American Journal of Civil Engineering and Constructions (AJCEC)

VOLUME 1 ISSUE 2 (2025)

PUBLISHED BY
E-PALLI PUBLISHERS, DELAWARE, USA

American Journal of Civil Engineering and Constructions (AJCEC)

Volume 1 Issue 2, Year 2025
https://journals.e-palli.com/home/index.php/ajec

Investigating the Influence of Banana Leaf Ash on the Compressive Strength and Chloride Resistance of Concrete

Akinfenwa Aanu[1], Muhammed Awwal Imran[1*], Jamiu Lateef[2]

Article Information

Received: April 10, 2025

Accepted: May 12, 2025

Published: November 04, 2025

Keywords

Agricultural Waste, Banana Leaf Ash, Chloride Resistance, Compressive Strength, Concrete, Pozzolan, Supplementary Cementitious Material, Sustainable Construction

ABSTRACT

The high compressive strength, durability, fire resistance, and formability of concrete have made its use widespread in the construction industry. However, the production challenges and limitations (e.g., emission of large quantities of CO_2, labour intensity, etc.) of Portland cement, a major aggregate of concrete, have raised the need for a sustainable and viable alternative. Therefore, this study investigated the effect of partial replacement of OPC with Banana Leaf Ash (BLA) on compressive strength and chloride resistance of concrete. BLA has properties known as pozzolanic properties. This property is potentially beneficial for cement replacement. To carry out the investigation, concrete mixes were prepared with 0%, 10%, and 20% BLA replacement by weight of cement, maintaining a water-cement ratio of 0.5. Cube specimens were cast and cured in water (control) and solutions containing 1% and 2.5% calcium chloride ($CaCl_2$) for 28, 42, and 60 days. Compressive strength tests were conducted, which revealed that while strength generally increased with curing age in water, the 10% BLA replacement yielded the highest compressive strength compared to the control and 20% replacement across all curing media and ages. Concrete with 10% BLA demonstrated superior resistance to chloride attack, showing less strength degradation compared to the control and 20% BLA specimens in the 1% and 2.5% $CaCl_2$ solutions, and the optimal replacement level appears to be around 10%, at which point concrete's durability in chloride-rich environments was effectively enhanced.

INTRODUCTION

The global construction industry must find ways to incorporate sustainability into its operations, which calls for the development of environmentally friendly raw materials and the improvement of traditional ones (Lima *et al.*, 2021). Construction is one of the most important industries in any country, and as such, it is always looking for new and creative material solutions to satisfy its exacting standards for strength, durability, and affordability (Pheng & Hou, 2019). Concrete, on the other hand, is one of the most widely used building materials. This is because of strength, adaptability, affordability, and ease of moulding into diverse structural forms (Shelton & Harper, 1982). However, the production of Ordinary Portland Cement (OPC) is associated with substantial emissions of carbon dioxide (CO_2), a greenhouse gas that contributes to environmental concerns. OPC is the essential binder in concrete. Estimates suggest that producing 1000 kg of cement releases nearly 900 kg of CO_2. On top of that, high concentrations of CO_2 can pose health risks (He *et al.*, 2019; Mahasenan *et al.*, 2003). In response to sustainability goals and concerns over natural resource depletion and waste management, the beneficial use of industrial and agricultural byproducts is gaining significant traction (Huo & Peng, 2023). Incorporating wasted but reusable materials into construction products will help to reduce landfill burden and lessen the demand for naturally mined resources. It will also mitigate the environmental footprint of the construction industry (Shukla *et al.*, 2024). The most promising application is the use of these byproducts to supplement or replace cement in concrete. This approach is economically attractive due to the high cost of cement and environmentally beneficial as it integrates waste materials into a stable, solidified matrix (Chen *et al.*, 2024; Dachowski & Kostrzewa, 2016). In this regard, a lot of research has focused on recycling various ashes, such as fly ash, coal bottom ash, wood ash, and rice husk ash, as supplementary cementitious materials (SCMs) (Yin *et al.*, 2018).

Agricultural waste is enormous and is often an underused resource. In Nigeria alone, materials like banana leaves, pseudostems, and stalks are generated in large quantities, approximately 2.73 million tonnes annually. Typically, these wastes are left to decompose in fields, where they also contribute to environmental concerns (Kolawole *et al.*, 2024; Nwakaire *et al.*, 2016; Phiri *et al.*, 2024). Transforming this biomass into valuable commodities, such as Banana Leaf Ash (BLA), could offer a sustainable waste management solution and add economic value. BLA contains predominantly amorphous silica (48.7 %), which reacts with portlandite ($Ca(OH)_2$) to form additional calcium–silicate–hydrate (C–S–H), densifying the microstructure and potentially improving durability (Tavares *et al.*, 2022). (Islam *et al.*, 2024) indicated in their study that BLA possesses pozzolanic properties. A pozzolan, as defined by ASTM C 125-13, is a siliceous or siliceous and aluminous material that reacts chemically with calcium hydroxide in the presence of

---

[1] Department of Building, Obafemi Awolowo University, Ile-Ife, Osun State, Nigeria
[1] Department of Civil and Environmental Engineering, Case Western Reserve University, Cleveland, Ohio, United States
[*] Corresponding author's e-mail: awwalimran.imran@gmail.com

water at ordinary temperatures to form compounds with cementitious properties (Donatello *et al.*, 2010). Studies by (Ikumapayi *et al.*, 2024; Singh *et al.*, 2007) confirmed the pozzolanic potential of BLA as an SCM in construction that offers cost savings and environmental benefits. The pozzolanic activity stems primarily from the reaction of amorphous silica in the ash with calcium hydroxide ($Ca(OH)_2$), a byproduct of cement hydration, to form additional calcium silicate hydrate (C-S-H) gel, the main binding phase in hardened concrete. This reaction can enhance the microstructure and durability of concrete.

