Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 7, No. 06, June, 2021

Assessment and Evaluation of Blended Cement Using Bamboo Leaf Ash BLASH Against Corrosion

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Received 23 February 2021; Revised 03 May 2021; Accepted 12 May 2021; Published 01 June 2021

Abstract

Concrete provides a high degree of protection against corrosion of embedded steel reinforcement. Owing to the harsh environmental conditions and the presence of aggressive elements from the marine environment, deteriorating corrosion affects the durability of reinforced concrete structures. This study evaluated the effectiveness of bamboo leaf ash BLASH as a supplementary cementing material or admixture with Portland cement to improve the durability of reinforced concrete structures. Specimens of 0, 10, 15, and 20% BLASH mixtures were prepared using 16, 20, and 25 mm Ø steel reinforcements. A total of 100 cylindrical specimens were cast and used in this study. The specimens were accelerated by corrosion using impressed current techniques and a galvanostatic method in a simulated environment. The results show that specimens with a BLASH content of 10% exhibited superior performance and exhibited longer corrosion initiation and propagation times. It has a higher resistance to acid penetration and lower corrosion rates. The crack parameters of the specimen with BLASH admixtures, such as the crack width and crack frequency, were negligible. The use of BLASH as an admixture strengthens its durability and improves its residual strength and serviceability.

Keywords: Bamboo-Leaf Ash; Admixtures; Crack Parameters; Pull-out Strength; Compressive Strength; Splitting Tensile Strength.

1. Introduction

Concrete is a composite material consisting of a binding medium within which aggregates are embedded [1]. Concrete, which has high alkalinity, initially provides a highly alkaline environment for composite materials [2]. Alkaline is used to form a passive film on a steel surface [3]. It provides a high degree of protection against the deterioration of the embedded steel reinforcement [4]. The embedded deformed steel reinforcement is protected to maintain its durability, ensure its safety [5], and function effectively [6]. However, one limitation of concrete, even of good quality, is the presence of microcracks, voids, and capillary pores, where deteriorating agents such as chloride can easily penetrate the structures [1], which in turn causes the loss of the protective characteristics of concrete [6, 7]. In addition to poor concrete quality and poor design and construction, owing to harsh environmental conditions, the deterioration of reinforced concrete structures occurs [1, 2]. Thus, it is noted that the interaction between the type of material and environmental exposure affects the deterioration of all structures [8]. Among the deterioration, corrosion of steel reinforcement due to chloride intrusion in concrete structures is the root cause of the deterioration problem of most structures located in coastal areas [2, 9].

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http://dx.doi.org/10.28991/cej-2021-03091707

Corrosion of steel reinforcement, particularly in coastal areas, is a severe problem, and its prediction of occurrence is essential for structural and material engineers [10]. The deterioration due to corrosion of steel reinforcements significantly affects the durability of concrete structures [11]. When the corrosion of embedded steel reinforcement is initiated, it is difficult to stop its propagation, which affects its safety, loading capacity, and service life [12]. Corrosion causes a reduction in the steel bar area and bond strength between steel and concrete [13, 14], which leads to cracking, spalling, and delamination of the concrete cover [5]. According to Ademola and Buari (2014), corrosion has a detrimental effect on its structural performance, which significantly reduces the lifespan of structures [15]. Corrosion reduces the residual capacity of steel reinforcement, which affects the extent of residual serviceability of structures [16, 17].

On the other hand, cement, a basic component of concrete, is widely accepted as a common construction material because of the availability and abundance of raw materials, low costs, and adaptability of concrete to various shapes [13, 18-20]. However, the production of Portland cement is considered a major contributor to greenhouse gas emissions [21]. It releases about one ton of CO_2 emitted into the atmosphere [22], which is a major cause of global warming [13, 15].

Thus, researchers are currently on the challenge of using waste materials with pozzolanic properties in concrete production as cement replacement materials [23]. The selection of effective corrosion protection materials and methods must consider the environmental impacts as environmentally friendly, cost-effective, and compatible with concrete materials [10, 22]. Furthermore, to minimize the deterioration due to corrosion, the permeability and adequate concrete cover should be considered [6, 11].

Corrosion inhibitors, also known as barriers [3], help to prevent or minimize the corrosion of reinforced concrete structures. These admixtures can slow down or prevent the corrosion of the reinforcing steel in concrete. It was first investigated in the 1960s [7]. These alternative materials are generally selected based on the additional functionality that they offer and their cost-effectiveness [24]. Note that the protection mechanism of corrosion-inhibiting admixtures is already an integral part of the concrete matrix, thus directly reducing the permeability of the concrete [3].

Commonly used corrosion inhibitors, which are admixtures of cement include fly ash, slag cement formerly called ground granulated blast furnace slag, silica fume, rice husk, eggshell, and areca nut husk ash [19, 25]. Fly ash admixtures are one of the most well-known corrosion inhibitors that are popularly known. It exhibited better corrosion resistance than ordinary Portland cement concrete [26]. The higher resistivity of the fly ash admixture is evident from the reduced level of corrosion with fly ash concrete [12, 14].

In some countries, such as the Philippines, a significant amount of bamboo is processed, generating high volumes of solid waste. According to Thomas et al., bamboo is the highest-yielding and abundant construction material that can be found in any locality. It has an estimated annual production of 20 million tons worldwide [20]. It has proven to be an agro-waste product that is highly useful in the construction industry [27]. In addition, according to Kumar and Vasugi (2020), bamboo is best suited for use in construction because of its mechanical and chemical properties [28]. Apart from bamboo residues that are used as fibers, bamboo leaves are often burned in open landfills, negatively impacting the environment [23]. Bamboo leaf ash is a good pozzolanic material that reacts with calcium hydroxide to form calcium silicate hydrate [29, 30].

A mixture of Portland cement and bamboo leaf ash is known as “blended cement“ or “composite cement [31]. Several studies have been performed to evaluate the characteristics of bamboo leaf ash in the partial replacement of Portland cement in construction. Akhtar and Sarmah (2018) investigated the physical and mechanical properties of partially replaced bamboo ash cement mortars. The compressive strength increases with curing time and decreases with increasing amounts of additives. A 10% bamboo leaf ash admixture was found to be optimum with better durability performance [19]. Kumar and Vasugi (2020) also reviewed and examined the physical and mechanical properties of bamboo-reinforced structural elements with geopolymer concrete. The bamboo material in geopolymer concrete enhanced its strength and proved its suitability for sustainable construction [28].

Frías et al. (2012) conducted a detailed scientific study of Brazilian bamboo leaf ash using different techniques such as XRF, XRD, SEM/EDX, FT-IR, and TG/DTG. The results of the study reveal that bamboo leaf ash cement with 10% and 20% yields better behavior with good physical and mechanical requirements for the existing European standards [32]. Ademola and Buari (2014) also examined the durability of bamboo leaf ash blended with cement in a sulfate environment. Blended cement with bamboo leaf ash has been proven to be resistant to magnesium sulfate, sodium sulfate, and calcium sulfate media, but it was found to perform better in soils rather than in seawater facilities [15]. Zea Escamilla and Habert (2014) prepared several percentages by weight of bamboo leaf ash to assess its strength and durability as a partial replacement in concrete. The 10% bamboo leaf ash had better results than the other bamboo leaf ash admixtures [23]. Dhinakaran and Chandana (2016) evaluated the compressive strength, pozzolanic activity, sorptivity, and porosity of blended calcined bamboo leaf ash. Fifteen percent of bamboo leaf ash was found to be useful as a replacement for cement, but with little compromise in its strength and durability characteristics. Their work also verified that there is a substantial cost reduction in the replacement of cement with bamboo leaf ash. The cost incurred for cement was reduced by approximately 15% of its original value [33]. However, Dwivedi et al. (2006) reported that 20% bamboo leaf ash admixtures have a compressive strength comparable to that of ordinary Portland cement even after 28 days of curing [29].

Bannaravuri and Birru (2018) introduced bamboo leaf ash as an effective admixture for the development of aluminum alloy-based composites with 0, 2, 4, and 6% BLA content. The density of the fabricated composites decreased with the addition of bamboo leaf ash particles, and the hardness and tensile strength improved significantly [34]. Moraes et al. (2019) characterized bamboo leaf ash production with auto-combustion based on its pozzolanic behavior. Bamboo leaf ash admixtures are classified as highly conductive and have high pH values [35]. Onikeku et al. (2019) also examined the use of bamboo leaf ash as a supplementary cementitious material. BLA improved the split tensile, compressive, and flexural strength benchmarks by 10% as the optimum reinforcement level. BLA can be considered a good pozzolanic material that can reduce the cost of construction and improve concrete properties [36]. In addition, Kolawole et al. (2021) evaluated bamboo leaves and clay brick waste for their potential to serve as sustainable pathways for cementitious composites. The 10% BLA mixture helps achieve acceptable strength and resistance to chemical attacks [37].

