in order to achieve eco-friendly and durable concrete structures. These results prove BLA to be a promising and sustainable cement replacement material, satisfying the goal of achieving ecofriendly construction practices.

4.5. *Resistance to sulphate attack*

4.5.1. *Change in weight due to sulphate attack*

Throughout the 7-day and 28-day exposure periods, all concrete mixtures exhibited an increase in weight, as indicated in Fig. 11. This weight gain mirrors the earlier findings observed during acid attack testing. It is primarily attributed to the absorption of liquid and the formation of compounds like calcium sulphate.

However, a slight weight loss is evident after the 90-day exposure period. This differs from the weight change pattern observed during acid attack, where weight loss was more pronounced. The reduced weight loss during sulphate attack can be attributed to minimal surface deterioration, suggesting that sulphate ions may not be as corrosive as acid in this context.

Of significance is the observation that the specimen with 0 % BLA showed the most substantial weight change. This result points to improved weight stability resistance to sulphate assault. On the other hand, samples with higher BLA fractions showed less variation in weight. Better concrete performance is a result of BLA's facilitation of the development of more calcium silicate hydrate gel (C–S–H)

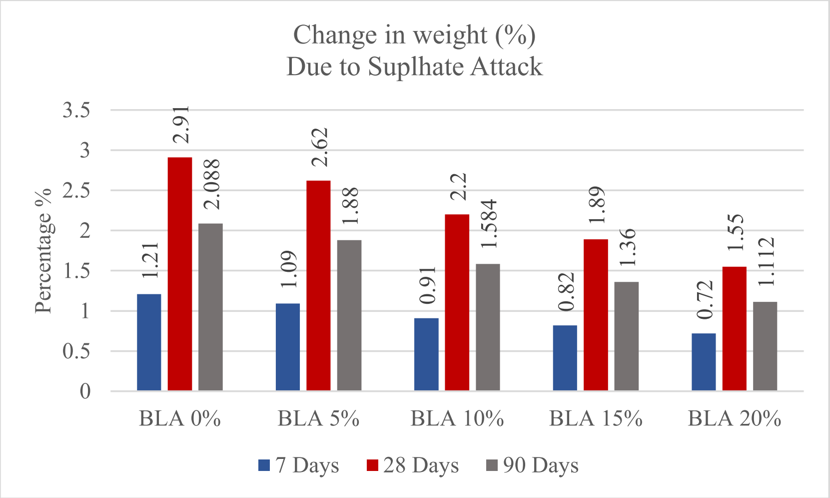

Fig. 11. Change in weight due to sulphate attack (%).

within the concrete matrix. This extra gel limits the entry of hostile ions by decreasing the permeability of the concrete.

In conclusion, adding BLA to concrete improves its resilience to weight changes brought on by sulphate assault. This improvement is ascribed to decreased permeability brought about by the production of more C–S–H gel, which inhibits the entry of hostile ions and enhances the durability of the concrete.

4.5.2. Change in compressive strength due to sulphate attack

The difference in compressive strength of concrete specimens subjected to sulphate attack is well illustrated in Fig. 12. The observations provide important insights, mirroring the behavior seen during sulphate attack.

During the first exposure periods (7 days and 28 days), the compressive strength of all concrete mixtures increased. Ettringite and gypsum production are credited with causing this initial strength boost. By filling the pores in the concrete, these compounds create a denser, more densely packed matrix.

However, as the exposure to sulphate was extended to 90 days, a decline in compressive strength became evident across all concrete mixes. This decline can be attributed to the expansive nature of the products formed (ettringite and gypsum), which require additional space to expand. This expansion generates internal stresses within the matrix, adversely affecting compressive strength.

The control mix with 0 % BLA which is characterized by increased porosity [43], has shown a significant amount of change in weight and overall greater stresses. Thus, it experienced a more prominent reduction in compressive strength. While the mixes with higher proportion of BLA incorporated shown a better performance. The secondary C–S–H gel generated by BLA fills up the pores, hence reducing permeability and limits the formation of expansive products [56]. This becomes the reason for reduced volumetric expansion and the better compressive strength.

Effects of BLA on the concrete specimen under sulphate attack can be seen in Fig. 13.

In summary, using banana leaves ash in concrete can lead to improved performance against sulphate attack with showcasing the reduced change in weight and also improved compressive strength as compared to the conventional concrete mix. These findings support the potential of BLA as a durable supplementary cement replacement material.

These findings have been also confirmed by Tanwar et al. (2021). Their study revealed the BLA potentials as cement replacement material against durability attacks which showed reduced volumetric expansions as compared to the conventional concrete. This reduction in expansion is a sign of limitation of internal cracks and subsequent strength loss which favors the durability of concrete.