Chloride-induced corrosion of steel reinforcement is a major deterioration mechanism that affects reinforced concrete structures worldwide. This is mostly prevalent in those exposed to marine environments, de-icing salts, or industrial chemicals (Ali *et al.*, 2024). While the high alkalinity of good-quality concrete typically forms a protective passive layer on embedded steel, the ingress of chloride ions beyond a certain threshold (as low as 0.15 % by weight of cement) can break down this layer and initiate corrosion if sufficient moisture and oxygen are present (Kenny & Katz, 2020). Since durability is a critical aspect of concrete performance, the resulting rust products occupy a larger volume than the original steel, inducing tensile stresses that lead to cracking, delamination, and spalling of the concrete cover that compromises the structural integrity of the concrete through loss of bond and reduction in rebar cross-sectional area (Li *et al.*, 2007). Chloride ions can originate internally from contaminated mix constituents (e.g., aggregates, water, and admixtures containing chlorides like $CaCl_2$ used as accelerators) or externally from environmental exposure (Jinlong *et al.*, 2025). However, the rate of chloride penetration depends on the concrete's quality (permeability) and the exposure conditions. One effective strategy to mitigate chloride attack and enhance concrete durability is the partial replacement of OPC with SCMs, which includes pozzolanic materials like BLA (subpa-asa *et al.*, 2022). These finely divided materials contribute to durability through several mechanisms. Firstly, the physical presence of fine SCM particles refines the pore structure of the concrete matrix which reduces its permeability and hinders the ingress of aggressive substances like chloride ions (pore refinement effect). Secondly, the pozzolanic reaction consumes $Ca(OH)_2$ and produces additional C-S-H gel, which is more stable and contributes to strength and density (pozzolanic effect). $Ca(OH)_2$ is susceptible to leaching and attack by some chemicals, which makes it important to be eliminated (Frías & Cabrera, 2000). (Bhutto *et al.*, 2024; Falola *et al.*, 2023) found that replacing up to 20% of cement with BLA increased compressive strength, suggesting an optimum replacement level within this range.

However, despite preliminary studies indicating the pozzolanic nature of BLA, a comprehensive investigation into its specific effect on the resistance of concrete to chloride ingress concerning varying exposure levels and durations is warranted. Addressing the challenges of sustainable waste management for banana crop residues and reducing the environmental impact of cement production provides strong justification for this research. Using BLA as an SCM could simultaneously reduce the need for landfilling agricultural waste and decrease the demand for OPC and lead to lower CO_2 emissions. Therefore, the aim of this study is to investigate the effects of BLA as a partial cement replacement on the chloride resistance of concrete, evaluating its influence on durability properties in an aggressive chloride environment. To achieve this purpose, the study will pursue the following objectives: (1) to investigate the effect of BLA on the compressive strength of concrete; (2) to determine the effects of varying chloride concentrations on the compressive strength of BLA-blended cement concrete; and (3) to evaluate the effect of the duration of chloride exposure on the compressive strength of concrete containing BLA. While SCMs generally improve durability, there is limited data for BLAs under aggressive chloride environments. This research addresses that deficiency by providing empirical evidence for BLA's optimum replacement level to resist chloride-induced deterioration, thus contributing to sustainable concrete technology and waste valorisation. The findings will contribute to understanding the potential of BLA as a viable SCM for producing more durable and sustainable concrete for applications where chloride resistance is key.

MATERIALS AND METHODS

This investigation employed a laboratory-based experimental methodology to evaluate the strength and durability characteristics of concrete incorporating Banana Leaf Ash (BLA) as a partial replacement for Ordinary Portland Cement (OPC) when exposed to a chloride environment. All experimental work was conducted at the Department of Building laboratory, Obafemi Awolowo University, Ile-Ife, Osun State, Nigeria.

Materials

The materials used were commercially available Ordinary Portland Cement (Elephant brand), conforming to BS EN 197-1 requirements (British Standards Institution, 2019) (the chemical composition is detailed in Table 1). Banana leaves were collected from plantations in Ekiti State and Ife, Osun State. These leaves were thoroughly dried, burnt under controlled conditions, calcined, and sieved to obtain fine and uniform ash for use as an SCM. The specific gravity and chemical composition of the resulting BLA are presented in Tables 2 and 1. Fine aggregate (sand) and coarse aggregate (crushed granite, 20 mm maximum size) were procured from local suppliers and subjected to preliminary testing. Potable tap water conforming to BS EN 1008 (British Standards Institution, 2002), sourced from the university's water supply, was used for mixing and curing. Analytical grade calcium chloride ($CaCl_2$) salt was purchased locally to prepare the chloride solutions for curing. Standard mould oil was used to lubricate the inner surfaces of the casting moulds.

Table 1: Physical properties of aggregates (British Standards Institution, 1999, 2022; Malisch, 2014)

Property	BLA	Sand	Granite	Test Standard
Fineness modulus	-	3.04	6.95	BS EN 12620
Coefficient of uniformity (Cu)	-	3.38	1.55	BS EN 12620
Coefficient of curvature (Cc)	-	0.92	0.90	BS EN 12620
Specific gravity	1.78	2.62	2.72	BS EN 1097-6
Bulk Density (uncompacted kg/m³)	-	1501	1381	BS 812-2
Bulk Density (compacted kg/m³)	-	1631	1466	BS 812-2

Source: Author's elaboration (BLA physical data determined via pycnometer; aggregates via standard sieve and density tests.)

Table 2: Chemical compositions of OPC and Banana leaves ash (BLA) (British Standards Institution, 2005)

Oxide Composition	OPC (%)	BLA (%)	Standard
Ferrous oxide (Fe_2O_3)	4.60	1.40	BS EN 196-2
Silica (SiO_2)	23.00	48.70	BS EN 196-2
Calcium Oxide (CaO)	65.00	8.69	BS EN 196-2
Aluminum Oxide (Al_2O_3)	6.20	2.60	BS EN 196-2
Magnesium Oxide (MgO)	2.06	-	BS EN 196-2
Sodium Oxide (Na_2O)	0.19	0.21	BS EN 196-2
Potassium Oxide (K_2O)	0.40	-	BS EN 196-2
Sulphite (SO_3^{2-})	1.43	-	BS EN 196-2
Loss on ignition (LOI)	3.80	5.06	BS EN 196-2

Source: Author's elaboration (High SiO_2 and elevated loss on ignition confirm BLA's pozzolanic potential)

Equipment

For the equipment, a standard cast iron cubic mould of size 100 mm x 100 mm x 100 mm was used for casting test specimens. A standard set of sieves was used for the particle size distribution analysis of aggregates. Manual mixing was performed using trowels. Standard slump cone apparatus was used to measure the workability of fresh concrete mixes according to BS EN 12350-2. A standard steel tamping rod was used for compacting concrete in the moulds. An electronic balance with 0.1g accuracy was used to weigh materials. Water tanks and containers were used to hold specimens during curing in water and calcium chloride solutions, respectively. An ELE2000 compression testing machine, conforming to BS EN 12390-4, was used to determine the compressive strength of the hardened concrete cubes in accordance with BS EN 12390-3. A pycnometer aided specific gravity determination, and a drying oven was inferred for aggregate preparation.