Several studies have also been conducted to evaluate the effectiveness of other by-product waste agro-materials against corrosion deterioration. Chowdhury et al. (2015) evaluated the suitability of wood ash as a partial replacement for conventional concrete. The results showed that the strength of the concrete blended mixtures decreased with increasing wood ash content, but the strength increased with increasing age [16]. Kouloumbi and Batis investigated the corrosion resistance of mortar with Greek fly ash immersed in a 3.50% sodium chloride solution. This improved the corrosion behavior of the steel reinforcing bars.

The results indicated that a mixture of fly ash improved the corrosion behavior of the reinforcing steel bars [26]. In the work of Montemor et al. (2000), the corrosion behavior of blended cement with fly ash, which is up to 50% of the total binder, was tested. The addition of fly ash generally leads to an increase in the corrosion initiation time and a decrease in its corrosion rate [38]. Alaneme et al. (2014) investigated the corrosion and wear behaviors of Al matrix hybrid composites with agro-waste products such as bagasse, rice hush, bamboo leaves, groundnut, and coconut shell, in a 3.50% chloride medium. Electrochemical studies and wear tests were performed, and it was verified that 4% weight of bamboo leaf ash was observed to have a higher resistance than the other composite samples produced [18]. Gurdián et al. (2014) evaluated industrial by-products mixed with cement as recycled aggregates. The results show that there are no significant differences in the resistance of such mixtures to natural chloride attacks. However, considering the carbonation attack, none of the mixtures exhibited highly aggressive conditions and had higher corrosion values than ordinary Portland cement [39]. Andrade et al. (1991) investigated the corrosion resistance of different types of blended cement against the ingress of chloride from natural Mediterranean Sea water using a polarization resistance technique for a period of five years. Blended cement lengthens the initiation period of corrosion compared to plain concrete and has a lower corrosion rate [31]. In a study of Sharp et al. (2014), the durability of concrete mixtures with supplementary cementitious material SCMs was evaluated. The results verified that SCMs reduce the permeability and absorption of concrete and increase the durability of the structures [4]. From the work of Brühwiler and Mivelaz (1999), chloride ingress under climatic conditions and the effect of early cracks were examined. It was concluded that permeability has an overall control over the quality of the cover concrete of new structures [8]. Bheel et al. (2020) studied wheat straw ash as an admixture with cement. The strength of the concrete decreased as the percentage of WSA increased. The 10% replacement was comparable to that of conventional concrete. A decrease in strength was noted for 20 and 30% replacement of cement by WSA [21]. Abdul et al. (2019) studied the strength of wheat straw ash admixtures. It reduces the compressive strengths and mechanical properties of mixtures; however, flexural and indirect tensile strengths are significantly enhanced [40].

Although there are relatively few studies on the technological use of bamboo leaf ash reported in the literature, only a few studies have been conducted to evaluate the effectiveness of bamboo leaf ash as a corrosion inhibitor of reinforced concrete structures, particularly those exposed to coastal areas. This experimental study aimed to assess the effectiveness of BLASH in establishing mixtures with high durability and high resistance to corrosion, which helps to lengthen the design life and serviceability of structures exposed to a severely aggressive environment.

This study was conducted using the experimental procedures. The galvanostatic method using the impressed current technique was used to accelerate corrosion in an artificially controlled environment. Several measurements of the data were conducted after a period of accelerated corrosion. Crack parameters such as crack widths and crack frequency, corrosion variables such as corrosion rates, mass loss rate and corrosion levels, bond strength, durability, and residual strength were evaluated. The effectiveness of bamboo leaf ash BLASH against corrosion deterioration of structures exposed to excessive marine environments.

2. Materials and Methods

2.1. Research Flow Chart

The flow charts for the research methodology are as follows in Figure 1:

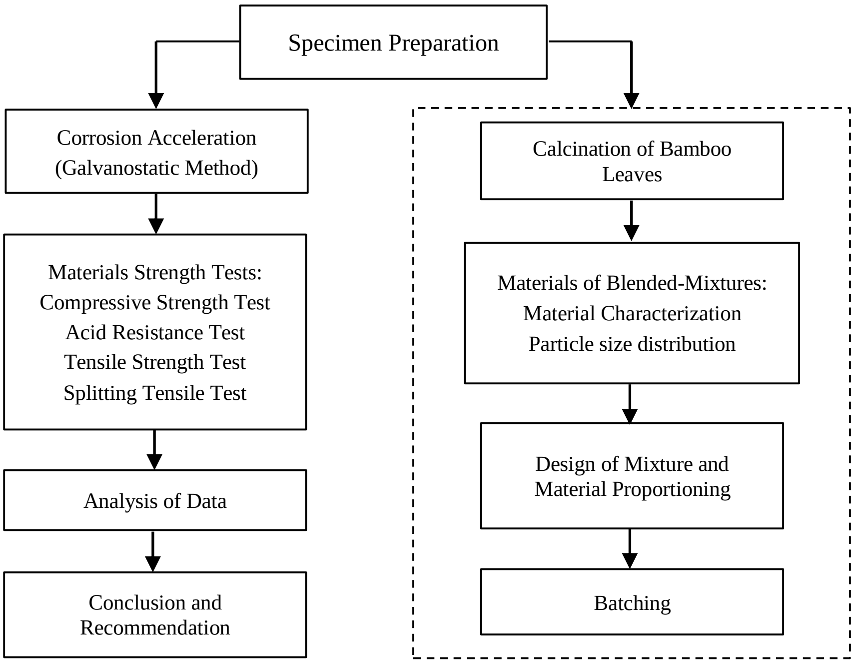

Figure 1. Research flow chart

2.2. Calcination of Bamboo Leaves

Bamboo leaves from Bayog species were collected during the leaf ash preparation. Figure 2 shows a photograph of the bamboo leaves. The bamboo leaves were dried in the sun in open air for complete combustion. The ash was allowed to cool before removal after burning. The ash of the bamboo leaves was kept in a well-sealed plastic or polythene to avoid moisture absorption. The dried sample was kept immediately to avoid attacks by environmental elements, which might reduce its strength. After calcination, the ashes were ground and sieved to below 90μm, fineness similar to that of Portland cement.

Figure 2. Photograph of Bamboo leaf

2.3. Particle Size Distribution

Sieve analysis was carried out on the bamboo leaf ash. Table 1 shows the particle size distribution of the bamboo leaf ash. Sieving analysis was also performed for fine and coarse aggregate materials that were used in the experiments for characterization. The aggregates used were free of organic matter. Figure 3 shows the gradation curves of the bamboo leaf ash.

Table 1. Sieve Analysis of Bamboo Leaf Ash

Sieve size (inch)	Sieve size (mm)	Weight Retained (g)	Weight Passing (g)	Cumulative % of Passing
No. 4	4.74	9	1.8	98.20
No. 8	2.36	17.8	3.60	94.60
No. 16	1.18	55.5	11.1	83.50
No. 30	0.60	129.8	26	57.50
No. 50	0.300	100.2	20	23.20
No. 100	0.150	93.60	18.7	4.50
No. 200	0.075	10.10	2.0	2.50