4.5.3. Expansion of mortar bars due to sulphate attack

The expansion in mortar bars due to sulphate attacks is one of the key indicator of concretes performance under durability attacks. This test measures the amount of length change in mortar bars which is due to the formation of crystals of gypsum and ettringite inside the matrix.

Fig. 14 provides a clear representation of the length change measured during the sulphate exposure period of these mortar bars. These results support our previous findings regarding the impacts of formation of expansive products inside the concrete such as ettringite and gypsum.

It can be seen clearly that the mix with 0 % BLA has shown the maximum length change among all the other mixes while the mix with 20 % BLA has shown the least expansion. This alignment with previous findings underscores the influence of BLA in reducing the detrimental effects of sulphate attack.

In summary, the results of the expansion test further emphasize the positive impact of BLA on concrete's resistance to sulphate attack. The reduced length change in mortar bars with increasing BLA content aligns with the overarching theme of improved performance in the presence of this supplementary material.

4.6. Environmental impact of BLA (CO2 emission comparison)

The assessment of carbon emissions associated with construction materials is crucial for achieving environmental sustainability in the building construction industry [57]. While specific carbon emission factors for Banana tree leaves ash (BLA) are not readily available in the literature, parallels can be drawn with established supplementary cementitious materials. For instance, fly ash, a common alternative to cement, is reported to have a carbon emission factor of 0.0270 kg CO2-e/kg, while Ground Granulated Blast Furnace Slag (GGBFS) stands at 0.1430 kg CO2-e/kg [58]. Considering the compositional similarities and manufacturing processes involved, it is reasonable to estimate that the carbon emission factor for BLA falls within the range of 0.0270–0.1430 kg CO2-e/kg. This estimation underscores the potential of BLA as an environmentally sustainable alternative to conventional cement in concrete production. Furthermore, comparative analysis reveals that BLA exhibits a substantial reduction in carbon emissions, ranging from 82 % to 96 % in comparison to typical cement production, which typically emits 0.82 kg CO2-e/kg. The carbon emission factors for various materials and activities involved in making of concrete can be seen in Table 5 [58]. Based on these factors the total reduction in the CO_2 emission in concrete incorporated with banana leaves ash is calculated in Table 6. The emissions of concrete are in accordance with the quantities of material used for making of concrete mentioned in Table 3. This embodied carbon was calculated by using Equation (1) [59–62].

$$CO_2 = \sum_{i=1}^{n} (W_i \times CO_{2i-e}) \quad (1)$$

where, CO_2 is total embodied CO_2 of 1 m^3 concrete, in kg CO_2/m3

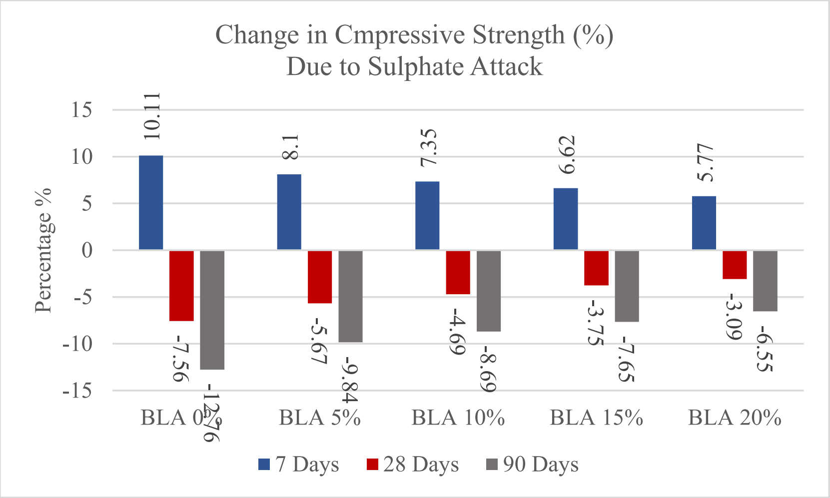

Fig. 12. Change in compressive strength due to sulphate attack.