Preliminary Investigations

The preliminary investigations involved a sieve analysis on both fine and coarse aggregates according to BS EN 933 Pt. 1:1997, which was to determine particle size distribution, fineness modulus, coefficient of uniformity (Cu), and coefficient of curvature (Cc). The relative density (specific gravity) of sand, granite, and BLA was determined following procedures in BS 812: Part 107 and was calculated for each sample using equation 1:

$$\text{Relative density} = A/(A-(B-C)) \qquad ....(1)$$

Where A is the mass of the sample of the saturated and surface-dried aggregate, B is the mass of the vessel with the sample topped up with water and C is the mass of the vessel full of water. Uncompacted and compacted bulk densities of the aggregates were determined according to BS 812: Part 2: 1975. The percentage passing and the cumulative percentage of soil/material retained were calculated using equation 2:

Percentage retained on the sieve

$$= ((W1 - W2))/W \times 100 \qquad ....(2)$$

Where W1 is the weight of the sieve in g and W2 is the weight of the sieve plus soil in g. The resulting values are tabulated in Tables 1 and 2 and in the supporting document.

Experimental Procedures

The experimental procedures started with mixed design and proportioning. Concrete mixes were designed with a constant water-cementitious material ratio (w/cm) of 0.5. Three main mixes were prepared based on BLA replacement levels: 0% BLA (control), 10% BLA (90% OPC, 10% BLA by weight), and 20% BLA (80% OPC, 20% BLA by weight). Batching of all constituent materials was done by weight. For mixes containing BLA, the required amounts of OPC and BLA were thoroughly dry-mixed before adding aggregates. The dry components were mixed thoroughly before adding the predetermined water quantity. Mixing was performed manually using trowels until homogeneity was achieved. Immediately after mixing, workability was assessed using the slump test as per BS EN 12350-2: 2009.

Casting of 100mm cubic specimens followed immediately after the slump test. Oiled moulds were filled in layers approximately 50mm deep, each manually compacted with 25 strokes of the tamping rod. The top surface was levelled. Specimens remained in moulds for 24 hours in a stable environment. After demoulding, curing was performed at 20 ± 2 °C. At ages 28, 42, and 60 days, three cubes per mix per medium were retrieved, wiped surface-dry, and tested for compressive strength on an ELE2000 compression machine per BS EN 12390-4. The degree of deterioration (%) was calculated as strength loss relative to water-cured control using equation (3):

$\text{Deterioration} = (f_{cu,water}-f_{cu,chloride})/f_{cu,wate}r \times 100$ ....(3)

Where f_(cu,water) is the mean compressive strength (in N/mm^2) of the concrete cube specimens that were cured in plain water (the control condition) for a specific duration (e.g., 28, 42, or 60 days). $f_{cu,chloride}$ is the mean compressive strength (in N/mm^2) of the concrete cube specimens that were cured in the chloride solution (e.g., 1% or 2.5% $CaCl_2$) for the same specific duration as the corresponding water-cured specimens being compared. At each testing age, three cubes were retrieved from each curing condition for each mix type. Specimens were surface-dried and immediately tested for compressive strength using the ELE compression machine according to BS EN 12390-3. The maximum load at failure was recorded, and compressive strength was calculated (see calculation in the supporting document).

RESULTS AND DISCUSSION

The experimental investigation produced data on the properties of the constituent materials and the compressive strength development of concrete mixes incorporating Banana Leaf Ash (BLA) under different curing conditions.

Material Characterization

Material characterisation revealed specific properties of the aggregates and BLA. Sieve analysis results indicated that the fine aggregate (sand) was medium-graded with a fineness modulus of 3.04, while the coarse aggregate (granite) was uniformly graded with a fineness modulus of 6.95, both deemed suitable for concrete production (Gandage, 2023). The specific gravity was 2.62 for sand and 2.72 for granite. The specific gravity of the BLA used was 1.78. Chemical composition analysis showed BLA contained 48.70% silica (SiO_2) and 8.69% calcium oxide (CaO), compared to 23.00% SiO_2 and 65.00% CaO in OPC, supporting its potential pozzolanic nature. Figure 1 shows the plotting grading curve of the sieve analysis results (details in the supporting document; Tables 1 and 2 were used to plot grading curves).

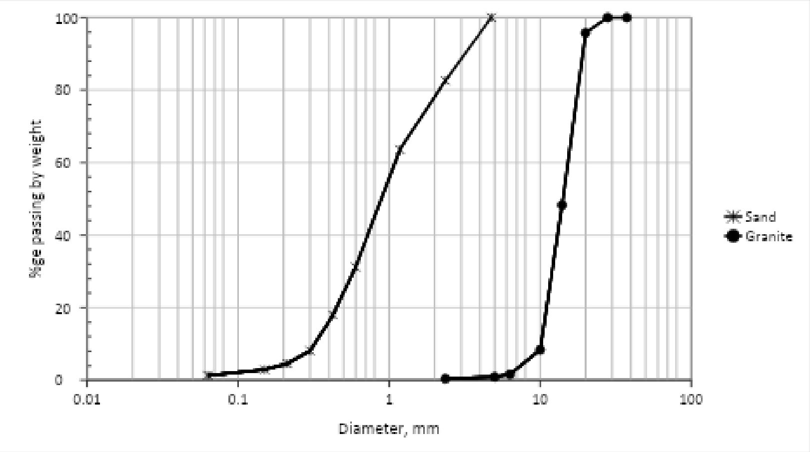

Figure 1: Grading curve of sand and granite

Compressive Strength

The mean compressive strength results for concrete cubes at 28, 42, and 60 days, cured in water (control), 1% $CaCl_2$ solution, and 2.5% $CaCl_2$ solution, are summarised in Tables 3, 4, and 5 (detailed results in supporting document Tables 5-7). When cured in water (control), the 0% BLA concrete showed progressive strength gain, reaching 32.00 N/mm^2 at 60 days. Concrete with 10% BLA replacement achieved lower strengths (e.g., 28.40 N/mm^2 at 60 days), and 20% BLA replacement yielded the lowest strengths (e.g., 25.00 N/mm^2 at 60 days), although all mixes gained strength over time.

Table 3: Compressive strength corresponding to percentage replacement of concrete cubes cured in water (control)

OPC (%)	BLA (%)	Compressive strength N/mm^2 (28 days)	Compressive strength N/mm^2 (42 days)	Compressive strength N/mm^2 (60 days)
100	0	25.52	30.20	32.00
90	10	24.64	27.31	28.40
80	20	22.32	23.70	25.00

Source: Author's elaboration

Curing in 1% $CaCl_2$ solution showed different trends. The control concrete's strength decreased over time, from 24.20 N/mm² at 28 days to 19.60 N/mm² at 60 days. On the other hand, the 10% BLA mix showed the highest strength at 28 days (26.77 N/mm²) and maintained significantly higher strength than the control at 60 days (25.83 N/mm²). This indicated better resistance. The 20% BLA mix performed better than the control initially but its strength decreased over time, ending lower than the 10% mix at 60 days (15.80 N/mm²).

