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# Utilization of Sugar Mill Waste Ash as Pozzolanic Material in Structural Mortar

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**Abstract:** Bagasse is produced as a waste in the sugar production process, which is used as fuel to stoke boilers in the sugar mills. The concluding product of this burning is residual sugarcane bagasse ash (BA), which is normally dumped or used as low-quality fertilizer. The ash for this study was collected from a reputed sugar mill located in the northern region of Bangladesh. Type I Portland cement (PC) was partially replaced with that finely ground bagasse ash without any pretreatment. The ground BA was used as a replacement for Portland cement at 5, 10, 15, 20, 25 and 30% of BA, respectively, in structural mortar. In addition, chemical characterization, specific gravity, X-ray diffraction (XRD), scanning electron microscopy (SEM), setting time, a strength activity index, compressive strength, water absorption, density and durability in a chloride environment of mortar were determined. The strength activity index result indicates that the used BA has the pozzolanic properties to be used as a partial cement replacement. The results showed that, at the age of 56 days, the mortar samples containing 5–15% ground bagasse ash had higher compressive strengths than the control mixture (mortar without ground bagasse ash). Mortar containing 15% ground bagasse ash had the highest mechanical and durability properties. Therefore, the substitution of 15% BA is acceptable for producing good quality structural mortar in the civil engineering construction field except in chloride environments.

**Keywords:** bagasse ash; pozzolanic material; cement; structural mortar

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## 1. Introduction

Since the beginning of human civilization, people have utilized different materials to build their houses. With the start of the Industrial Revolution, the progressive use of cement binder started to make the buildings stronger and durable [1]. Cement is a fundamental element to produce concrete and mortar. The emission of carbon dioxide is the biggest problem in the cement manufacturing process [2]. Large amounts of carbon dioxide are leading to increasing global warming [3,4]. From cement plants alone, the overall rate of global carbon dioxide emission is almost 7% [5]. This necessitates the use of alternative products as supplementary cementitious ingredients in cement manufacturing. It helps to bring significant reductions in carbon emissions.

Supplementary cementitious materials (SCMs) can be produced from a wide variety of waste products, including those from agriculture, industry, municipalities and even from natural waste [1]. Different SCMs come from the waste of both industrial and agro-industrial sources. Industrial waste-based SCMs are fly ash, ground granulated blast-furnace slag, bottom ash, silica fume, limestone powder, etc. SCMs from agricultural waste, such as palm oil fuel ash (POFA), rice husk ash (RHA), sugarcane bagasse ash (BA), etc., are widely used in construction research [1,6]. The application of these industrial wastes as SCMs could contribute to appropriate waste management and reduce a large quantity of fossil fuel burning. SCMs are well known for their capabilities to improve suitable material properties, such as flowability, strength and durability [5,7].

Countries such as India and Bangladesh grow plenty of sugarcane to produce sugar. Bangladesh produced approximately 3.2 million tons of sugarcane in 2019 alone [8]. While utilizing sugarcane to produce sugar, the mills also generate over 800,000 tons of bagasse, a leftover material from sugar mills after juice extraction, each year [9]. Bagasse ash is a sugar mill waste that is obtained from the burning of bagasse waste. Figure 1 reveals the step-by-step process of bagasse ash production from a sugar mill. The ash from bagasse is about 0.6 to 0.7 percent of the weight of the sugarcane [7,10].

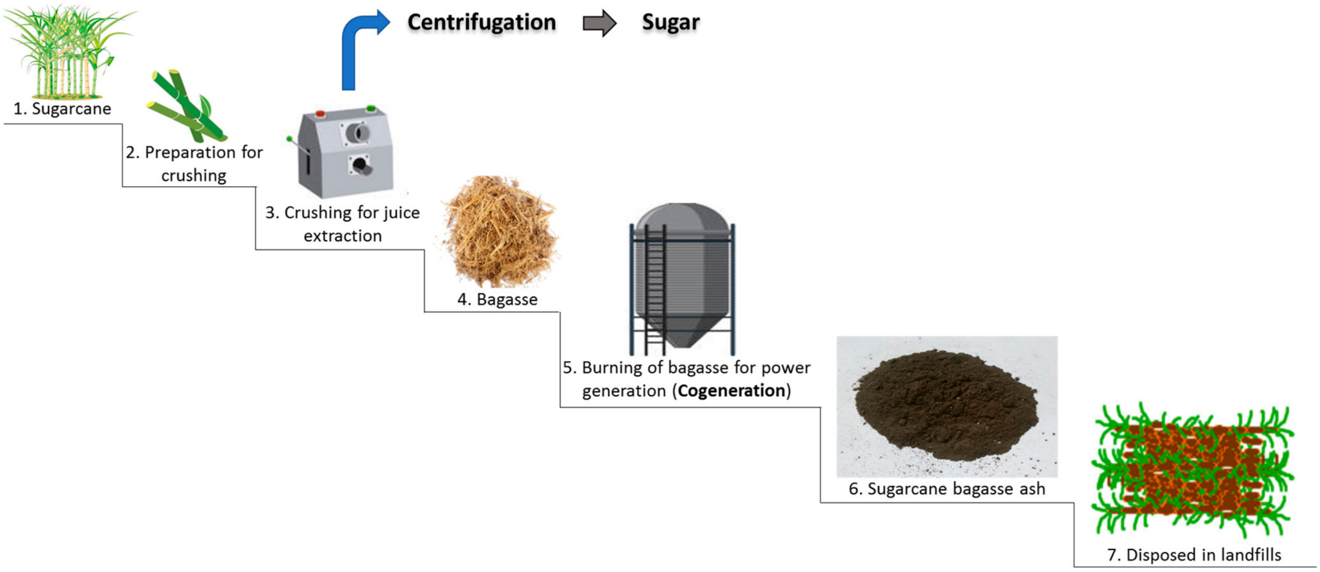


**Figure 1.** Steps of sugarcane bagasse ash production.

Nowadays, excess amounts of bagasse ash are dumped into landfill sites, which is a major threat to the environment [11]. Nowadays, this ash is largely disposed to landfills in Bangladesh. Currently, Bangladesh's sugarcane sector is looking for better ways to dispose of the waste generated during the sugar production process [12]. Figure 2 highlights the key problems that occur due to the lack of the proper disposal of BA. Furthermore, there is no environmentally friendly way to dispose of ash to landfills. Thus, an alternative method of utilizing this ash needs to be investigated.