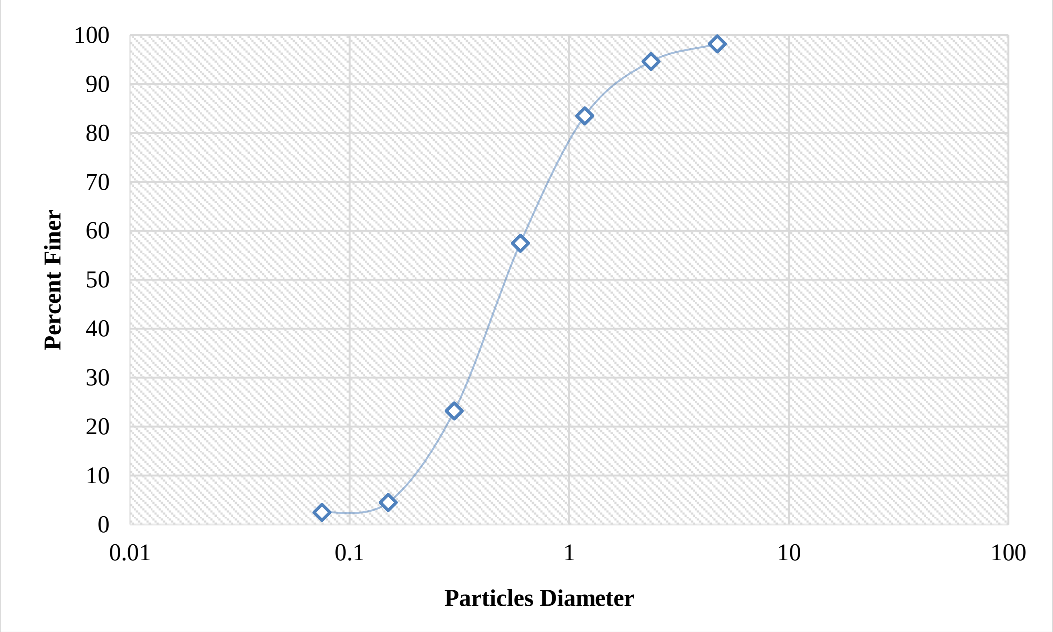

Figure 3. Gradation Curve

2.4. Specimen Preparation

After calcination, ash from the Bayog leaf was used as an admixture. The percentage by weight of the mixture of bamboo leaf ash with cement was 0% for the control specimen and 10, 15, and 20%. The material mixtures were designed according to the ACI-211 mix proportion for the Class AA mixture. The water-to-cement ratio is 0.45. The ratio of 0.45, based on the maximum permissible water-to-cement ratio for concrete exposed to severe exposure to seawater. Table 2 lists the designed mixtures of materials used in the experiments.

Table 2. Designed Mixtures of Materials

Cement-BLA mixture	Sand	Gravel	Water / Cement ratio
1	1.90	2.14	0.45

A cylindrical specimen with a diameter of 150 mm and height of 300 mm was cast. Table 3 shows the specimen description with the corresponding percentage of bamboo leaf ash BLASH and cement for each specimen preparation. A total of 36 cylindrical specimens were prepared and subjected to an experimental study. Freshly mixed concrete with bamboo leaf ash content was scooped into a mold. Each mold was filled in three layers with concrete, and each layer was rammed 25 times with a tamping rod. All specimens were cured in water for hydration periods of 14 and 28 day.

In this work, the initial curing conditions that affect the chloride resistance of concrete were carefully performed in a curing tank with samples completely immersed in the curing media for the target hydration periods. The curing conditions of concrete influence the hydration process.

Table 3. Description of Specimen for Corrosion Acceleration

Specimen ID No.	BLA Content (%)	Dimensions (mm)	Reinforcement Diameter (mm)
I-1	0		
I-2	10		16
I-3	15		
I-4	20		
II-1	0		
II-2	10	150 diameter – 300 height	20
II-3	15		
II-4	20		
III-1	0		
III-2	10		25
III-3	15		
III-4	20		

Specimens were grouped with three (3) different diameters of the steel reinforcement: 16 mm, 20 mm, and 25 mm deformed rebars. Each reinforcement, without confinement, was placed in the midst of a cylindrical specimen, as shown in Figure 4, a detail of cast specimens. After 24 h, the cast specimens were de-molded and immersed in potable water for curing. All specimens were subjected to water immersion curing for 28 days, based on ASTM C192. Figure 5 shows a schematic of the cylindrical specimen. All 12 specimens were prepared and subjected to accelerated corrosion.

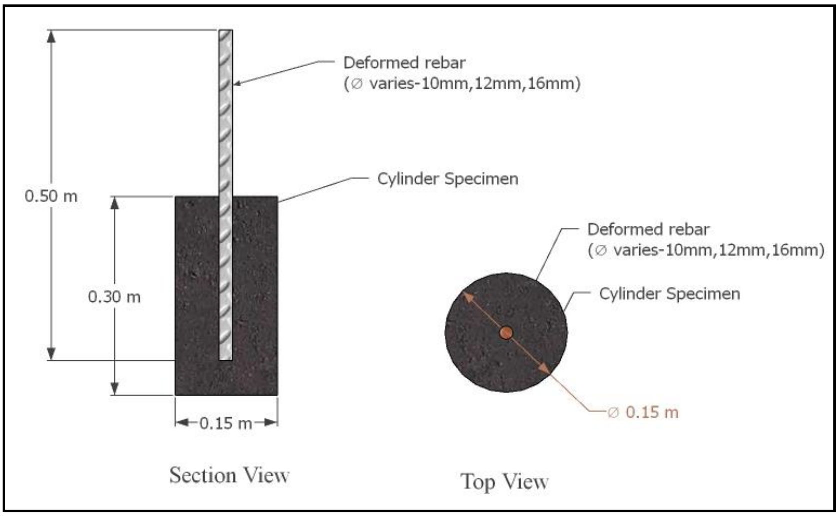

Figure 4. Detail of Specimen

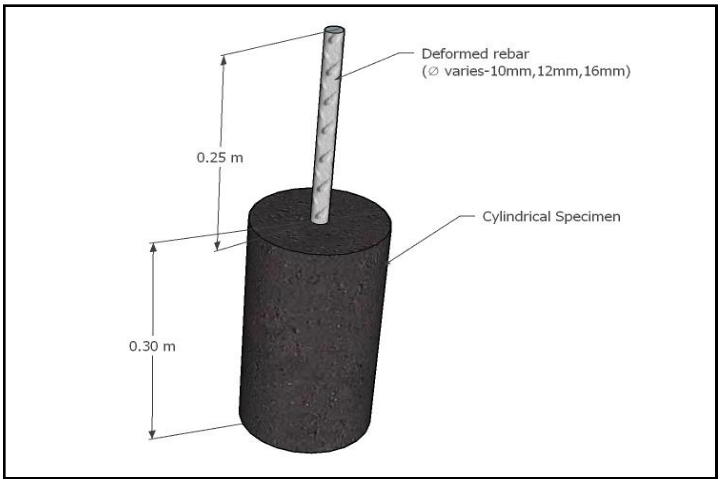

Figure 5. Scheme of a Concrete Cylindrical Specimen

2.5. Accelerated Corrosion Program

The galvanostatic method was used to accelerate the reinforcement corrosion with a constant current density of 50 Ampere/cm^2. After 28 days of curing, the sample specimens were partially immersed in a 5% NaCl solution as a simulated environment for a period of 1 month. Every other day, the specimens were subjected to acceleration for 30 min. In the galvanostatic method, the wire is connected to the positive and negative poles. Figure 6 shows a scheme for accelerating the corrosion of cast specimens.

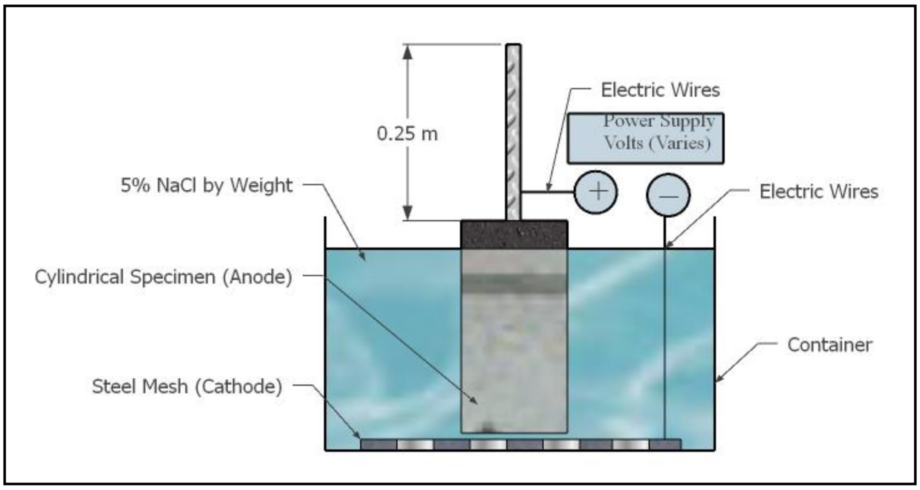

Figure 6. Illustrations of Accelerating Corrosion of Specimens

2.6. Compressive Strength Test

Specimens with different cement-bamboo leaf ash mixture contents were subjected to compressive strength tests. The descriptions are presented in Table 4. A total of 16 cylindrical specimens with a designed mixture of 28 MPa for 28 periods were cast. After 7 and 28 days of water curing, it was tested using a calibrated universal testing machine (UTM).