Table 4: Compressive strength corresponding to percentage replacement of concrete cubes cured in 1% $CaCl_2$

OPC (%)	BLA (%)	Compressive strength N/mm² (28 days)	Compressive strength N/mm² (42 days)	Compressive strength N/mm² (60 days)
100	0	24.20	22.19	19.60
90	10	26.77	25.56	25.83
80	20	18.40	17.26	15.80

Source: Author's elaboration

In the more aggressive 2.5% $CaCl_2$ solution, the detrimental effect was more pronounced. The control concrete's strength dropped significantly from 21.56 N/mm² at 28 days to 16.96 N/mm² at 60 days. The 10% BLA replacement again demonstrated superior performance and maintained considerably higher strength (20.35 N/mm² at 60 days) compared to both the control and the 20% BLA mix. The 20% BLA replacement exhibited the lowest strength and highest degradation, dropping to 11.50 N/mm² at 60 days.

Table 5: Compressive strength corresponding to percentage replacement of concrete cubes cured in 2.5% $CaCl_2$

OPC (%)	BLA (%)	Compressive strength N/mm² (28 days)	Compressive strength N/mm² (42 days)	Compressive strength N/mm² (60 days)
100	0	21.56	19.56	16.96
90	10	23.20	21.95	20.35
80	20	16.70	13.74	11.50

Source: Author's elaboration

Figures 2-4 graphically illustrate the compressive strength trends for water, 1% $CaCl_2$, and 2.5% $CaCl_2$ curing conditions, respectively. Figures 5-7 show the degree of deterioration (calculated as percentage strength loss relative to the 0% BLA control in the same curing medium and age, based on the interpretation of tables in the supporting document) under the different curing regimes. These graphs visually confirm the trends observed in the tabulated data.

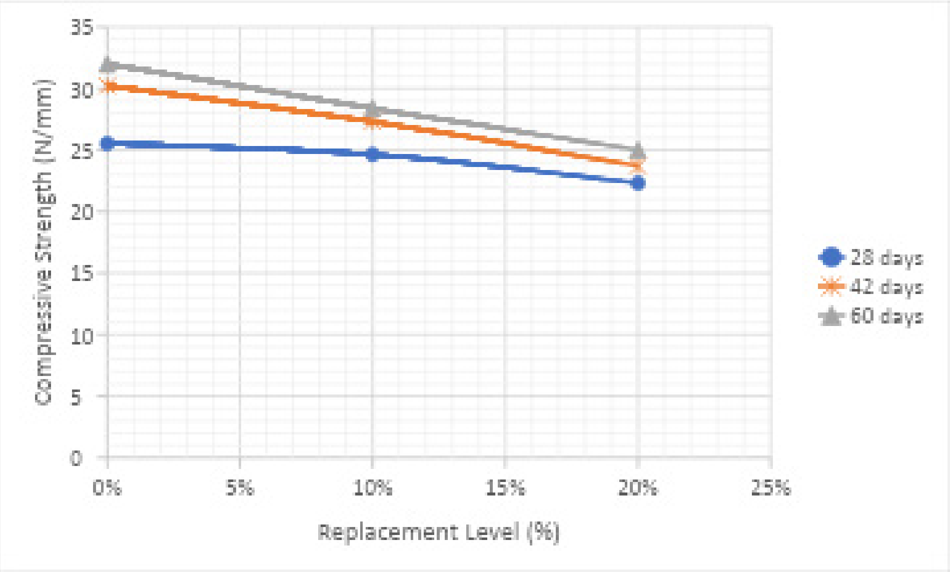

Figure 2: Compressive strength corresponding to percentage replacement with BLA in concrete cubes cured in water (control)

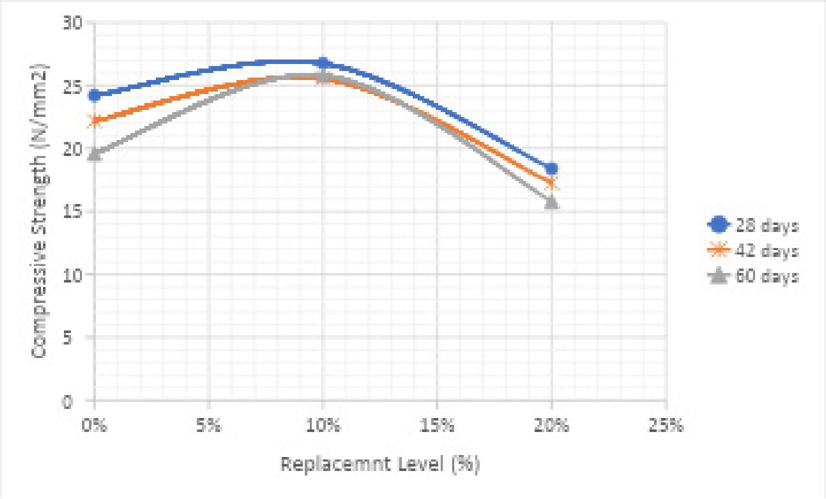

Figure 3: Compressive strength corresponding to percentage replacement with BLA in concrete cubes cured in 1% $CaCl_2$

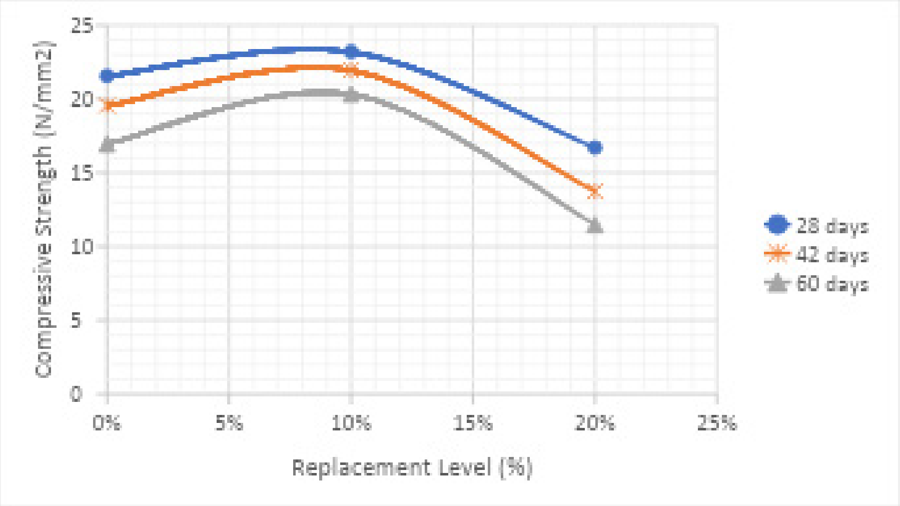

Figure 4: Compressive strength corresponding to percentage replacement with BLA in concrete cubes cured in 2.5% $CaCl_2$