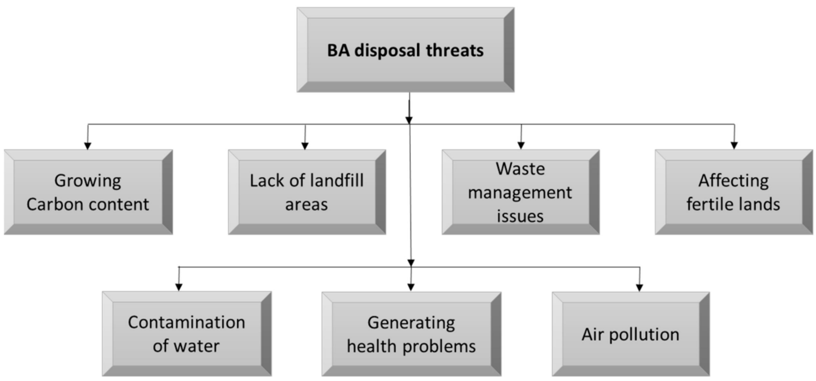


**Figure 2.** Problems associated with disposal of bagasse ash.

Sugarcane bagasse ash (SCBA) can be utilized as a substitute for traditional building materials, such as cement or sand. According to the findings of numerous studies, SCBA has the potential to be utilized as a supplementary cementitious material, thereby resolving the environmental concerns related with its disposal [7,11,13]. Even though it costs as much as fly ash, using bagasse ash can reduce its negative effects on the environment and the amount of trash in landfills. Meanwhile, bagasse ash shows excellent pozzolanic properties for making ceramic products due to its light weight, high strength, durability and workability. It contains a significant amount of silica (87%) and is, therefore, beneficial as an SCM [13].

SCBA is produced in an uncontrolled manner in sugar mill boilers. The interaction of the amorphous or partially crystalline active phases (silica and alumina) with the carbon concentration during the calcining process is what determines the quality of SCBA. It is generally anticipated that the burning of ashes under regulated conditions is required to get high pozzolanic characteristics. The key factor influencing SCBA quality is how the calcining process interacts with the amorphous or partially crystalline active phases (silica and alumina), as well as the carbon concentration [7]. SCBA with a high amount of amorphous silica and a low loss-on-ignition can be produced by burning the bagasse at the optimal time, heating rate and temperature. SCBA's chemical composition can be altered, according to some research, by re-calcining it, particularly to reduce the amount of carbon present [14]. Grinding is required in addition to burning to make SCBA particles more consistent and help regulate their particle sizes. Therefore, various methods of grinding have been investigated in order to increase the surface area of SCBA, which ultimately results in greater pozzolanic activity [10].

The high burning temperature and incomplete combustion in boilers reduce the reactivity of ash, resulting in a high carbon content and the presence of crystalline silica [15,16]. Due to its inherent properties, such as a high proportion of silica in the form of quartz, which is one of the primary components of natural sand, SCBA has been shown to be useful even in its low-reactivity condition for application in construction [17,18].

In high-performance concrete, the addition of pozzolanic minerals as mineral admixtures increases both the concrete's strength and durability. The mechanical properties of the concrete composition are improved when pozzolanic materials are added to cement because the silica ($SiO_2$) in these minerals reacts with the free lime produced during cement hydration to form more calcium silicate hydrate (C-S-H) as new hydration products [13,19]. The controlled burning of agricultural waste at temperatures below 700 °C causes ash to transition into amorphous silica. The specific surface area of the ash directly relates to the amorphous silica's reactivity [6,20]. When the ash reaches the desired degree of fineness, it is either ground into a powder or pulverized before being combined with cement in a cementitious mix. As a result, the characteristics of agricultural ash are determined by the burning time, the burning temperature it reaches, the time taken to cool down and the grounding process [11]. Therefore, uncontrolled burning, normally performed in agro-industries, affects the production of high-quality amorphous silica.

Even though Bangladesh produces a lot of BA during the harvesting season, its environmentally friendly disposal is still a great problem. The produced BA is mostly disposed to open landfill and thus may cause health and environmental hazards. The purpose of this research is to identify the properties of the sugar mill-produced BA as an alternative construction material. Therefore, this study aims to determine whether it is possible to use uncontrolled burned BA as a supplementary cementitious material in terms of fresh, mechanical and short-term durability of structural mortar. Even though this study was undertaken from a local perspective, its results can also be implemented globally as a sustainable solution in other countries (such as Brazil, India, Thailand, China, Pakistan, Mexico, etc.) that produce approximately 1,889,268,880 tonnes of sugarcane annually.

Identification of Structural Mortar

Mortar is a type of material that is made up of fine aggregate, a binding material such as cement or lime and the appropriate amount of water [15]. It is applied as a paste and then hardens when used to join masonry or other structural parts. Mortar strength is not important while it is being used for plastering or rendering. In some contexts, mortar is frequently used in construction works where it involves load bearing [21]. The term "structural mortar" refers to a type of mortar that is used in situations when it is required to provide strength and resist some external forces [21]. In circumstances such as these, the effectiveness of the entire construction is directly influenced by the cohesiveness of the mortar. In most cases, it is preferable to have a higher strength of such mortar. The required compressive strength of structural mortar for various applications is outlined in Table 1. When it comes to getting structural mortar to have the appropriate qualities and a decent mix design, BA can be a helpful alternative material to be used as an SCM.

**Table 1.** Strength criteria for structural mortar in accordance with various codes.

| Codes | Purpose | Minimum 28 Days Strength (MPa) |
|---|---|---|
| ASTM C270-14a, 2014 [22] | Masonry work (Type M) | 17.2 |
| EN 1504-3, 2006 [23] | Structural repair (Class R3) | 25 |
| Florida Department of Transportation, 2017 [24] | Concrete repair | 27.6 |
| ACI 549.1R-93, 1993 [25] | Thin reinforced cementitious products | 35 |
| EN 1504-3, 2006 [23] | Structural repair (Class R4) | 45 |

Improving the fresh properties of structural mortar, as well as its mechanical properties after it has been hardened, can be accomplished by using an appropriate amount of BA. This leads to get a way to make best use of BA waste in construction. Based on the above discussions and the strength requirements given by the various codes, it is expected that a mortar mix will be referred to as structural mortar when it exceeds 25 MPa. Therefore, BA-incorporated mortar should achieve a strength higher than 25 MPa.

## 2. Experimental Program

The entire experimental program was divided into two parts following standard testing procedures. The initial stage involved identifying the characteristics of BA, including its physical characteristics and chemical composition. On the other hand, the majority of the mechanical properties of structural mortar were investigated in the second stage. The initial and final setting times, water absorption, density, compressive strength, and strength and mass loss in a chloride environment were investigated under the mechanical properties of mortar with BA.

## 3. Materials and Methodology

### *3.1. Materials Used*

Ordinary Portland cement (OPC), standard river sand and Ottawa sand, bagasse ash (BA) and normal water were the main materials for conducting the experimental tests. For all the mortar mixtures, ordinary Portland cement (OPC) was utilized according to ASTM C-150 and ASTM C618-05 standards [26,27].

Locally available standard river sand was used to prepare the structural mortar, whereas Ottawa sand was used for strength activity index (SAI) test as fine aggregate. Dry and ground BA was mixed with cement as the supplementary cementitious material for the preparation of mortar. The mortar was mixed with potable tap water, free from oil, sugar impurities and chlorides. No superplasticizer or additives were used during the preparation of mortar.

### *3.2. Collection and Processing of Bagasse Ash*

Annually, Bangladesh produces a lot of sugarcane. Most of the commercial sugar mills are in the northern part of Bangladesh. BA was collected from one of these sugar mills. The mill authorities only use it for filling the landfills and other purposes. Figure 3 clearly representing that there is no planned way of disposing the bagasse, even before it is used for cogeneration. From the figure, it is quite obvious that there is no specific plan or utilization scheme for the BA after being disposed. Figure 4 shows the raw BA which was collected from the sugar mill.