Table 4. Description of Specimen for Compressive Strength Test

Designation of Samples	Dimension (mm)	Content		Age (Days)	
		Cement (%)	BLA (%)	7	28
CT-A	150 diameter – 300 height	100	0	2	2
CT-B		90	10	2	2
CT-C		85	15	2	2
CT-D		80	20	2	2

2.7. Acid Resistance Test

After 28 days of curing in water, the cast specimen was immersed in a 5% sulfuric acid H_2SO_4 solution. All edges and surfaces were maintained without crack-up and immersed in water for a period of 10-days. Before the specimen was immersed in an acid solution, the weight of the specimen was measured. After 10 days, the cylinder was removed and weighed again to determine the weight loss due to acid penetration. The compressive strength of each specimen was determined before and after chemical testing. Descriptions are presented in Table 5.

Table 5. Description of Specimen for Acid Resistance Test

Designation of Samples	Dimension (mm)	Content		QTY
		Cement (%)	BLA (%)	
ART-A	150 diameter – 300 height	100	0	2
ART-B		90	10	2
ART-C		85	15	2
ART-D		80	20	2

2.8. Tensile Strength Test

After the specimen was subjected to an acceleration program, the concrete specimen was crushed and the steel reinforcement bar was removed. The steel reinforcement rebars were weighed before and after the acceleration. The steel reinforcement was subjected to tensile strength testing.

2.9. Calculating Parameters

The weights of the rebars before and after corrosion acceleration are tabulated. Area reduction was determined using the weight of the corroded bars.

$$A_{cs} = W_f / (L x \gamma_{iron}) \quad (1)$$

Where:

A_{cs} = Actual area of corroded reinforcement bar (mm^2);

W_f = weight of reinforcement after corrosion, and rust removed (g);

L = Length of the specimen (mm);

γ_{iron} = 0.00785 g/mm^3 (steel).

The actual mass of rust per unit surface area in accordance with ASTM G1 on rebars extracted from the concrete specimen after the accelerated corrosion test was computed as follows:

$$Mac = \frac{(W_i - W_f)}{\pi DL} \quad (2)$$

Where:

M_{ac} = actual mass of rust per unit surface area of the bar (g/cm^2);

W_i = Initial weight of the bar before corrosion (g);

W_f = Weight after corrosion (g) for a given duration of induced corrosion (t);

D = Diameter of the rebar (cm);

L = Length of the rebar sample (cm).

Rate of corrosion was determined using corrosion current density, i_{corr} :

$$i_{corr} = \frac{M_{ac}F}{EWt} \quad (3)$$

Where:

i_{corr} = corrosion current density ($\mu Amp/cm^2$);

M_{ac} = actual mass of rust per unit surface area of the bar (g/cm^2);

F = Faraday’s constant (96487 Amp-sec);

EW = equivalent weigth of steel (27.925 for steel);

t = time of accelerating corrosion (sec).

The corrosion level was expressed using the equation:

$$C_r = \frac{G_0 - G}{g_0 L} \times 100\% \quad (4)$$

Where:

G_o = is the initial weight of the reinforcement before corrosion;

G = is the weight of reinforcement after removal of the corrosion products;

g_o = is the weight per unit length of the reinforcing bar;

L = is the bond length.

2.10. Splitting Tensile Test

After curing the specimen for 7 and 28 d, the immersed specimens were removed and allowed to dry. The machine was set in the required range, diametrical lines, and dimensions of the specimen. The specimen was loaded continuously without shock at uniform rates until failure occurred, and the failure load was recorded.

The splitting tensile strength formula used was:

$$T_{sp} = 2P/\pi \, DL \tag{5}$$

Where:

T_{sp} = Splitting tensile strength

P = Applied load

D = Diameter of the specimen

L = Length of the specimen

3. Results and Discussion

The following discusses the results of the various experiments conducted to evaluate and assess the effectiveness of bamboo leaf ash as a corrosion inhibitor admixture of cement.

3.1. Compressive Strength

Figure 7 shows that the curing time and percentage content of admixtures with bamboo leaf ash are the two primary factors that influence the compressive strength of the blended cement mixtures. When the percentage content of BLASH increased, the compressive strength of the blended cement mix decreased. However, at each BLASH percentage, the compressive strength increased with an increase in the curing period. As the curing time increased, the compressive strength of the samples also increased. At 28 d of curing, the compressive strength was higher compared with the other shortest curing periods (7, 14, and 21 days). However, although the compressive strength of blended cement with BLASH content increased with time, their values were lower than those of the control specimen (0% bamboo leaf ash).

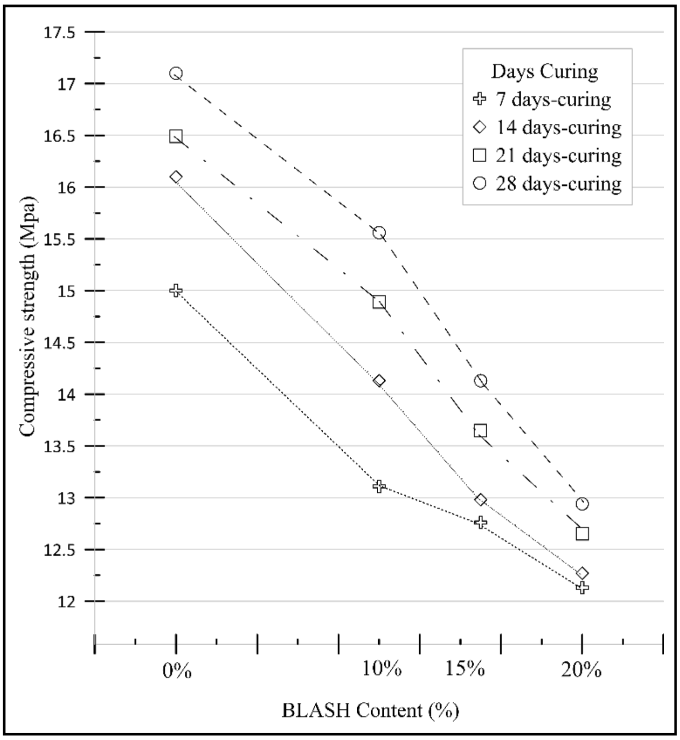

Figure 7. Correlation of BLASH content (%) with Compressive Strength

As shown in Figure 7, the compressive strength of the blended cement mixtures decreased when the percentage of bamboo leaf ash increased. The compressive strength of the mixtures with BLASH content (10, 15, and 20%) was lower than that of the control mixture with 0% BLASH content. The compressive strength of blended cement with 10% BLASH reduced the compressive strength of the cement by 10.89% (0% BLASH). The compressive strength of blended cement with 15% BLASH was reduced by approximately 17.22% compared to that of the control specimen. The compressive strength was reduced by 22.63% with 20% BLASH content in the mix compared to that of the control specimen.

Table 6. Compressive Strength of freshly Blended Cement-BLASH Mixtures

Designation of Samples	BLA Content (%)	Compressive Strength (MPa)			
		@ 7 days	@ 14 days	@ 21 days	@28 days
CT-A	0	15.00	16.10	16.49	17.10
CT-B	10	13.11	14.13	14.89	15.56
CT-C	15	12.76	12.98	13.65	14.13
CT-D	20	12.13	12.27	12.65	12.94

As shown in Table 6, a mixture with a higher BLASH content has lower compressive strength; however, it increases in the latter days of curing, usually after 21 days of curing. From the same table, it was shown that a 10% BLASH content of mixtures provides a higher compressive strength after 28days of curing, as compared with other BLASH contents (15 and 20%).

Based on the work of Dhinakaran and Chandana (2016), for 10, 15, and 20% blended cement with bamboo leaf ash, the reduction in compressive strength at 28 days was 18, 10, and 16%, respectively [33]. The reduction was significant with 10 and 20% mixtures of bamboo leaf ash admixtures, but it had only a 10% reduction in strength when using 15% bamboo ash leaf admixtures. Compared with the results obtained, 10% mixtures of bamboo leaf ash had a lower reduction in strength, with 9% only at 28 days curing period, compared to other mixtures of BLASH (15 and 20%). Furthermore, according to Dhinakaran and Chandana (2016), with 25 and 30% bamboo leaf ash, the reduction in strengths drastically increases [33]. According to a similar study by Zea Escamilla and Habert (2014), the compressive strength of cement blended with bamboo leaf ash with 5, 10, and 20% was less than that of the control mixtures by 11, 21, and 41%, respectively. The results of the experiments conducted by Zea Escamilla and Habert (2014) were approximately twice those obtained from actual experiments. In both cases, the compressive strength decreased with an increase in the bamboo leaf ash content [23]. Similar to the work of Kumar and Vasugi (2020), the compressive strengths of blended cement with 10 and 20% had minimal reductions of 1.20 and 6.70%, respectively. However, at 28 and 90 d of curing, the strength of the specimens was equal to that of the control mortar [28].