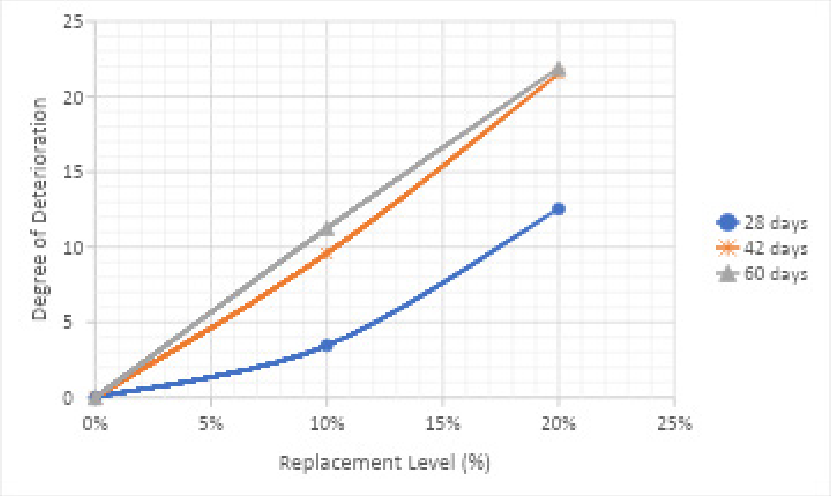

Figure 5: Degree of deterioration corresponding to percentage replacement with BLA in concrete cubes cured in water (control)

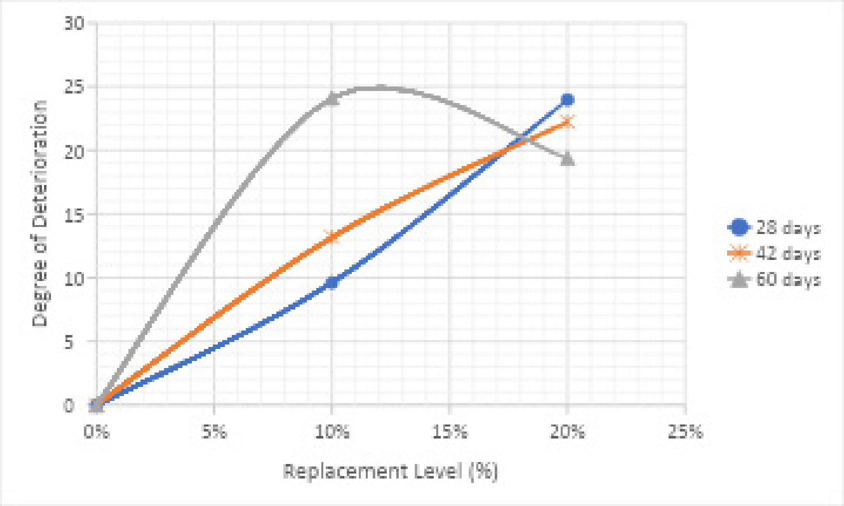

Figure 6: Degree of deterioration corresponding to percentage replacement with BLA in concrete cubes cured in 1% $CaCl_2$

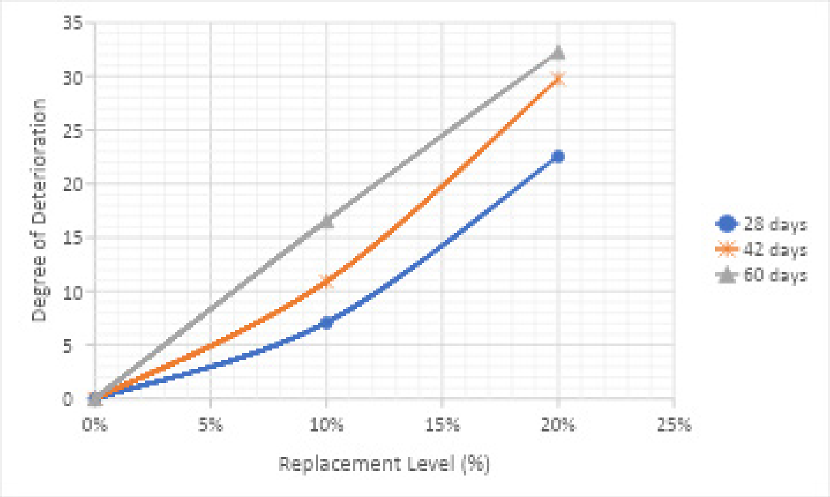

Figure 7: Graphical representation degree of deterioration corresponding to percentage replacement with BLA in concrete cubes cured in 2.5% $CaCl_2$

Discussion

The results obtained from this investigation provide valuable insights into the influence of Banana Leaf Ash (BLA) as a supplementary cementitious material (SCM) on the compressive strength and chloride resistance of concrete. The trends show the unique performance attributes that BLA imparts while also being consistent with well-established concrete technology principles. In the control curing condition (water), all concrete mixes demonstrated the expected behaviour of progressive strength gain with increasing curing age, which is due to the ongoing hydration of cementitious materials. However, the partial replacement of OPC with BLA led to a reduction in compressive strength compared to the 100% OPC mix at all tested ages (28, 42, and 60 days). The 10% BLA replacement resulted in strengths that were approximately 3-11% lower than the control, while the 20% BLA replacement showed a more significant reduction of 12-22%. This reduction in strength with increasing BLA content in water curing might be attributed to a dilution effect (lower clinker content) and potentially slower pozzolanic reaction of BLA compared to the hydration rate of OPC, especially at earlier ages. While BLA contains a high amount of silica (48.70%), its reactivity and contribution to strength development might be slower or less efficient than OPC hydration under standard water curing conditions, or the optimum replacement level for maximum strength gain in water might be less than 10%. This contrasts with findings by Bhutto *et al.* (2024) and Falola *et al.* (2023), who reported increased strength up to 20% BLA replacement, suggesting variations in BLA characteristics (e.g., processing, fineness, chemical composition) or experimental conditions could influence results. Nevertheless, the strength achieved even with 20% BLA replacement (25.00 N/mm² at 60 days) might still be adequate for certain structural applications.