**Figure 3.** Disposal site of bagasse ash (BA).

**Figure 4.** Raw bagasse ash (BA) collected from sugar mill.

The burning process of the ash in the mill was uncontrolled, and the color of the ash was black due to the existence of carbon. The raw BA contains some dust and other materials which are not suitable for direct use in a cementitious matrix as supplementary materials. There needs to be more refining and grinding for utilization in cement-based composites. Figure 5 represents the step-by-step process of utilizing BA in cement-based construction work. The raw ash was ground in a Los Angeles ball mill until it became as fine as cement particles that could pass through a 45 μm-opening sieve. The unburned bigger carbon particles were removed by sieving (sieve #325). Particle size distribution curves of ground BA and cement are shown in Figure 6. It is clear that particle size distributions are more even and smaller in BA compared to OPC.

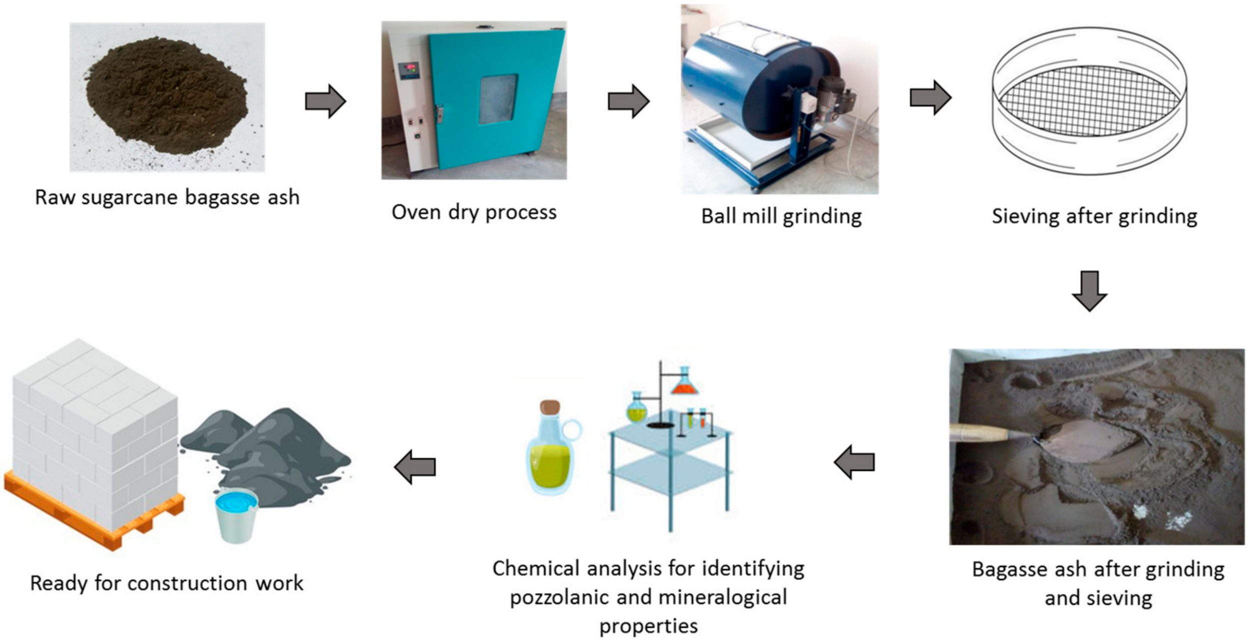


**Figure 5.** Simple process of utilizing sugarcane BA in construction industry.

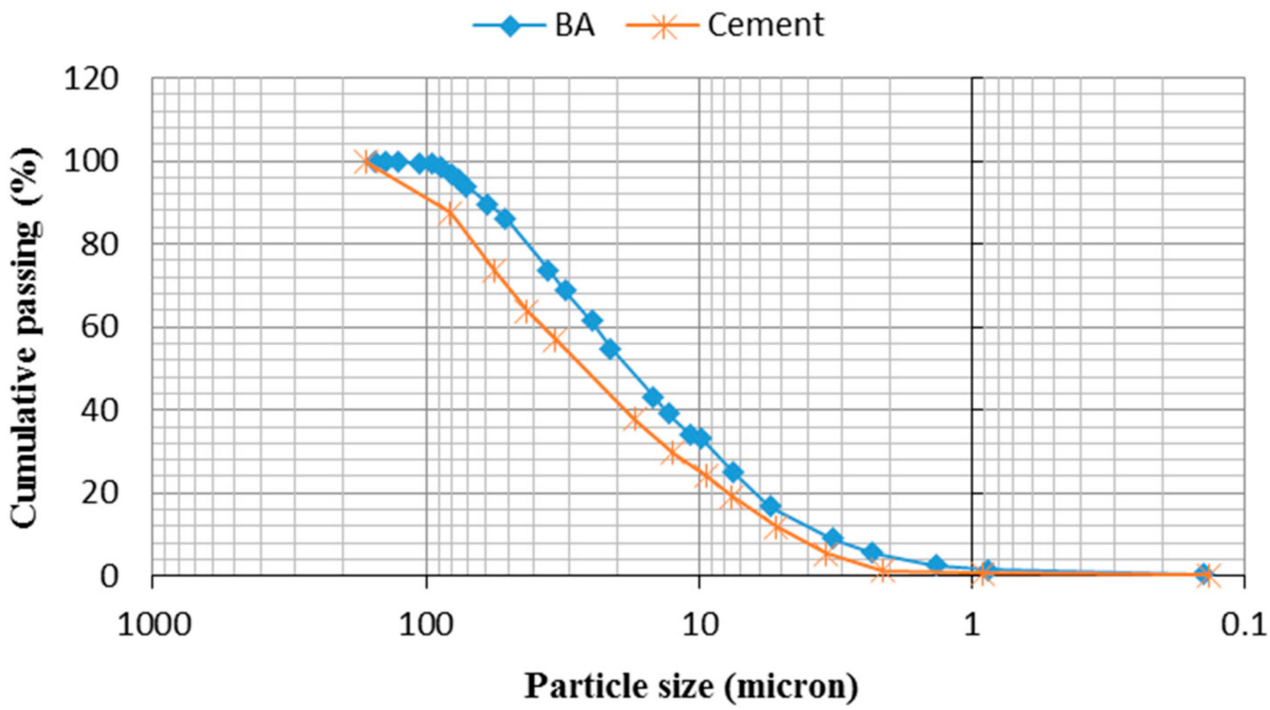


**Figure 6.** Particle size distribution of ground BA and cement.

*3.3. Characterization of BA*

3.3.1. Physio-Chemical Analysis of BA

The specific gravity of finer BA was characterized as per IS 4031 (Parts)-1995 [28], and fineness of OPC and BA were calculated according to IS 1727-1995 [29]. Table 2 provides an illustration of the physical characteristics of BA and cement as taken from the suppliers.