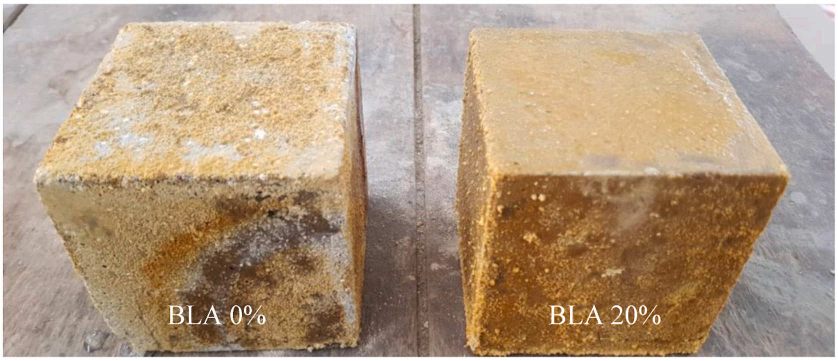

Fig. 13. Specimen after 90 days of sulphate exposure.

n is total raw materials in mix,
W_i is total amount in kilogram of material.
i to produces 1 m^3 concretes.
CO_{2i-e} is equivalent CO_2 value of material *i* in kg CO_2/kg

4.7. SEM analysis

SEM images were taken of concrete samples prepared with and without BLA after 28 days of curing, as displayed in Fig. 15(a and b). It can be observed that the conventional concrete specimen illustrates the interface between the cement matrix and aggregates, surrounded by hairline cracks and voids (Fig. 15 a). In contrast, when banana leaves ash is incorporated, concrete samples exhibit a denser interface, as seen in (Fig. 15 b), where the matrix is more uniform, and the presence of pores and cracks is negligible. This difference may be attributed to BLA's finer particle size compared to cement, enhancing the mechanical and durability properties of BLA composites.

5. Conclusions

This study sought to evaluate the impact of varying proportions of banana tree leaves ash (BLA) on the short-term durability properties of concrete and also to assess the efficiency of banana leaves ash as a supplementary cementitious material. The findings lead to the following conclusions.

1. The addition of 20 % banana tree leaves ash to the concrete mix led to a linear decrease in workability, reducing it from 68 mm to 35 mm. This resistance against workability is due to the roughness and irregular shape of BLA partials and greater specific surface area.

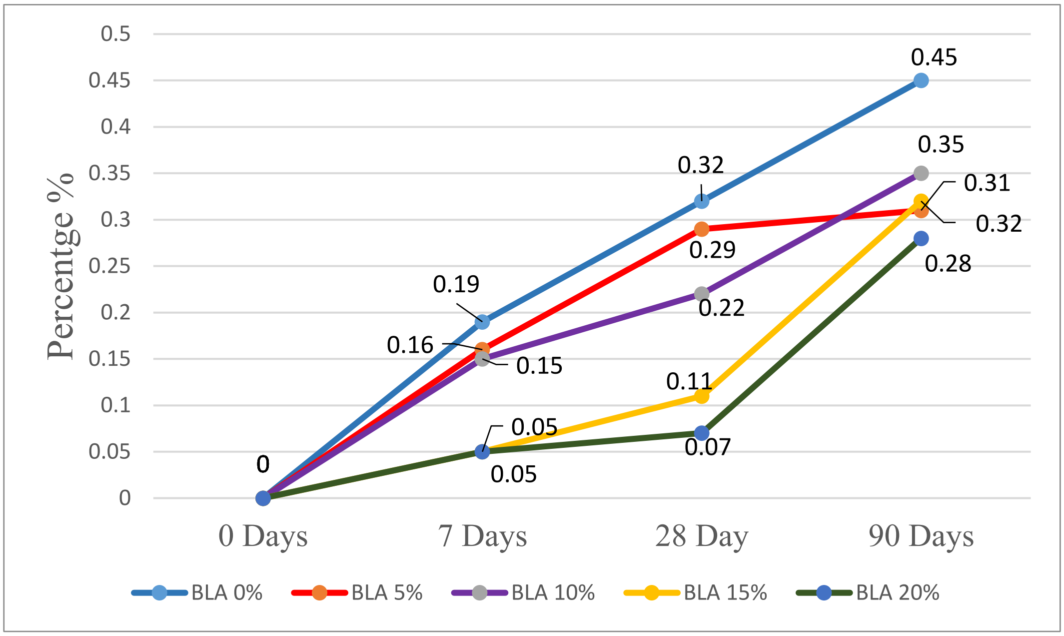

Fig. 14. Expansion of mortar bars under sulphate exposure (%).

Table 5
Carbon emission factors.

Description	Emission factor	Unit
cement	0.82	kg CO2-e/kg
Fine aggregate	0.0139	kg CO2-e/kg
Coarse aggregate	0.0357	kg CO2-e/kg
Concrete batching	0.0033	kg CO2-e/kg
Concrete transport	0.0094	kg CO2-e/kg
Fly ash	0.027	kg CO2-e/kg
GBFS	0.143	kg CO2-e/kg

Table 6
Total CO_2 emissions for one cubic meter of concrete.