The performance of the concrete mixes changed significantly when exposed to chloride ($CaCl_2$) solutions. As expected, the control concrete (0% BLA) exhibited a noticeable reduction in compressive strength over time when cured in both 1% and 2.5% $CaCl_2$ solutions. This degradation is consistent with the known detrimental effects of chloride ingress, which can disrupt the concrete matrix and, more critically in reinforced concrete (though reinforcement was not part of this study), initiate corrosion. The strength loss was more pronounced in the higher concentration (2.5%) solution, indicating a dose-dependent effect of chloride exposure.

On the other hand, the concrete containing 10% BLA demonstrated markedly improved resistance to the chloride environment. In both 1% and 2.5% $CaCl_2$ solutions, the 10% BLA mix consistently exhibited higher compressive strength than the control mix at all testing ages. At 28 days in 1% $CaCl_2$, the 10% BLA mix achieved a strength (26.77 N/mm^2) even higher than the control mix cured in plain water (25.52 N/mm^2). While its strength did decrease slightly over time in chloride solutions, the reduction was less severe than that observed in the control mix, indicating better durability. This enhanced performance is likely due to the pozzolanic reaction of BLA. The reaction consumes calcium hydroxide ($Ca(OH)_2$) and produces additional calcium silicate hydrate (C-S-H) gel. This process refines the pore structure of the concrete, making it denser and less permeable to the ingress of chloride ions. Furthermore, the consumption of $Ca(OH)_2$ can reduce potential interactions with chlorides that might otherwise be deleterious. The improved resistance at 10% replacement suggests that this level provides an optimal balance between the dilution effect and the beneficial pozzolanic contribution in resisting chloride attack.

The concrete with 20% BLA replacement, however, did not perform as well as the 10% mix in the chloride solutions. While it showed slightly better resistance than the control mix in 1% $CaCl_2$ at 28 days, its strength was consistently lower than the 10% mix. It degraded more significantly over time, especially in the 2.5% solution. This suggests that at 20% replacement, the negative impact of reducing the OPC content (dilution effect) outweighs the benefits of the pozzolanic reaction in terms of overall strength and resistance in these aggressive environments. The higher BLA content might lead to a less robust initial matrix or a slower overall reaction rate that cannot adequately compensate for the reduced OPC binder, especially under chemical attack. The results strongly indicate that the optimum level for BLA replacement, considering both strength and chloride resistance, lies closer to 10% than 20% under the conditions tested. The study successfully illustrates how a moderate amount of BLA (roughly 10%) can greatly increase the durability of concrete exposed to chloride environments, supporting the idea that waste materials can be used to improve concrete performance.

CONCLUSION

The experimental investigation into the effects of replacing Ordinary Portland Cement (OPC) with Banana Leaf Ash (BLA) on concrete properties leads to several key conclusions. Partial replacement of OPC with BLA influences compressive strength development; in standard water curing, both 10% and 20% BLA levels resulted in lower strength compared to the control, although strength gain occurred over time. Exposure to calcium chloride ($CaCl_2$) solutions caused a decrease in compressive strength for the control concrete, with greater degradation at higher concentrations. Incorporating BLA significantly improved chloride resistance; concrete with 10% BLA consistently showed higher strength and lower degradation than the control in both 1% and 2.5% $CaCl_2$ solutions. The 10% BLA replacement level demonstrated the most effective performance for chloride resistance, suggesting an optimal level around this percentage. Although 20% BLA offered some initial improvement over the control in 1% $CaCl_2$, its overall performance was inferior to the 10% mix, especially at longer durations and higher chloride levels. These findings support using BLA at an optimal level (around 10%) as a supplementary cementitious material to enhance concrete durability against chloride ingress, promoting sustainable construction. Further research is recommended to explore other durability aspects and the influence of BLA processing variables.

REFERENCES

Ali, M., Shams, M., Bheel, N., Almaliki, A., Mahmoud, A., Dodo, Y., & Benjeddou, O. (2024). A review on chloride induced corrosion in reinforced concrete structures: Lab and in situ investigation. *RSC Advances, 14,* 37252–37271. https://doi.org/10.1039/d4ra05506c

Bhutto, S., Abro, F.-R., Ali, M., Buller, A. S., Bheel, N., Gamil, Y., Najeh, T., Deifalla, A. F., Ragab, A. E., & Almujibah, H. R. (2024). Effect of banana tree leaves ash as cementitious material on the durability of concrete against sulphate and acid attacks. *Heliyon, 10*(7), e29236. https://doi.org/10.1016/j.heliyon.2024.e29236

British Standards Institution. (1999). *Testing aggregates: Part 2: Methods of determination of density.* British Standards Institution.

British Standards Institution. (2002). *Mixing water for concrete: Specification for sampling, testing and assessing the suitability of water, including water recovered from processes in the concrete industry, as mixing water for concrete.* British Standards Institution.

British Standards Institution. (2005). *Methods of testing cement: Part 2: Chemical analysis of cement.* British Standards Institution.

British Standards Institution. (2019). *Cement: Part 1: Composition, specifications and conformity criteria for common cements.* British Standards Institution.

British Standards Institution. (2022). *Tracked changes: Tests for mechanical and physical properties of aggregates: Part 6: Determination of particle density and water absorption.* British Standards Institution.

Chen, L., Yang, M., Chen, Z., Xie, Z., Huang, L., Osman, A. I., Farghali, M., Sandanayake, M., Liu, E., Ahn, Y. H., Al-Muhtaseb, A. H., Rooney, D. W., & Yap, P.-S. (2024). Conversion of waste into sustainable construction materials: A review of recent developments and prospects. *Materials Today Sustainability, 27,* 100930. https://doi.org/10.1016/j.mtsust.2024.100930

Dachowski, R., & Kostrzewa, P. (2016). The Use of Waste Materials in the Construction Industry. *Procedia Engineering, 161,* 754–758. https://doi.org/10.1016/j.proeng.2016.08.764

Donatello, S., Tyrer, M., & Cheeseman, C. R. (2010). Comparison of test methods to assess pozzolanic activity. *Cement and Concrete Composites, 32*(2), 121–127. https://doi.org/10.1016/j.cemconcomp.2009.10.008

Falola, O., Familusi, A., Olusami, J., Adewumi, B., & Olatunji, A. (2023). *Efficiency of Banana Leaf Ash as a Partial Replacement for Cement in Concrete Production.*

Frías, M., & Cabrera, J. (2000). Pore size distribution and degree of hydration of metakaolin–cement pastes. *Cement and Concrete Research, 30,* 561–569. https://doi.org/10.1016/S0008-8846(00)00203-9

Gandage, A. (2023). Admixtures in Concrete -A Review.