**Table 2.** Physical properties of OPC and BA.

| Materials | Specific Gravity | Fineness Passing 45 μm Sieve |
|---|---|---|
| OPC | 3.3 | 88 |
| BA | 1.87 | 97 |

The detailed chemical composition of cement and processed BA is provided in Table 3. The chemical compositions are well matched with the code requirements as per ASTM C618 [27]. The chemical analysis data show that BA has more than three times higher silica content than OPC. Alongside with good silica content, BA also contains significant amount of $Al_2O_3$, $Fe_2O_3$ and CaO. All these values are higher than the minimum requirement stated for class N pozzolan (>70%) according to ASTM C618 [27]. Moreover, the percentage of sulphur trioxide ($SO_3$) in OPC and BA are well below the maximum requirement of 4%, as specified by the same standard. The table shows that the BA contains more that 66% silica; therefore, it can be a good SCM.

**Table 3.** Chemical compositions of OPC and BA.

| Chemical Composition (%) | Sample Type | | Code Requirements | |
|---|---|---|---|---|
| | Cement | BA | ASTM C618 [27] | IS 3812-2015 [30] |
| Silicon dioxide, $SiO_2$ | 21.74 | 66.67 | - | >35 |
| Aluminum oxide, $Al_2O$ | 5.01 | 7.41 | - | - |
| Iron oxide, $Fe_2O_3$ | 3.17 | 2.78 | - | - |
| Calcium oxide, CaO | 63.67 | 7.32 | - | - |
| Magnesium oxide, MgO | 1.08 | 1.81 | - | <5 |
| Sulfur trioxide, $SO_3$ | 3.56 | 1.09 | <4 | <5 |
| $SiO_2 + Al_2O_3 + Fe_2O_3$ | - | 76.86 | >70 | >70 |

The X-ray diffraction (XRD) technique was used to determine the mineralogical characteristics of OPC and BA. XRD is a nondestructive procedure for detecting unknown minerals and materials. It is mostly suitable for detailed information about the chemical composition, physical properties and crystallographic structure of a material. The specification was 2-theta angle ranges from 5 to 90 degrees. In Figure 7, there is an increase in the intensity of the narrow reflections around 26° (2θ), which gives a good idea about how crystallized the BA samples are. The amorphous hump between (2θ) 20 and 30° clearly indicates the existence of amorphous silica [13,15,20]. As a result, the strong broad/wider peak in Figure 7 can be utilized to swiftly evaluate whether silica ($SiO_2$) is amorphous or not ($SiO_2$). Figure 8 illustrates the XRD analysis of BA; its peaks are labelled for their identification. The XRD analysis indicates the tested BA is crystalline in nature. The scanning electron microscope (SEM) analysis was executed according to the 30 KV VP-SEM method in the Bangladesh Council of Scientific and Industrial Research (BCSIR). Figure 8 represents the SEM images of finely ground BA. Using a scanning electron microscope (SEM), the morphological examination shows that the bagasse ash particles have a large surface area and rough surfaces, both of which may indicate a high porosity and a "spongy" texture [6,10]. The carbon pieces are not completely consumed due to incomplete combustion. The combination of this with the sponge-like particles results in a more permeable surface [6,19].