Total CO_2 emissions for one cubic meter of concrete					
	kg CO_2/m^3				
	BLA 0 %	BLA 5 %	BLA 10 %	BLA 15 %	BLA 20 %
Cement	352.6	334.97	317.34	299.71	282.08
BLA	0	3.16	6.33	9.50	12.66
Fine aggregate	9.02	9.02	9.02	9.02	9.02
Coarse aggregate	46.80	46.80	46.80	46.80	46.80
Total CO_2/m^3	408.42	393.96	379.49	365.03	350.57
% CO_2 reduction	0	3.54	7.08	10.62	14.16

2. The density of the concrete increased with the inclusion of 10 % BLA, rising from 2360 kg/m3 to 2373 kg/m3 due to finer BLA particles filling up the pores and densifying the matrix. However, this trend reversed when 20 % BLA was added because of its lower specific gravity, resulting in a density of 2349 kg/m3.
3. The incorporation of BLA significantly reduced water absorption from 6.1 % to 3.53 % when 20 % BLA was incorporated. The reason to this is as mentioned above due to the pore filling ability of ash the penetration of liquid was reduced.
4. The compressive strength of the concrete increased by 10 % when 10 % BLA was used. The increment is the result of pozzolanic reaction which takes place between the BLA and calcium hydroxide which forms additional C–S–H Gel However, with the addition of 15 % and 20 % BLA, the compressive strength decreased by approximately 5 % from its initial value. The slight decrement is possibly due to reduction of cement content which limits the formation of primary hydration product.

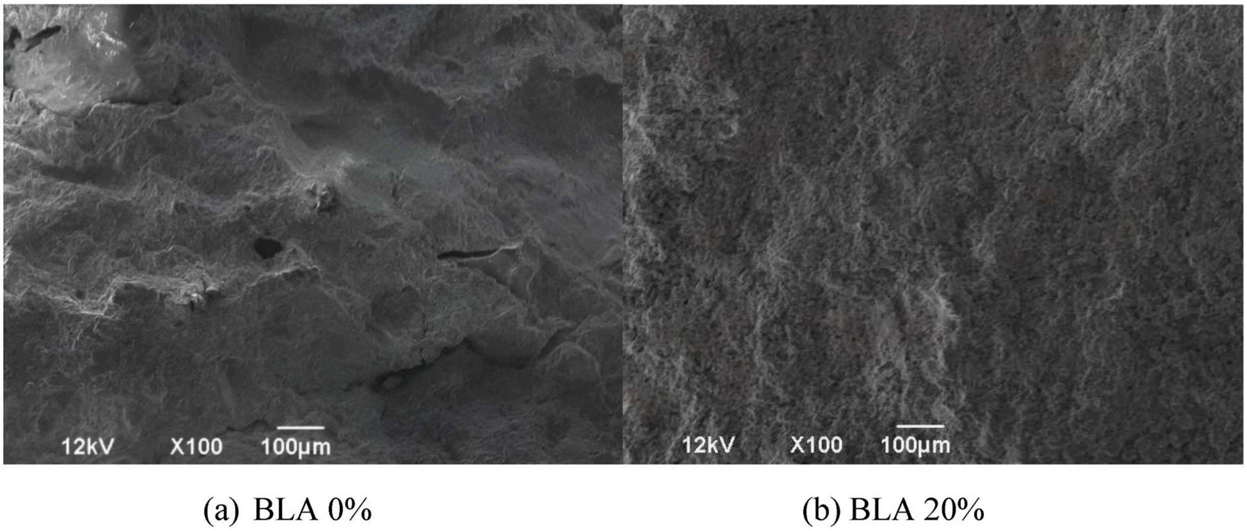

Fig. 15. SEM images of Concrete specimens.

5. Concrete's resistance to acid and sulphate attacks improved with the increasing BLA content. Although the enhancements were not substantial but the improvement is because of the BLA, which has refined the concrete's matrix and provided resistance against harmful attacks by limiting the ingression of aggressive ions.

In summary, BLA has proven to be an efficient material to serve as a partial cement replacement in concrete, particularly up to 10 %. Beyond this threshold, it remains suitable for applications where extreme strength is not the primary concern, as compressive strength may decrease when BLA exceeds 10 %.

Data availability statement

Data generated based on author's request.

Informed consent statement

Not Applicable.

Institutional review board statement

Not Applicable.

Funding

This research was funded by Taif University, Saudi Arabia, Project No. (TU-DSPP-2024-33).

CRediT authorship contribution statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors extend their appreciation to Taif University, Saudi Arabia, for supporting this work through project number (TU-DSPP-2024-33).

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