The increase in compressive strength with curing age and percentage of admixtures was confirmed by Akhtar and Sarmah (2018). when the percentage of bamboo increased from 5 to 25%, the compressive strength of the specimens decreased by 43.90 to 76% on the 7th day of curing, whereas during the 56th curing, it decreased by 20 to 70% compared to the control specimen with 0% bamboo leaf ash content [19]. In addition, similar to the findings of Ademola and Buari (2014), the compressive strength of the bamboo leaf ash-blended concrete up to 10% performed better and would be acceptable and considered as a good development for construction in any sulfate environment [15]. However, from the work of Frías et al. (2012), bamboo leaf ash blended with cement mortars showed compressive strength values that were practically equal to those of the control mortar after 28 days of curing [32]. According to Dwivedi et al. (2006), 20% bamboo leaf ash content has a compressive strength equivalent to that without ash [29]. Moreover, according to Moraes et al. (2019), all mortars with bamboo leaf ash content have the same strength as ordinary Portland cement, even after 90 days of curing [35]. However, compared to this study, 20% bamboo leaf ash had a greater reduction in strength compared to the control specimen (0% BLASH).

The reduction in compressive strength is due to incomplete hydration of the mixture of cement with BLASH at the ages of 7-14-21 days of curing. The later day`s strength increase of the mixtures with BLASH content is due to the pozzolanic reaction. Thus, more water is required for a higher percentage of BLASH content to achieve the required workability. The compressive strength at 28 d of hydration was comparable to that of the control specimen. As verified from this experimental study, 10% bamboo leaf ash-blended cement is acceptable and better than other percent content of bamboo leaf ash. Hence, concrete blended with bamboo significantly produces durable concrete mixtures, but with compromised strength. Thus, BLASH-blended cement is suitable for construction, but with a longer period of hydration or curing.

3.2. Acid Resistance

Concrete is susceptible to acid attack due to the high alkalinity of Portland cement concrete, which is why acid resistance is a desirable property for structural materials exposed in an aggressive marine environment, such as seawater. An acid attack causes the concrete to lose its strength and quickly deteriorates.

The weight reduction of the blended cement mixtures is shown in Figure 8. The control specimen (0% BLASH), once exposed to an acidic environment, showed a 0.70% reduction in weight. BLASH with 10% content had a lower weight reduction of 0.50%, and it had the highest resistance to acid attack compared with the 15 and 20% BLASH contents. With 10% BLASH content, the weight reduction was reduced to 0.50%; however, with further addition of BLASH in the mixtures, the weight reduction increased exponentially. The replacement of concrete with 10% BLASH helped to produce a mixture that enhanced the permeability of the concrete, which sealed the specimen and prevented the intrusion of acid chemicals into the produced mixtures.

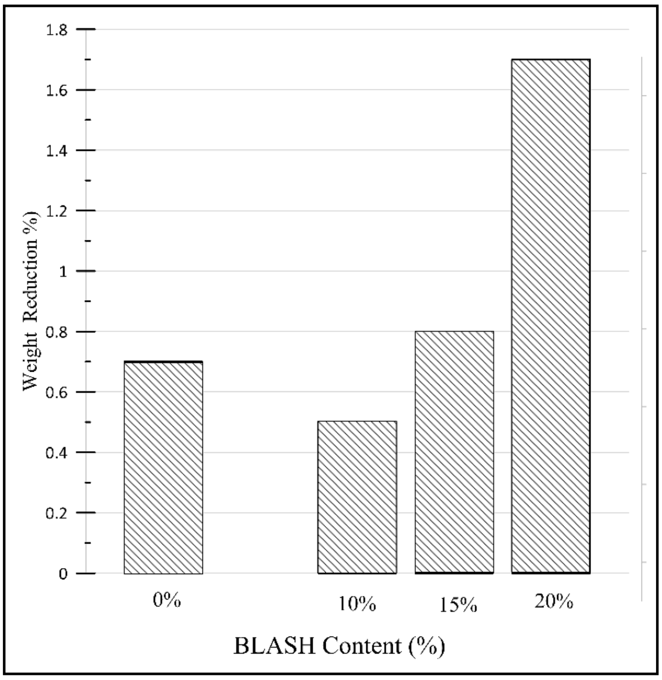

Figure 8. Weight Reduction in Acid Resistant Test

Table 7 lists the weight losses of the specimens during the acid resistance tests. The 10% BLASH content reduced the weight of the mixtures after the acid test was performed. Ten percent of BLASH mixtures signifies the right amount of admixtures with cement in order to produce structures highly resistant to the intrusion of calcium salts from marine water. This helps to lower the detrimental effects of all types of acids in structural concrete elements.

Table 7. Weight loss of Specimen in Acid Resistance Test

Designation of Samples	BLA Content (%)	Weight in Before Test	Weight in After Test	Weight Reduction (%)
ART-A	0	2.700	2.690	0.70
ART-B	10	2.675	2.630	0.50
ART-C	15	2.645	2.637	0.80
ART-D	20	2.750	2.733	1.70

Table 8. Compressive Strength after Acid Resistance Test

Designation of Samples	BLA Content (%)	Compressive Strength (MPa)		Strength Reduction (%)
		Before Acid Test	After Acid Test	
CT-A	0	17.10	15.30	10.53
CT-B	10	15.56	15.56	0.03
CT-C	15	14.13	12.20	13.66
CT-D	20	12.94	11.10	14.22

In Table 8, the compressive strengths of the samples with 0, 10, 15, and 20% bamboo leaf ash admixtures before and after the acid test are listed. As shown in Figure 9, a mixture with 10% BLASH content had a lower percent reduction in its compressive strength (0.03%) when it was exposed to acid chemicals. The 20% BLASH content has a higher percentage reduction of its compressive strength, which is 14.22%; 15% BLASH content has 13.66% reduction; and 0% BLASH a control specimen has a 10.53% reduction.

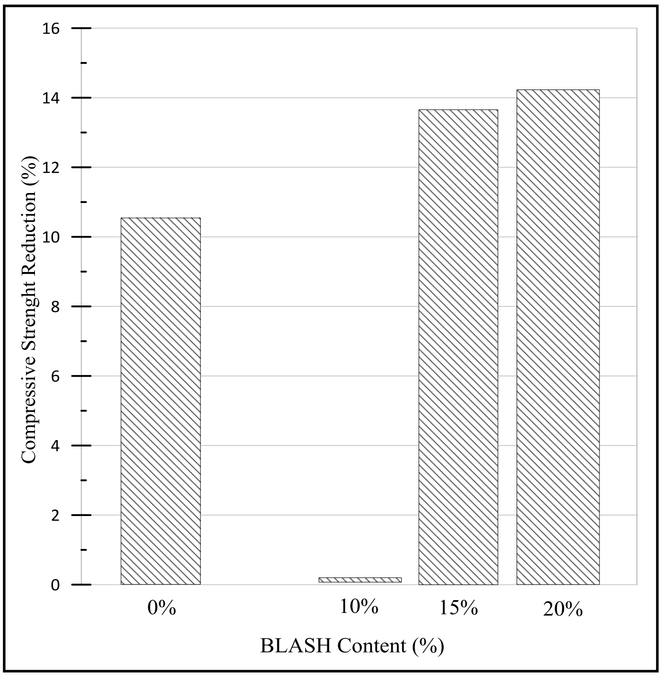

Figure 9. Compressive Strength Reduction in Acid Resistant Test

The results of this experimental study conformed to those of Andrade et al. (1991), who found that blended cement neutralizes sulfuric acid with 10% bamboo leaf ash from simulated marine water. However, with 15 and 20% bamboo leaf ash content, it triggers the corrosive property of sulfuric acid from the marine environment and reduces its compressive strength [31]. In addition, in a similar study by Zea Escamilla and Habert (2014), bamboo leaves blended with cement showed 0.60, 3, 0.50 and 2.20% reductions in strength for 0, 5, 10, and 15%, respectively [23]. Compared to the actual experiment conducted, a 10% BLASH content had the same percent reduction in strength. Kolawole et al. confirmed the results of this study. Bamboo leaf ash with a 10% admixture exhibited the highest resistance against the attack of deleterious acids. Thus, the durability of the structures can be improved by using a 10% bamboo leaf ash admixture.

3.3. Corrosion Variables

3.3.1. Mass Loss Rate

As shown in Figure 10, the two parameters affect the mass-loss rate of the embedded steel reinforcement specimens, percentage content of bamboo leaf ash, and diameter of deformed steel reinforcements. A small reinforcement (16 mm) diameter has higher loss rates compared to the two other larger reinforcement diameters (20 and 25 mm). A smaller reinforcement diameter (16 mm) is less resistant to corrosion deterioration; thus, it has a higher mass loss rate.