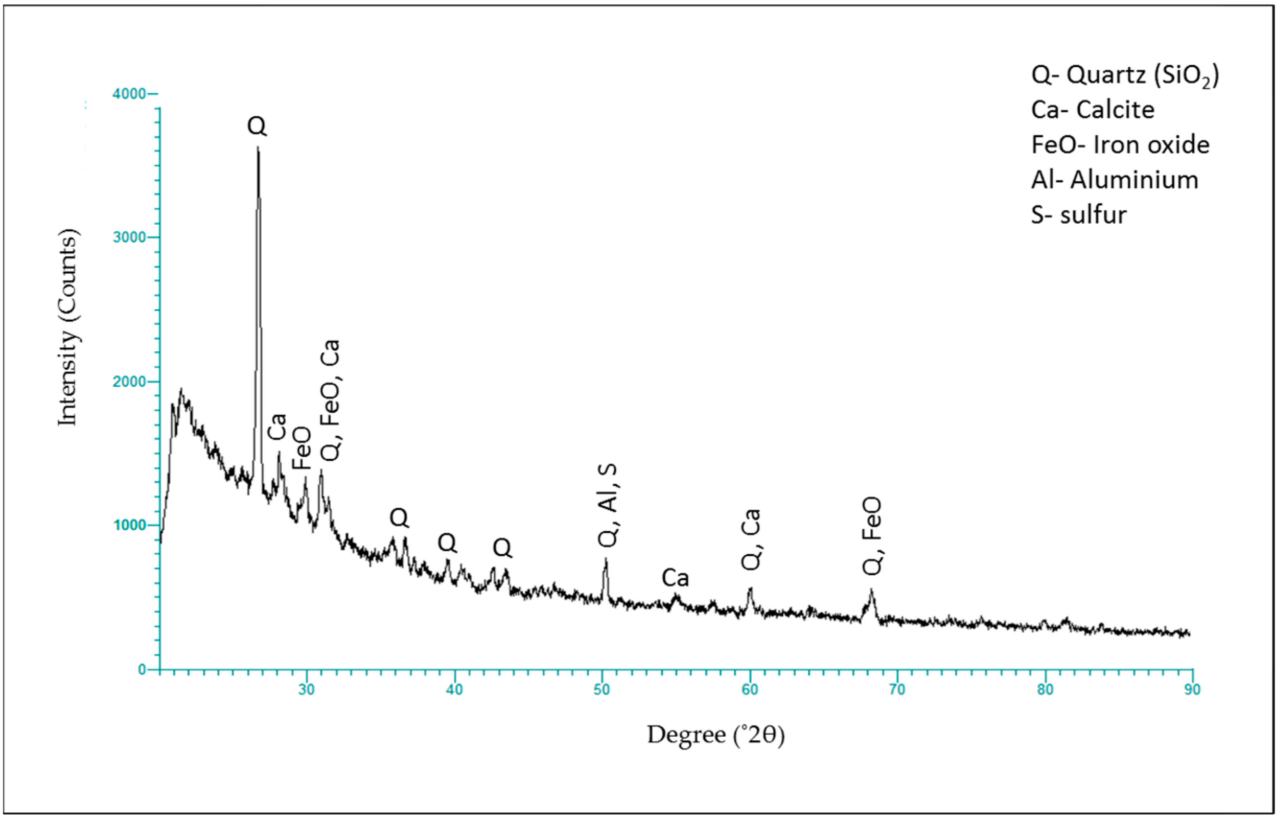


**Figure 7.** X-ray diffraction (XRD) analysis of BA.

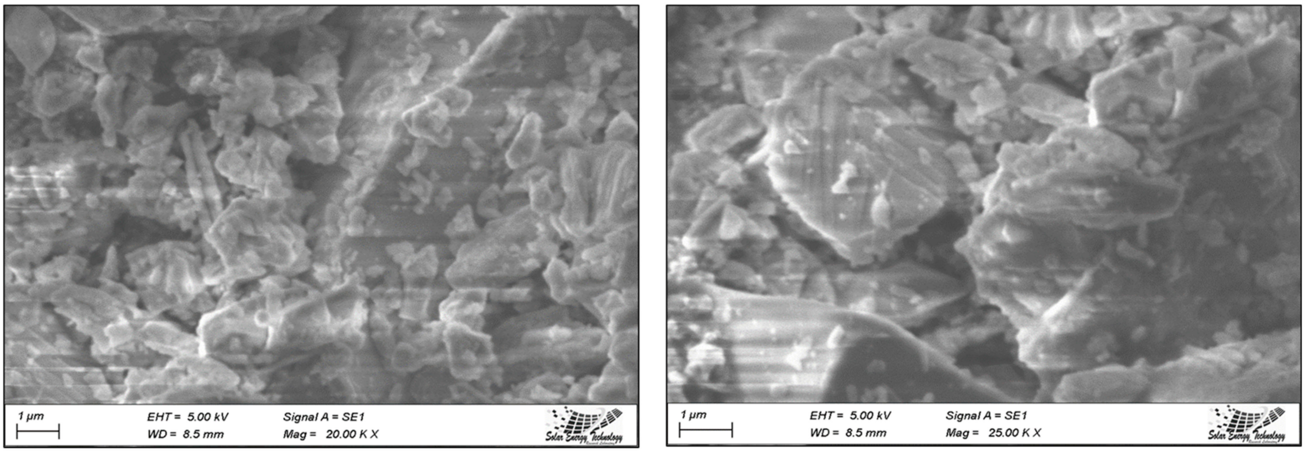


**Figure 8.** (**a**,**b**): SEM images of ground bagasse ash.

3.3.2. Structural Mortar Mix Proportions, Casting and Curing

The mortar mixes were designed and prepared in six separate percentages (5%–30% BA by weight of cement). The control mixture specimens were named M0, and the BA mortar specimens were named M1–M6. The summary of the mix design is given in Table 4. A Hobert mixture machine was used to proper the designed mortar. Afterwards, 12 cube specimens were casted for each type of mix (M0–M6), with the total number of 84 specimens. For compressive strength testing, cube specimens were used with the dimension of 50 mm × 50 mm × 50 mm. One day after the casting, the mortar samples were demolded and cured in normal water until those samples were ready for testing. The room temperature for water curing was maintained between 25 and 33 °C.

**Table 4.** Mix design of mortar with BA (for six cube batches).

| Mix Label | Quantities | | | | | |
|---|---|---|---|---|---|---|
| | BA (%) | W/C or W/(C + BA) * | Water (mL) | Cement (gm) | BA (gm) | Sand (gm) |
| Control, M0 | 0 | 0.56 | 280 | 500 | 0 | 1375 |
| M1 | 5 | 0.56 | 280 | 475 | 25 | 1375 |
| M2 | 10 | 0.56 | 280 | 450 | 50 | 1375 |
| M3 | 15 | 0.56 | 280 | 425 | 75 | 1375 |
| M4 | 20 | 0.56 | 280 | 400 | 100 | 1375 |
| M5 | 25 | 0.63 | 305 | 375 | 125 | 1375 |
| M6 | 30 | 0.63 | 305 | 350 | 150 | 1375 |

* Here, C = cement, W = water and BA = bagasse ash.

#### 3.3.3. Strength Activity Index

The pozzolanic property of BA was measured according to the ASTM C311 standard [31]. Cubic specimens (50 × 50 × 50 mm) were used to for the strength activity index (SAI) testing. The SAI is calculated from the results of a compressive strength test of mortar cubes. For the casting of the control mortar mix, 500 gm of OPC (compatible with 53 grades as per IS 12269 (IS 2008)) [32], 1375 gm of standard-graded sand (Ottawa sand) (as per IS 383 (IS 2007)) [33] and 242 mL normal water were used. For the preparation of mortar with BA and OPC, 20% mass of raw fine ground BA was replaced as a cementitious material. The mortar cube specimen containing zero percent pozzolana serves as the control mix. For each variant, three specimens were cast using Ottawa sand and a binder (cement and pozzolana). All the casted specimens were demolded after 24 h and cured in normal water. The compressive strength results of all the specimens were taken at 7 and 28 days of the specimen as per the code requirement (ASTM C311). The strength activity index was calculated using the control mortar mixture as a base. Mainly, the percentage ratio of the strength of the specimen with BA and the control mortar mix is referred to as strength activity index.

## 4. Structural Mortar Test

### *4.1. Setting Time of Blended Cement*

In line with ASTM C191-19, the initial and final setting times of the cement and BA pastes were determined with the help of Vicat's apparatus [34]. The Vicat test specified in ASTM C191 is widely used to measure the setting time of cement paste. The test involves determining how far a needle can go when it freefalls to the ground. Time taken for standard needle penetration of 25 mm is considered the initial setting time, whereas time taken for visibly zero penetration of the standard needle is considered as final setting time. In this instance, a w/c ratio of 28% was utilized. In order for the cement paste to be suitable for use in Vicat's apparatus, clean water was added to it, and then a trowel was used to make the top surface of the paste as smooth as possible before placing it below the Vicat's needle.

### *4.2. Saturated Surface Dry (SSD) and Dry Density*

The measurement of density was carried out in accordance with ASTM C642 [35]. The SSD (saturated surface dry) condition was achieved by eliminating the water that was present on the surfaces of the specimens. After that, the SSD weight of the samples were taken. The samples were then placed in an oven for 24 h at a temperature ranging from 100 to 110 degrees Celsius. Following that step, the specimen's dry weight was determined. The saturated surface dry (SSD) density was determined by employing the wet weight in the calculation, whereas the dry weight was utilized in the calculation of dry density. In order to determine both the SSD and the dry density, the following equation was utilized:

$$\text{Density} = \text{mass}/\text{volume}$$

### 4.3. Compressive Strength Test

For the compressive strength testing, cubic specimen in accordance with ASTM C109/C109M-21 was chosen [36]. For each mortar mix, the cubic specimen's dimensions were 50 mm × 50 mm × 50 mm. After 24 h casting, the test specimens were demoulded and then cured in normal water. At 7, 14, 28 and 56 days, the specimens were tested in a universal testing machine (UTM). The mean values of three samples are used to represent the compressive strength of each mix.

### 4.4. Water Absorption

Water absorption is a percentage quantity of the pore volume or porosity in hardened mortar. For measuring the water absorption, the mortar specimens with different BA replacement levels (50 mm × 50 mm × 50 mm) were kept in saturated condition until their testing ages. As per ASTM C642-06, water absorption of mortar with BA was determined after 28- and 56-day specimen age [35]. The amount of water absorbed by a specimen is determined as the difference in mass between the saturated mass and the oven-dry mass of the specimen expressed as a percentile fraction.

### 4.5. Chloride Durability

The short-term durability performance of mortar with BA was examined in chloride-saturated solution. For each mortar mix, three cubic specimens (50 mm × 50 mm × 50 mm) in total were cast. After 24 h, all specimens were demoulded and cured for 28 days before placed in a chloride-saturated solution to complete a total of 90 days to check the chloride durability. A 20% NaCl solution was used as the chloride-saturated solution. This durability evaluation was carried out in accordance with the method described in BIS 3025 (Part 32)-2003, which was also adopted by Katare and Madurwar [37,38]. This method suggests all six faces of a cube should be subjected to chloride solution. Later, both the loss of compressive strength and mass were determined after 90 days of chloride exposure.