He, Z., Zhu, X., Wang, J., Mu, M., & Wang, Y. (2019). Comparison of CO2 emissions from OPC and recycled cement production. *Construction and Building Materials, 211,* 965–973. https://doi.org/10.1016/j.conbuildmat.2019.03.289

Huo, J., & Peng, C. (2023). Depletion of natural resources and environmental quality: Prospects of energy use, energy imports, and economic growth hindrances. *Resources Policy, 86,* 104049. https://doi.org/10.1016/j.resourpol.2023.104049

Ikumapayi, C., Omotayo, O., & Akande, S. (2024). Evaluation of RHA/BLA pozzolanic cement concrete properties. *Journal of Civil Engineering, Science and Technology, 15,* 166–178. https://doi.org/10.33736/jcest.5016.2024

Islam, Md. H., Law, D. W., Gunasekara, C., Sobuz, Md. H. R., Rahman, Md. N., Habib, Md. A., & Sabbir, A. K. (2024). Assessing the Influence of Banana Leaf Ash as Pozzolanic Material for the Production of Green Concrete: A Mechanical and Microstructural Evaluation. *Materials, 17*(3), 720. https://doi.org/10.3390/ma17030720

Jinlong, L., Dongyi, L., Yang, X., Rong, H., Xian, C., Zhang, Z., Huang, W., & Li, S. (2025). Chloride ion binding in cementitious materials: A review of influencing factors and control methods. *Case Studies in Construction Materials, 22,* e04201. https://doi.org/10.1016/j.cscm.2024.e04201

Kenny, A., & Katz, A. (2020). Steel-concrete interface influence on chloride threshold for corrosion – Empirical reinforcement to theory. *Construction and Building Materials, 244,* 118376. https://doi.org/10.1016/j.conbuildmat.2020.118376

Kolawole, I. D., Kolawole, G. O., Sanni-manuel, B. A., Kolawole, S. K., Ewansiha, J. U., Kolawole, V. A., & Kolawole, F. O. (2024). Economic impact of waste from food, water, and agriculture in Nigeria: Challenges, implications, and applications—a review. *Discover Environment, 2*(1), Article 1. https://doi.org/10.1007/s44274-024-00086-6

Li, C. Q., Zheng, J., Lawanwisut, W., & Melchers, R. E. (2007). Concrete delamination caused by steel reinforcement corrosion. *Journal of Materials in Civil Engineering, 19*(7), 591–600. https://doi.org/10.1061/(ASCE)0899-1561(2007)19:7(591)

Lima, L., Trindade, E., Alencar, L., Alencar, M., & Silva, L. (2021). Sustainability in the construction industry: A systematic review of the literature. *Journal of Cleaner Production, 289,* 125730. https://doi.org/10.1016/j.jclepro.2020.125730

Mahasenan, N., Smith, S., & Humphreys, K. (2003). The Cement Industry and Global Climate ChangeCurrent and Potential Future Cement Industry CO2 Emissions. *Greenhouse Gas Control Technologies - 6th International Conference,* 995–1000. https://doi.org/10.1016/B978-008044276-1/50157-4

Malisch, W. R. (2014). *Aggregates for concrete.* BSI Customer Relations.

Nwakaire, J., Obi, O., & Ugwuishiwu, B. (2016). Agricultural waste concept, generation, utilization and management. *Nigerian Journal of Technology, 35*(4), 957–964. https://doi.org/10.4314/njt.v35i4.34

Pheng, L. S., & Hou, L. S. (2019). The Economy and the Construction Industry. *Construction Quality and the Economy,* 21–54. https://doi.org/10.1007/978-981-13-5847-0_2

Phiri, R., Mavinkere Rangappa, S., & Siengchin, S. (2024). Agro-waste for renewable and sustainable green production: A review. *Journal of Cleaner Production, 434,* 139989. https://doi.org/10.1016/j.jclepro.2023.139989

Shelton, D., & Harper, J. (1982). *An overview of concrete as a building material* (G82-623). University of Nebraska–Lincoln Extension.

Shukla, B. K., Bharti, G., Sharma, P. K., Sharma, M., Rawat, S., Maurya, N., Srivastava, R., & Srivastav, Y. (2024). Sustainable construction practices with recycled and waste materials for a circular economy. *Asian Journal of Civil Engineering, 25*(7), Article 7. https://doi.org/10.1007/s42107-024-01111-y

Singh, N., Das, S. S., & Dwivedi, V. (2007). Hydration of bamboo leaf ash blended Portland cement. *Indian Journal of Engineering and Materials Sciences, 14*(4), 69–76.

Subpa-asa, P., Nito, N., Fujiwara, S., & Date, S. (2022). Evaluation of the prediction and durability on the chloride penetration in cementitious materials with blast furnace slag as cement addition. *Construction Materials, 2*(1), 53–69. https://doi.org/10.3390/constrmater2010005

Tavares, J. C., Lucena, L. F. L., Henriques, G. F., Ferreira, R. L. S., & dos Anjos, M. A. S. (2022). Use of banana leaf ash as partial replacement of Portland cement in eco-friendly concretes. *Construction and Building*

Materials, 346, 128467. https://doi.org/10.1016/j.conbuildmat.2022.128467

Yin, K., Ahamed, A., & Lisak, G. (2018). Environmental perspectives of recycling various combustion ashes in cement production – A review. *Waste Management, 78,* 401–416. https://doi.org/10.1016/j.wasman.2018.06.012

Appendix

Details of Laboratory Analysis of Samples

Table 1: Sieve Analysis of Sand

Diameter (mm)	**Mass of Sieve (g)**	**Mass of Sieve & Soil (g)**	**Soil Retained (g)**	**Soil Retained (%)**	**Cumulative Soil Retained (%)**	**Soil Passing (%)**
4.75	385	385	0.0	0.0	0.0	100.0
2.36	380	483.5	103.5	17.3	17.3	82.8
1.18	365	479.3	114.3	19.1	34.5	63.7
0.60	340	534.5	194.5	32.4	66.9	31.3
0.425	325	404.2	79.2	13.2	80.1	18.1
0.30	320	379.4	59.4	9.9	90.0	8.2
0.21	315	336.3	21.3	3.6	93.6	4.6
0.15	300	310.2	10.2	1.7	95.3	2.9
0.075	290	299.6	9.6	1.6	96.9	1.3
Pan	250	257.8	7.8	1.3	98.2	0.0
Total			599.8	100.0		

Sum of cumulative soil retained (%) on 9 sieves: (150µm, 300µm, 600µm, 1.18mm, 2.36mm, 4.75mm) = 304mm

Fineness modulus =

Coefficient of uniformity (Cu) =

Coefficient of curvature (Cc) =

where, D60 is the diameter of aggregates at 60 percent passing;

D30 is the diameter of aggregates at 30 percent passing;

D10 is the diameter of aggregates at 10 percent passing.