In each group with different reinforcement diameters (16, 20, and 25 mm), BLASH with 10% content had the lowest mass loss rates. When the amount of BLASH content increased by more than 10%, the rate of mass loss was higher than that of the control specimen (0% BLASH). Thus, when the percentage of BLASH increased further, the mass loss rate increased exponentially.

The results of experiments conducted by Alaneme et al. (2014) confirmed that an increased percentage of bamboo leaf ash leads to a decrease in the corrosion resistance of the specimens [18]. However, an accurate amount of bamboo leaf ash (10%) developed a matrix of concrete that improved its resistance against the intrusion of deteriorating elements that could alter the diameter and weight of the embedded steel reinforcement. This helps prevent the penetration of deleterious products that cause corrosion of the embedded reinforcement steel.

Specimens that have a lower resistance against corrosion deterioration have higher corrosion rates, and they have a significant reduction in mass [17]. The reduction in the cross-sectional area of steel rebars was greater with 15% and 20% BLASH content as compared with 10% content of bamboo leaf ash admixtures. Thus, the quality of the cement-blended admixtures was improved by 10% BLASH content.

The results verified that the corrosion resistance of the mixtures decreased when the amount of bamboo leaf ash increased. Furthermore, the mass loss rate is directly correlated with the rate of corrosion of the specimen [16]. However, the corrosion rates of the specimens depend on the quality of the concrete mixtures that protect the embedded steel reinforcement specimens.

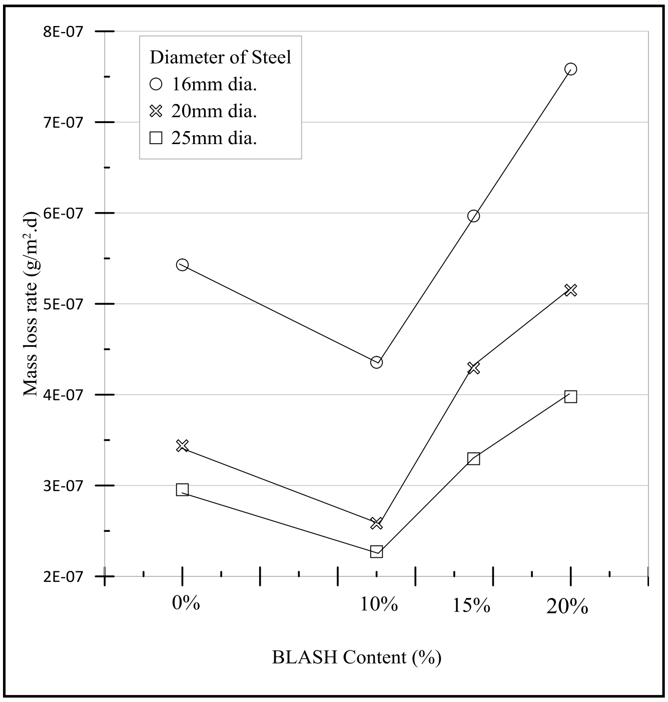

Figure 10. Correlation of Corrosion rates & BLASH content

3.3.2. Corrosion Level

In Figure 11, the blended cement mixture with 10% BLASH content has a lower corrosion level. The control sample had a maximum corrosion level of 5.74%, and 10% BLASH had a maximum corrosion level of 4.92%. With a further increase in bamboo leaf ash, 15% BLASH had a maximum corrosion level of 6.99%, and 20% BLASH had a maximum corrosion level of 9.08%.

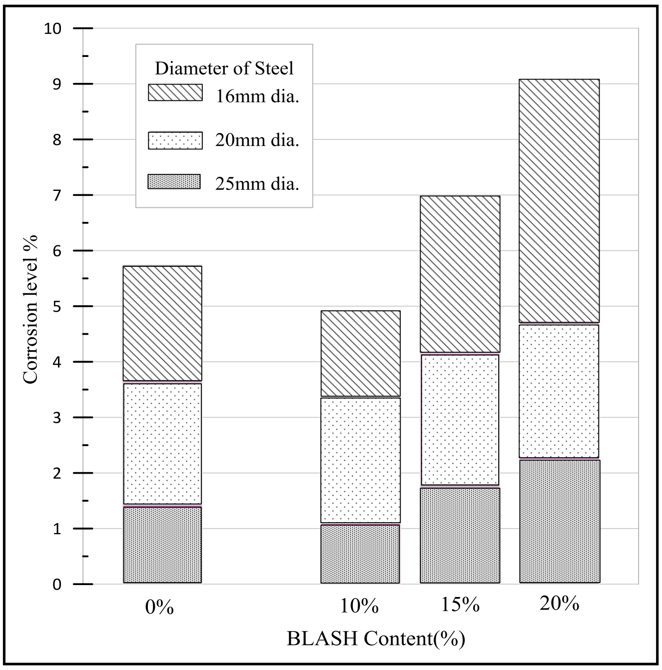

Figure 11. Correlation of BLA content & Corrosion level

A mixture with 10% BLASH content had a lower corrosion level than the other BLASH contents (15 and 20%). Cement blended with 10% bamboo leaf ash developed a mixture that has a lower permeability because a mixture has a higher resistance against ingress of deleterious substances that cause corrosion deterioration of the embedded reinforcement steel. The 10% bamboo leaf ash admixtures enhanced the quality of mixtures of the blended cement by reducing its permeability, and it was evident that the lower corrosion levels were acquired for each specimen with different deformed steel reinforcement diameters. This reveals that a good quality mixture enhanced by using 10% bamboo leaf ash admixtures provides perfect protection for the embedded steel reinforcement owing to the reduced corrosion level of the specimens compared to other samples with a higher percentage of bamboo leaf ash.

Table 9. Interpretation of Corrosion rates [38]

Corrosion rate (mm/yr)	Degree of corrosion
<0.00001	Insignificant (passive)
<0.001	Low
0.001-0.01	Moderate
0.01-0.03	High
>0.03	Very high

** 1micrometer = 0.001 mm*

Montemor et al. (2000) provided a criterion for determining the degree of corrosion. Table 9 presents an interpretation of on the corrosion rates. Control specimens (0% BLASH) with corrosion rates from 0.00137-0.0035 mm/year were categorized as moderates in corrosions; 10% BLASH with corrosion rates from 0.00105-0.0030 mm/year, 15% BLASH with corrosion rates from 0.00169-0.00428 mm/year, and 20% BLASH with corrosion rates from 0.00217-0.00555 mm/year, were considered moderate corrosion. As shown in Table 9, a specimen with a higher corrosion rate can be predicted as be at more risk of its deterioration [38].

3.4. Crack Indices

3.4.1. Crack Width

As shown in Figure 12, the 10%-BLASH content had negligible crack widths in the 16, 20, and 25 mm diameter deformed steel reinforcements, respectively. 0%-BLASH has a wider crack width (0.31 mm), 15%-BLASH has 0.003 mm crack widths, and 20%-BLASH has 0.003 mm cracks.

A mixture of 10% bamboo leaf ash admixtures helped to limit the width of the cracks formed on the surface of the concrete. A mixture of 10% bamboo leaf ash enhanced the bonds of finer particles that constituted the blended concrete mix. It helps to resist the formation of hairline cracks, which could be a pathway for the deleterious elements to penetrate the concrete surface.

According to Dacuan and Abellana (2020), a wider crack width accelerates the ingress of deleterious substances into the concrete surface. This leads to a faster deterioration in the corrosion of steel reinforcements [17]. As shown in Figure 12, mixtures of cement with more than 10% bamboo leaf ash content are more prone to deterioration because they have wider crack widths.

Furthermore, according to Dacuan and Abellana (2021), the width of the crack due to corrosion has a linear correlation with the corrosion level. High corrosion levels lead to a significant amount of rust products that push the surface of the concrete, resulting in wider cracks on its surface [9].