## 5. Results and Discussions

### 5.1. Strength Activity Index

The detailed strength activity index testing procedure is shown in Figure 9. According to ASTM C 618-12a [27], the SAI minimum strength requirement for the natural pozzolan and fly ash mixture compared to the control mixture is >0.75 (75%) at 7 and 28 days. It is observed that at both 7 and 28 days, the SAI value for the mortar with 20% BA was 91% and 93%, respectively, compared to the strength of control mixture. Therefore, the BA in this study can be classified as pozzolans. The above stated test result shows the optimistic pozzolanic activity for the 20% replacement presented in Table 5. Good fineness and a high silica content are the main causes which help to increase the rate of the SAI. A strong calcium silicate hydrate (C-S-H) reaction is expected to be observed with the 20% substitution of cement with BA [14]. This reaction arrangement is the main product of the hydration of Portland cement and is primarily responsible for the strength in cement-based materials [20]. On the other hand, a reverse reduction in the SAI ratio can be observed when the optimum replacement level of BA with cement increases as cement contains more calcium oxide (CaO) than BA, which plays a crucial role in cement hydration. Therefore, BA has the ability to be used as an active pozzolanic material to replace a part of cement in the process of preparing concrete or structural mortar.

Mortar specimen with

Testing of BA mortar specimen

**Figure 9.** Determination of strength activity index (SAI).

**Table 5.** Strength activity index (SAI) of bagasse ash (BA) *.

| Specimens | 7-Day Strength (MPa) | SAI (%) | 28-Day Strength (MPa) | SAI (%) |
|---|---|---|---|---|
| OPC mortar | 30.75 | - | 47.05 | - |
| Mortar with 20% BA | 28.25 | 91 | 44.14 | 93 |

* Where SAI = strength activity index and BA = bagasse ash.

### *5.2. Initial and Final Setting Time*

There was a noticeable difference in the amount of time needed to set up for the 1 to 30% BA replacements. Figure 10 displays the outcomes of the initial and final setting times with respect to the percentage of cement replacement. It is anticipated that both the initial and final setting times will steadily increase as more BA is gradually replaced with cement. The primary point is that BA absorbs more water than cement because it is porous and has a large surface area. This is one of the main causes of BA, which contributes to its character cement [14,20]. As most pozzolans slow down the hydration rate, it was expected that the setting time would increase [5,7,39–41]. To improve this condition, the controlled burning of ash is required. At a cement replacement level of 0 and 20%, the initial setting time was recorded as 55 and 190 min, respectively. For 0 and 20%, the final setting time was calculated to be 225 and 355 min, respectively. However, as per IS 8112-1995 [42], all the values are good and within the acceptable constraints. The result from the graph of setting time indicates that up to a 20% replacement of bagasse ash is acceptable.

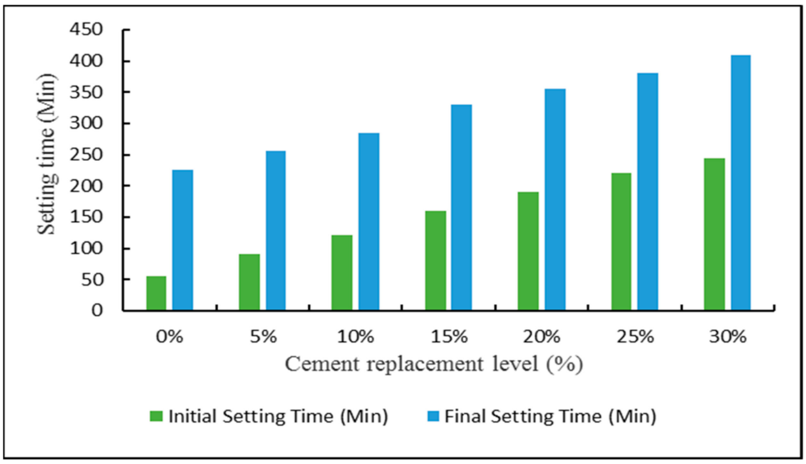


**Figure 10.** Initial and final setting time of cement paste with BA.

### *5.3. Density*

By filling the internal voids of specimens, SCMs also act as a filler in concrete or mortar. The results of SSD and dry density with the partial replacement of BA is presented in Figure 11. The results shows that the densities reduced with the addition of the BA ratio in the mortar mix. This behavior indicates that there is a decrease in the internal packing effect which failed to fill the internal void of the mortar specimens [43]. The change in density is linked to the change in porosity. Due to the evaporation of water during the drying process, the density has decreased (dehydration of hydrates such as the C–S–H and portlandite CH) [44]. In this experiment, the 15% BA mixture had the lowest density because BA has a much inferior specific gravity than cement and fine aggregate, thus reducing the mass per unit volume. The low specific gravity of BA and increasing BA content in the mix up to 10% results in the dust content in the mortar mix increasing, which results in a reduction in mortar density [43,45]. It was also stated that the higher quantity of the BA replacement of OPC by weight preceded an increase in paste volume, from which the density of BA was poorer than that of OPC, resulting in the lower density of the concrete [46].