Table 2: Sieve Analysis of Granite

Diameter (mm)	**Mass of Sieve (g)**	**Mass of Sieve & Soil (g)**	**Soil Retained (g)**	**Soil Retained (%)**	**Cumulative Soil Retained (%)**	**Soil Passing (%)**
28.00	385	385	0.0	0.0	0.0	100.0
20.00	380	497.6	117.6	4.2	4.2	95.8
14.00	365	1694.9	1329.9	47.5	8.4	48.3
10.00	340	1457.1	1117.1	39.9	48.3	8.4
6.30	325	515.4	190.4	6.8	55.1	1.6
5.00	320	339.6	19.6	0.7	55.8	0.9
2.36	315	329	14.0	0.5	56.3	0.4
Pan	250	261.2	11.2	0.4	56.7	0.0
Total			2799.8	100.0		

Sum of cumulative soil retained (%) on 9 sieves: (150µm, 300µm, 600µm, 1.18mm, 2.36mm, 4.75mm) = 695mm

Fineness modulus =

Coefficient of uniformity (Cu) =

Coefficient of curvature (Cc) =

where, D60 is the diameter of aggregates at 60 percent passing;

D30 is the diameter of aggregates at 30 percent passing;

D10 is the diameter of aggregates at 10 percent passing.

Table 3: Specific Gravity of Granite

S/N	**Description**	**Weight (g)**
1	Weight of Empty Pycnometer (g) W1	700
2	Weight of Empty Pycnometer + Sample (g) W2	1250
3	Weight of Empty Pycnometer + Sample + Water (g) W3	2040
4	Weight of Empty Pycnometer + Water (g) W4	1700
	Specific Gravity	2.62

Table 4: Specific Gravity of Sand

S/N	Description	Weight (g)
1	Weight of Empty Pycnometer (g) W1	700
2	Weight of Empty Pycnometer + Sample (g) W2	1380
3	Weight of Empty Pycnometer + Sample + Water (g) W3	2130
4	Weight of Empty Pycnometer + Water (g) W4	1700
	Specific Gravity	2.72

Table 5: Specific gravity of banana leaves ash

S/N	Description	Weight (g)
1	Weight of Empty Pycnometer (g) W1	700
2	Weight of Empty Pycnometer + Sample (g) W2	1255
3	Weight of Empty Pycnometer + Sample + Water (g) W3	2045
4	Weight of Empty Pycnometer + Water (g) W4	1700
	Specific Gravity	2.64

Table 6: Compressive strength and strength factor (100% H_2O)

Curing age (days)	Replacement levels (%)	Compressive strength (N/mm^2)			Mean compressive strength	Strength factor	Degree of deterioration
		i	ii	iii			
28	0	25.20	24.70	26.66	25.52	100	0
	10	24.20	24.00	25.72	24.64	96.55	3.45
	20	22.10	21.40	23.46	22.32	114.34	12.54
42	0	31.40	29.30	29.90	30.20	100	0
	10	28.61	26.92	26.40	27.31	90.43	9.57
	20	23.15	22.62	25.33	23.70	127.43	21.52
60	0	33.00	31.50	31.50	32.00	100	0
	10	29.00	28.61	27.59	28.40	88.75	11.25
	20	24.21	25.50	25.29	25.00	128	21.88

Table 7: Compressive strength and strength factor (1% CaCl2)

Curing age (days)	Replacement levels (%)	Compressive strength (N/mm^2)			Mean compressive strength	Strength factor	Degree of deterioration
		i	ii	iii			
28	0	24.80	24.00	23.80	24.20	100	0
	10	28.00	26.50	25.80	26.77	90.40	9.60
	20	20.20	19.00	16.00	18.40	131.21	23.97
42	0	23.14	21.90	21.53	22.19	100	0
	10	27.13	25.63	23.92	25.56	86.82	13.18
	20	19.59	16.81	15.39	17.26	128.56	22.22
60	0	21.00	19.20	18.60	19.60	100	0
	10	26.00	24.50	27.00	25.83	75.88	24.12
	20	18.80	14.00	14.60	15.80	124.05	19.39

Table 8: Compressive strength and strength factor (2.5% $CaCl_2$)

Curing age (days)	Replacement levels (%)	Compressive strength (N/mm^2)			Mean compressive strength	Strength factor	Degree of deterioration
		i	ii	iii			
28	0	23.00	21.24	21.44	21.56	100	0
	10	24.40	23.00	22.20	23.20	92.93	7.07

	20	16.50	18.20	15.40	16.70	129.10	22.54
42	0	20.55	18.47	19.66	19.56	100	0
	10	23.70	21.98	20.17	21.95	89.11	10.89
	20	14.60	12.14	14.48	13.74	142.36	29.75
60	0	17.40	16.61	16.93	16.98	100	0
	10	22.00	21.50	17.55	20.35	83.44	16.56
	20	12.70	11.50	10.30	11.50	147.65	32.27

Table 9: Compressive strength corresponding to percentage replacement of concrete cubes cured in water (control)

		Compressive strength N/mm^2		
OPC %	**BLA %**	**28 days**	**42 days**	**60 days**
100	0	25.52	30.20	32.00
90	10	24.64	27.31	28.40
80	20	22.32	23.70	25.00

Table 10: Compressive strength corresponding to percentage replacement of concrete cubes cured in 1% $CaCl_2$

		Compressive strength N/mm^2		
OPC %	**BLA %**	**28 days**	**42 days**	**60 days**
100	0	24.20	22.19	19.60
90	10	26.77	25.56	25.83
80	20	18.4	17.26	15.8

Table 11: Compressive strength corresponding to percentage replacement of concrete cubes cured in 2.5% $CaCl_2$

		Compressive strength N/mm^2		
OPC %	**BLA %**	**28 days**	**42 days**	**60 days**
100	0	21.56	19.56	16.96
90	10	23.20	21.95	20.35
80	20	16.70	13.74	11.50