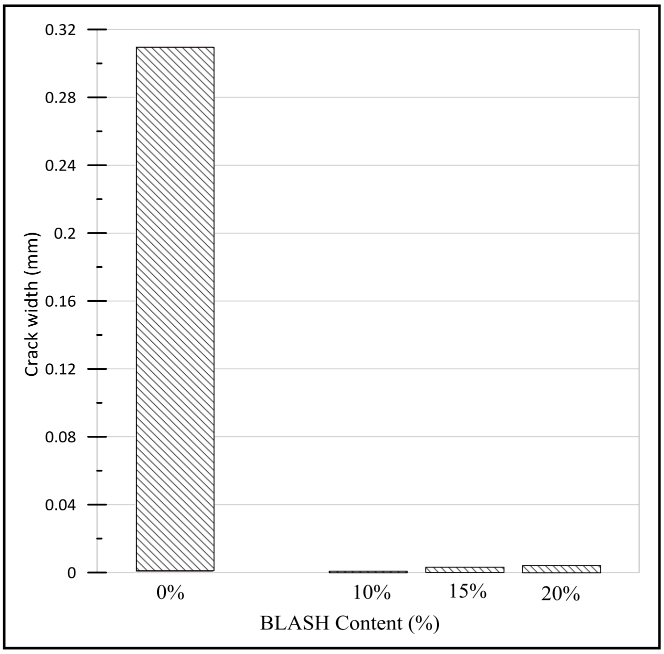

Figure 12. Correlation of BLASH content with Crack Width

3.4.2. Crack Frequency

As shown in Figure 13, 0%-BLASH had the highest number of cracks frequency, with a maximum of 52 crack formations; 15%-BLASH has 20 cracks, and 20%-BLASH has 25 cracks. Cracks were formed using a 10% BLASH. A mixture of 10% bamboo leaf ash enhances the quality of the mixtures by which the formation of hairline cracks resists. Crack formation was not detected in the specimens with 10% BLASH. However, increasing the amount of bamboo leaf ash in concrete mixtures leads to the formation of fewer cracks on the concrete surface. As shown in Figure 13, a mixture of bamboo leaf ash prevents the formation of cracks. Bamboo leaf ash admixtures reduced the number of cracks formed on the concrete surface. The specimen with ordinary Portland cement has a significant number of cracks on the concrete surface, as shown in the same figure.

Although the diameter of the steel reinforcement affects the formation of cracks, it was verified that a mixture of blended cement with admixtures that covers up to protect the embedded steel reinforcement significantly affects the deterioration of reinforced concrete structures. A quiet consideration should be given to the quality of the mixtures used in the construction with cement admixtures. This reveals that an accurate percentage of bamboo leaf ash admixtures enhances the quality of the mixtures, which improves their permeability and pore spaces. The 10% bamboo leaf ash content significantly enhanced the concrete blended mixtures by reducing the crack formation on its surfaces.

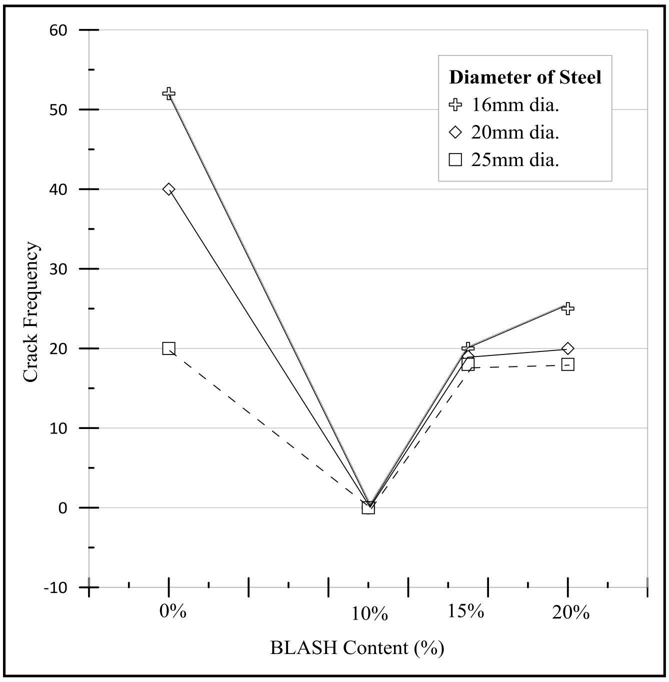

Figure 13. Correlation of BLASH content with Crack Frequency

3.5. Bond Strength

The bond strength of concrete and steel reinforcement is influenced by the quality of the mixtures, and the sizes of the main reinforcement used. A larger reinforcement diameter (25 mm) has a higher bond strength than a smaller reinforcement diameter (16 and 20 mm).

As shown in Figure 14, a mixture with 10% BLASH content has a higher bond strength, which is consistent for the three groups of steel reinforcements of different sizes. The 10% BLASH content significantly enhanced the bond strength between the particles in the mixtures. The higher bonds that develop in the mixtures of blended cement help to resist the penetration of deleterious elements and protect the reinforcement steel against corrosion deterioration.

According to Dacuan and Abellana (2021), the corrosion of steel reinforcement leads to a reduction in the bond strength between the steel and concrete interface [9]. However, it is a blended mixture of concrete that provides significant protection to the steel reinforcement and maintains the bond strength between the surfaces of two materials, steel and concrete elements. Although steel, which has a higher corrosion resistance, is used when it is exposed to deleterious substances owing to the poor quality of mixtures, deterioration of concrete structures will still occur. Thus, a 10% bamboo leaf ash admixture helps to develop a strong bond between steel and concrete by reducing the permeability of the mixtures and prohibiting the ingress of chloride ions.

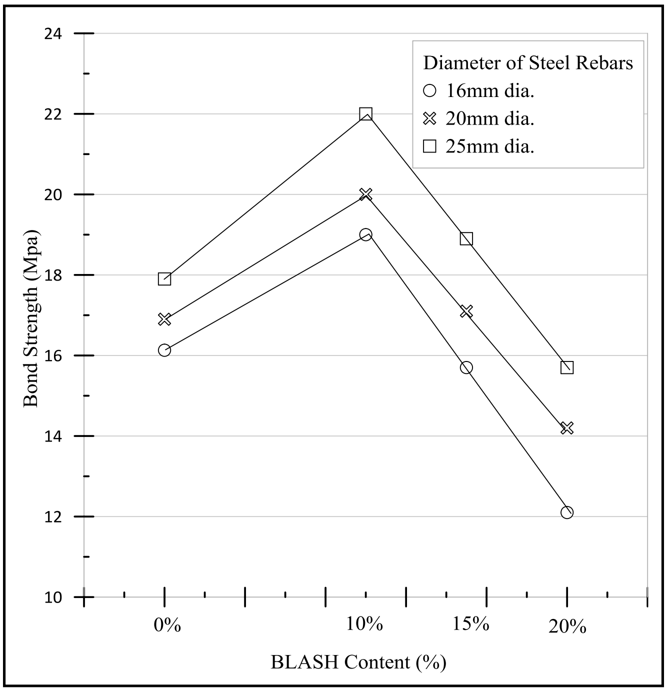

Figure 14. Correlation of Bond Strength and BLA content

3.6. Durability

Corrosion formation leads to an alteration in the yield strength of the steel reinforcement rebars. The reduction in the steel cross-sectional area led to a reduction in the strength of the steel rebar. It was used to estimate the residual strength of steel reinforcement. A normalized cross-sectional area, which is the ratio of the corroded cross-sectional area to its original area, was used to determine the residual strength of the corroded reinforcement structures in terms of its rebar cross-sectional area.

$$R.S = A_{st} / A_o \tag{6}$$

Where: R.S = Residual strength; A_{st} = Area of the rebar at time t (years); A_0 = Area before corrosion (t_0=0).

$$A_{st} = \frac{n\pi}{4}[\varphi - r_{corr}(t - t_0)]^2 \tag{7}$$

Where: φ = Diameter of the rebar; n = Number of bars in a layer; r_{corr} = Rate of corrosion in terms of penetration rate (mm/year); t = Time of corrosion (years); t_0 = Corrosion initiation time.