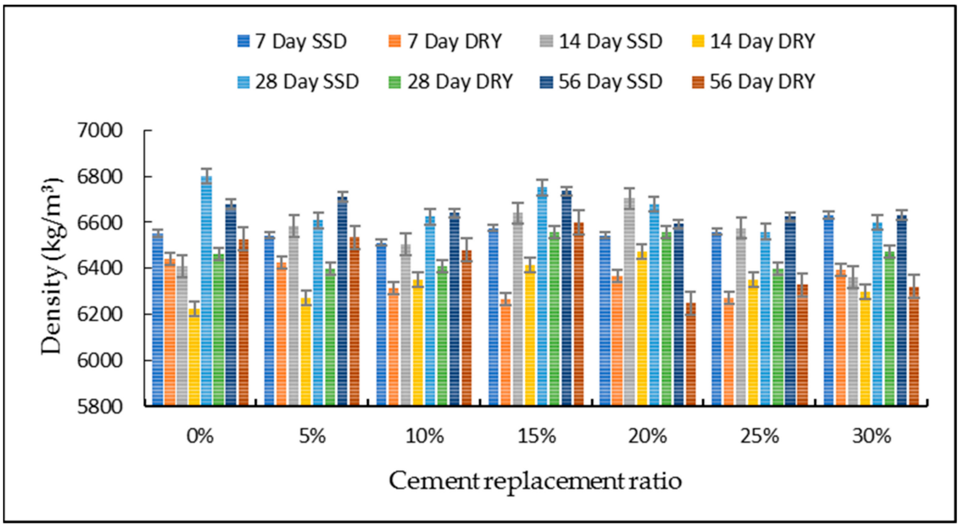


**Figure 11.** Density in SSD and dry conditions.

### *5.4. Compressive Strength of Mortar*

One of the fundamental qualities of concrete or mortar is compressive strength. It denotes the total quality of the mortar or concrete, where performance characteristics demonstrate the strength of the binder (cement) in the combination. Figure 12 shows how compressive strength changes over time for all mortar samples from 0 to 30% replacement level (at room temperature). When the data for compressive strength for 7, 14, 28 and 56 days of curing time are compared, it can be shown that compressive strength increases with BA up to the 15% replacement. Once it reaches 15% BA, the compressive strength of mortar achieves the highest strength compared to the control specimens. This can be shown by comparing the data for compressive strength at 7, 14, 28 and 56 days of curing time. Figure 12 illustrates quite clearly that the relative increase in compressive strength of the 15% BA-blended mortar in contrast with the control mortar at both 28 and 56 days of curing shows strength improvements of 12 and 10%, respectively, over the control mortar's strength. As in earlier works, the reasons for the development of compressive strength in BA mortar and the increase in compressive strength up to the 15% cement replacement of BA may be due to the silica content, fineness, specific surface area, degree of reactivity of BA and pozzolanic reaction between calcium hydroxide and reactive silica in BA. Additionally, the degree of reactivity of BA plays some part in the process of developing compressive strength [7,10,18,47–51]. According to the findings, an increase in compressive strength may be attributed to the packing effect of BA due to particle fineness, the quantity of the cement replacement and the age of the mortar. These findings are quite comparable to findings on the use of other pozzolans, such as fly ash, palm oil fuel ash, silica fume, etc., [52–54]. When compared to the strength of the control specimens, the value of the strength drops to a lower level in the 20, 25 and 30% of BA replacements, respectively, which indicates a reduction in overall strength. This is due to the presence of unburned carbon in sugarcane bagasse ash and nonreactive silica and the lesser amount of CSH gel from cement hydration [49].

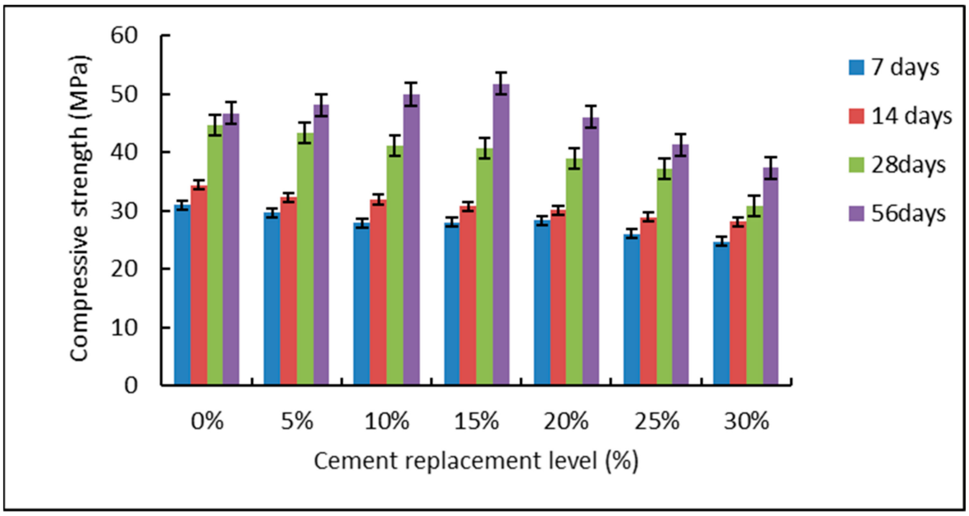


**Figure 12.** Compressive strength of blended BA mortars.

According to Paya et al. [51], combustion produces ash that are high in unburned matter, silicon and aluminium oxides. They stated that bagasse ash must be chemically, physically and mineralogically characterized before it can be used as a binder in a cementitious matrix [51,52]. Cordeiro (2004) demonstrated that mechanical grinding in a vibratory mill can appreciably enhance the BA's pozzolanic action. As a result, it is not surprising that the unburned carbon content is important in optimization. Based on the particle size distribution curves, the fineness of BA is higher than that of cement, and BA contains a high volume of silica, which is sufficient to use it as pozzolanic material according to a previous study [7,55]. Therefore, it is quite feasible for BA to be utilized as a supplementary material with cement (the binder) provided that the burning process is controlled, and the appropriate qualities for the pozzolans are maintained.

According to the values of the compressive strength of mortar given in the chart, it can be said that the 10% and 15% replacement specimens show higher strength at 56 days compared to the control mix. Therefore, in terms of strength, up to the 15% replacement can be achieved. It is worth noting that, most of the values of the replacement of bagasse ash are above or similar to the value of the control mixing, which proves that bagasse ash has the ability to use it as an alternative cementitious or filler material.

By filling in the spaces between cement particles, SCM particles reduce the volume of voids in the concrete or mortar and make it stronger, which is called the filler effect. Hydration is affected in two ways by the surface of SCM particles. SCM particles help the hydration products form precipitates by giving them more places to start [6,56]. In addition, calcium ions stick to the surface of the SCM, making the Ca/Si ratio lower. This makes the initial C–S–H (calcium silicate hydrate) layer more stable [56,57]. The SCM performs a pozzolanic activity by interacting with the by-product of cement hydration, $Ca(OH)_2$ (portlandite), resulting in the creation of extra C-S-H gel (secondary C-S-H). As it reduces porosity in the bulk cement paste and increases the interfacial binding between aggregate particles, this secondary C-S-H improves mortar strength and density [16,20]. It is also confirmed that when BA is present in Portland cement paste, it represents pore-refining capacity [38].

It is also notable from Figure 9 that at an early stage (28 days), the rate of compressive strength gained slowly and decreased gradually after 15% replacement. The condition behind the decreasing early strength is due to non-reactive BA [41]. Therefore, to obtain BA with good pozzolanic properties, it must be burned at a controlled temperature to obtain reactive silica and possess good fineness for a better packing effect.

### *5.5. Water Absorption*

Figure 13 displays the water permeability property of BA-mixed mortar specimens after curing for 28 and 56 days, respectively. These values reflect the amount of saturated water absorbed by the specimens. The addition of BA to the mixture resulted in an increase in water absorption. In addition, it is noticed that the water absorption rate decreased with time. At an early stage (on 28 days), the BA replacement level ranged from 5 to 30%, resulting in an increase of between 340 and 540% relative to the control mortar mix. This could be explained by the presence of pores in the BA, which results in a high absorption rate [58]. However, this growing trend was shown to increase after 56 days of curing. The observed variation ranged from 330 to 630% of that of the control mixture. This was due to the mortar samples' lower density, which enhanced their water absorption properties [59].