Table 8. Residual Strength of Corroded Rebars (16 mm-diameters)

t (years)	Residual Strength (%)			
	BLA-0%	BLA-10%	BLA-15%	BLA-20%
0	100	100	100	100
10	99.68	99.75	99.65	99.56
20	99.37	99.49	99.31	99.12
30	99.06	99.24	98.96	98.68
40	98.74	98.99	98.62	98.24
50	98.43	98.74	98.27	97.81
60	98.11	98.49	97.93	97.37
70	97.80	98.23	97.59	96.94
80	97.49	97.98	97.24	96.50
90	97.18	97.73	96.90	96.07
100	96.87	97.48	96.56	95.64

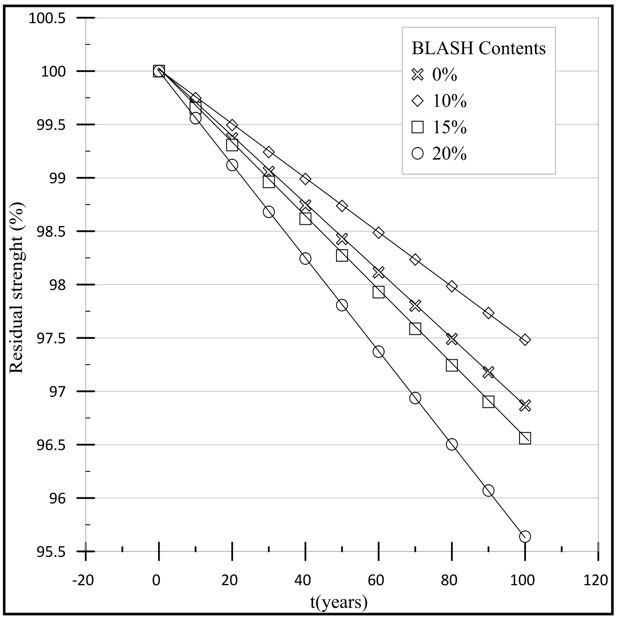

Figure 15. Influence of BLASH Content to Residual Strength (16 mm diameter)

Table 9. Residual Strength of Corroded Rebars (20 mm-diameters)

t (years)	Residual Strength (%)			
	BLA-0%	**BLA-10%**	**BLA-15%**	**BLA-20%**
0	100	100	100	100
10	99.84	99.88	99.80	99.76
20	99.68	99.76	99.60	99.52
30	99.52	99.64	99.40	99.28
40	99.36	99.52	99.20	99.04
50	99.20	99.40	99.00	98.81
60	99.04	99.28	98.81	98.57
70	98.88	99.16	98.61	98.33
80	98.72	99.04	98.41	98.09
90	98.57	98.92	98.21	97.86
100	98.41	98.80	98.01	97.62

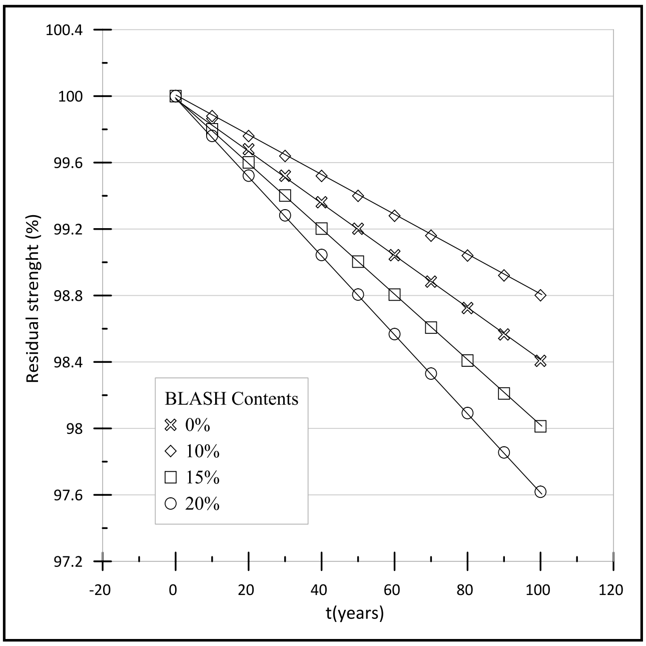

Figure 16. Influence of BLASH Content to Residual Strength (20 mm diameter)

Table 10. Residual Strength of Corroded Rebars (25 mm-diameters)

t (years)	Residual Strength (%)			
	BLA-0%	**BLA-10%**	**BLA-15%**	**BLA-20%**
0	100	100	100	100
10	99.84	99.88	99.80	99.76
20	99.68	99.76	99.60	99.52
30	99.52	99.64	99.40	99.28
40	99.36	99.52	99.20	99.04
50	99.20	99.40	99.00	98.81
60	99.04	99.28	98.81	98.57
70	98.88	99.16	98.61	98.33
80	98.72	99.04	98.41	98.09
90	98.57	98.92	98.21	97.86
100	98.41	98.80	98.01	97.62

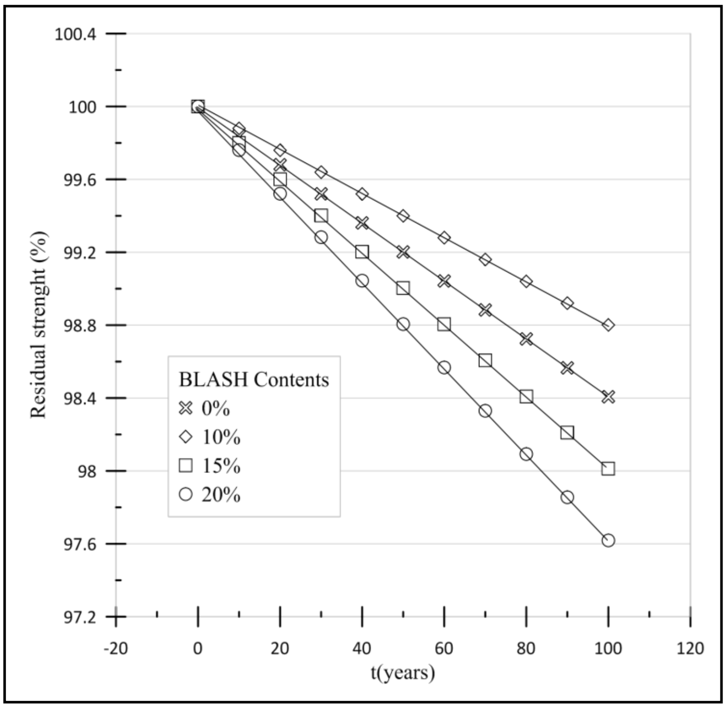

Figure 17. Influence of BLASH Content to Residual Strength (25 mm diameter)

Tables 8, 9, and 10 list the residual strengths of the corroded rebar for deformed steel diameters of 16, 20, and 25 mm, respectively. Figures 15 to 17 illustrate the residual strengths of each deformed rebar with different percentage mixtures of bamboo leaf ash admixtures. It was verified from all figures that for all sizes of steel reinforcement diameters, 10% bamboo leaf ash admixtures have a lower reduction in their residual strength once they are afflicted with corrosion deterioration of the steel reinforcement used. The addition of 10% bamboo leaf ash admixtures significantly lengthened the time required for the initiation of corrosion and propagation.

The overall results indicate that the strength of mixtures blended with bamboo leaf ash increases gradually up to 10%, but there is a reduction in strength of 15 and 20% due to extension in the initial and final settings and a quick loss of workability. The results proved that a 10% replacement of cement by BLASH was the optimum percentage for obtaining maximum strength values.

The results were confirmed by Zea Escamilla and Habert (2014), durability significantly improved with 10% replacement of cement with bamboo leaf ash BLASH [23]. The durability of mixtures with a 10% bamboo ash admixture was enhanced by reducing the permeability of the mixtures blended with an accurate amount of admixtures, thus strengthening its resistance against the attack of deleterious elements such as acid and chloride ions. Generally, the replacement of ordinary Portland cement with bamboo leaf ash improves the physical and mechanical properties of mixtures, and the durability is enhanced.

4. Conclusions

The following were the conclusions:

- The compressive strength of the blended cement mixtures decreased as the percentage of bamboo leaf ash BLASH increased. However, as the curing time increased, the compressive strength of the samples also increased.
- The replacement of concrete with 10% BLASH helped to produce a mixture that enhanced the permeability of the concrete, which sealed the specimen and prevented the intrusion of acid chemicals into the mixtures.
- When the amount of BLASH content increased by more than 10%, the rate of mass loss was higher than that of the control specimen (0% BLASH).
- The 10%-BLASH had negligible crack widths, both in 16, 20, and 25 mm diameter steel reinforcements. 0%-BLASH has a wider crack width (0.31 mm), 15%-BLASH has 0.003 mm crack widths, and 20%-BLASH has 0.003 mm cracks.
- A larger reinforcement diameter (25 mm) has a higher bond strength than a smaller reinforcement diameter (16 and 20 mm). The quality of the mixtures significantly affected the bonding between cement and steel. The 10% BLASH content has a higher bond strength, which is consistent for the three groups of steel reinforcements of different sizes.
- The overall results of the mechanical strength properties indicate that the strength values increase gradually up to 10%, but for 15 and 20%, there is a reduction in strength values due to extension in initial and final settings and quick loss of workability. The results proved that a 10% replacement of cement by BLASH was the optimum percentage for obtaining maximum strength values.

5. Declarations

5.1. Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in article.

5.3. Funding

The study was funded by ERDT-DOST in the School of Engineering at the University of San Carlos.

5.4. Acknowledgements

The authors acknowledge the graduate scholarship funding from ERDT-DOST at the School of Engineering at the University of San Carlos.

5.5. Conflicts of Interest

The authors declare no conflict of interest.

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