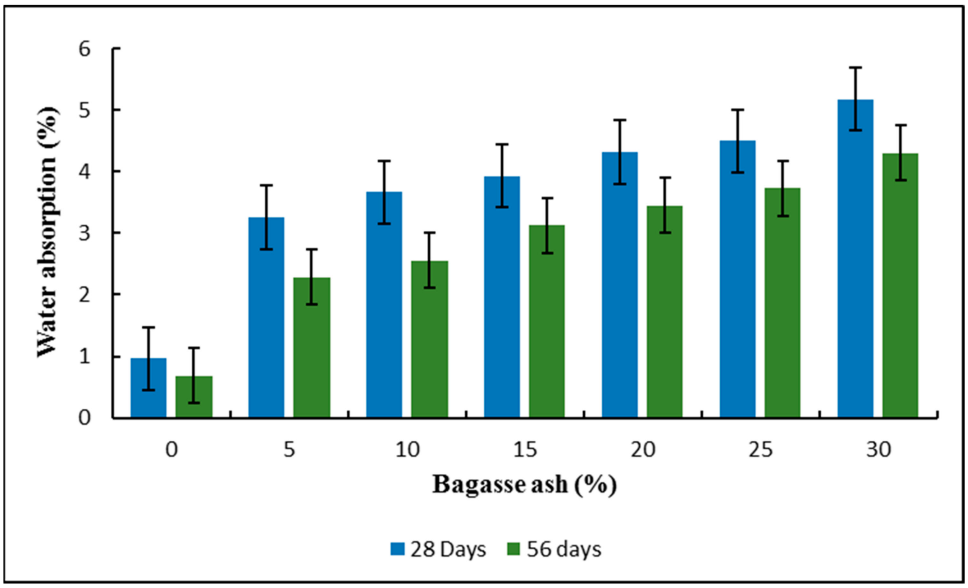


**Figure 13.** Water absorption of BA-OPC mortar.

When finer SCMs are used, increasing the amount of BA in mortar can have a positive effect on the reduction of permeable spaces. This is because finer BA have the potential to fill holes, so they gradually close pores [6,16,39]. This phenomenon is known as the "filler effect." It is also clear that the inclusion of BA leads to a reduction in the number of permeable gaps when prolonged curing occurs. This is due to the fact that BA is of a finer particle size than OPC, as well as the fact that it is hygroscopic in nature [15,21].

### *5.6. Durability Test*

The durability properties of SCM containing concretes/mortar are vital for the sustainable design of infrastructures. Sugarcane bagasse ash, rice husk ash, palm oil fuel ash, corn cob ash, etc., are good agro-industry-based pozzolans for utilizing in mortar and concrete after proper processing. Previously, it was observed that the durability properties of mortar were improved by the filler effect of agro-industrial ash (rice husk ash) [15,39]. Chloride also physically interacts with the materials due to interaction at the pore solution/paste interface. This may decay the internal pores of mortar which can affect the durability of mortar. BA-containing samples with pore openings may weaken the mortar interface, which leads to the strength loss and weight loss of mortar samples which were cured in chloride water [37,38].

In Figure 14, the durability properties of blended BA mortars are presented. It is mainly based on the strength and mass loss observation after the mortar specimen exposed in a chloride environment. After being subjected to NaCl solution, the specimens showed a reduction in both their mass and compressive strength, as presented in Figure 14. The 90 days' strength decreased with respect to the normal compressive strength which was cured in normal water (showed in Figure 12). From Figure 14, it is observed that until the 15% cement replacement level, the strength percentage reduced slowly, and the percentage is near or lower than 1.5%. After the 15% cement replacement level, the strength loss percentage increased faster, and at the 30% cement replacement level, it is more than 2.5%. The pore filling capacity of BA helped to slowed down the strength loss in the chloride environment, but when the cement replacement level increased to more than 15%, the lack of binders led to rapid strength loss.

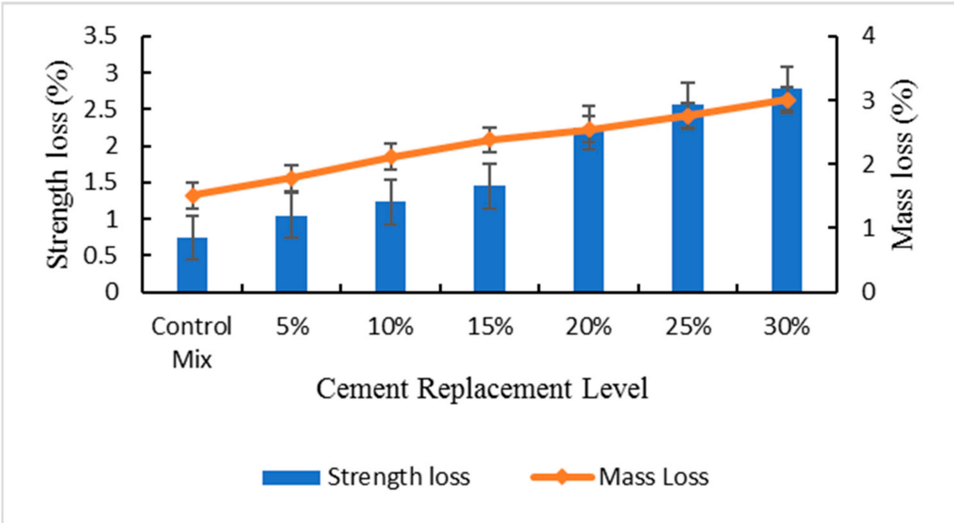


**Figure 14.** Compressive strength and mass loss in chloride environment (90 days).

On the other hand, the maximum mass loss was detected at the 30% cement replacement level. In the majority of the instances, an increase in the quantity of BA in the mortar mix resulted in a greater loss of mass. The decrease in weight can be attributed to the dissolution of total particles [44,58].

Ganesan et al. (2007) observed a higher resistance to chloride penetration for bagasse ash-blended specimens compared to the control mixture [7]. In comparison to the control and the fly ash-blended concrete, the bagasse ash-blended concrete showed significantly increased levels of both strength and durability [14]. It has been demonstrated that concrete containing mineral admixtures is significantly more resistant to chlorides and other agents that cause degradation [14,21]. To a large extent, it is influenced by a small number of criteria, including the manner in which the minerals react with the oxides during the hydration stage, the nature of the chlorides and the effects that they have [16,58,60]. As a consequence of these factors, the strength of mortar that contains BA can be affected negatively if it is exposed to a chloride environment.

## 6. Conclusions

A number of pertinent conclusions can be drawn based on the results and discussions. Based on the results of this experiment, BA has the potential to be partially utilized as an alternative to cement in the production of mortar. The most important findings learned are as follows:

1. BA incorporation prolongs the setting time (both initial and final) period. Though the increase in setting time values is still within the code's boundaries, an optimum level must be followed to maintain standard construction practice.
2. The strength activity index value attained above 90% after 7 and 28 days, which satisfies the ASTM requirements. Therefore, the employed BA has the required pozzolanic qualities.
3. Due good fineness, the inclusion of BA makes the structural mortar dense and thus improves the density and water absorption properties. Up to a 15% replacement of BA can be suitable for a dense mortar with low absorption properties.
4. The compressive strengths were excellent up to a 15% BA substitution. The primary factors are assumed to be the silica content, fineness for the required packing effect, specific surface area and the degree of reactivity of BA that helps to gain the strength. Above a 15% replacement, the strengths gradually started to decrease, and over 20%, it also started to consume more water as BA is hygroscopic in nature.
5. The durability test results demonstrate that the BA mortars in a chloride environment lose their strength and mass, which gives a clear indication that non-reactive BA can be harmful in a chloride environment.

It can be concluded that BA can successfully substitute up to 15% of ordinary Portland cement in structural mortar without sacrificing the desired properties. The performance of mortar will be enhanced by using BA in cement-based construction and would reduce the negative environmental impact by utilizing agro-industrial waste.

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