Available online at www.CivileJournal.org

Civil Engineering Journal

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

Vol. 10, No. 04, April, 2024

Properties and Microstructure of Treated Coal Bottom Ash as Cement Concrete Replacement

Moad Alosta [1], Ahmed Mamdouh [2], Hussein Al Mufargi [1], Farah N. A. Abd Aziz [2], Ahmed Rashid [2], Otman M. M. Elbasir [3], Husam Al Dughaishi [1, 4*]

[1] *Department of Civil and Environmental Engineering, College of Engineering, University of Nizwa, Ad-Dakhliyah, Oman.*

[2] *Housing Research Centre, Department of Civil Engineering, Faculty of Engineering, Universiti Putra Malaysia, Serdang, Selangor, Malaysia.*

[3] *Department of Civil Engineering, High Institute of Science and Technology, Qasr Bin Ghashir 22131, Libya.*

[4] *Department of Civil Engineering, Faculty of Engineering, Universiti Malaya, Kuala Lumpur 50603, Malaysia.*

Received 05 December 2023; Revised 14 March 2024; Accepted 19 March 2024; Published 01 April 2024

Abstract

Sustainable construction is a rapidly growing area of research focused on using industrial waste to replace Portland cement in concrete. This approach not only reduces CO_2 emissions from cement production but also serves as an effective way to diminish the environmental impact of concrete production. This study aims to investigate the properties of Coal Bottom Ash (CBA) after undergoing two different treatments: flotation and burning. It also evaluates the impact of CBA as a cement replacement in concrete with different replacement percentages (5%, 10%, 15%, and 20%). Chemical analysis of CBA has revealed that it can be classified as a pozzolanic material due to its high content of silicates, aluminates, and iron oxides. The microstructure of CBA showed a porous, angular, and irregular surface with many voids. The findings of this study revealed that the optimum mix was 10% CBA, resulting in a 2% increase in compressive strength compared to the control mix after 56 days of curing. Additionally, the study evaluated the effects of sulfate and chloride on concrete. It was found that the mix with the burning treatment showed an overall increase in strength, while the flotation treatment did not reach the control mix's strength in any of the curing periods. Furthermore, the results demonstrated that CBA has significant potential as a cement replacement material, and the burning treatment showed improvement in concrete's overall properties compared to the raw material in terms of mechanical and chemical properties while reducing greenhouse gas emissions and enhancing the environment.

Keywords: Industrial Waste; Material Properties; Coal Bottom Ash; Compressive Strength; Microstructure.

1. Introduction

1.1. Research Background

Concrete is one of the most widely used and versatile construction materials in the world, capable of being molded into various shapes and sizes and known for its high strength and durability [1–3]. It is used to build structures, bridges, dams, and other infrastructure, including the Burj Khalifa, the tallest building in the world, which was constructed with 333,000 cubic meters of concrete [4–6]. However, concrete also has a significant environmental impact, as its main ingredient, Portland cement, accounts for about 8% of global CO_2 emissions [7–10]. Furthermore, the production and disposal of concrete generate large amounts of waste and pollution.

* Corresponding author: husam@unizwa.edu.om

http://dx.doi.org/10.28991/CEJ-2024-010-04-08

Therefore, there is a need for more sustainable and eco-friendly alternatives to Portland cement in concrete production. One of the potential alternatives is the use of industrial waste materials, such as fly ash, slag, silica fume, and rice husk ash, as cement substitutes in concrete. These materials, known as pozzolans, are substances that react with calcium hydroxide and water to form cementitious compounds. Using pozzolans in concrete can reduce the amount of Portland cement required, thereby lowering CO_2 emissions and the cost of concrete production. Moreover, pozzolans can improve the properties and performance of concrete, such as its strength, durability, workability, and resistance to chemical attacks.

However, not all pozzolans are equally available and suitable for concrete production. Some, such as fly ash and slag, are in high demand and may face supply shortages in the future [11, 12]. Others, like silica fume and rice husk ash, are expensive and difficult to handle and store. Therefore, more research is needed on the feasibility and effectiveness of other pozzolanic materials that are abundant, inexpensive, and easy to use.

One such material is Coal Bottom Ash (CBA), a by-product of coal combustion in thermal power plants. According to the American Coal Ash Association (ACAA), 40.13 percent of the coal ash production rate, or 12 million tons of CBA, was produced in 2015 [13, 14]. CBA has been identified as a substance that endangers human health and safety. However, it also has a high potential to be used as a pozzolan in concrete due to its high content of silicate, aluminate, and iron oxide, which are the main components of pozzolanic reactions. Moreover, CBA's porous, angular, and irregular shape and texture can enhance the interlocking and bonding between aggregates and the cement paste in concrete.

The use of CBA as a cement substitute in concrete has been studied by several researchers, but the results are inconsistent and inconclusive. Some studies have reported that CBA can improve the strength, durability, and workability of concrete [15–22], while others have found that CBA can reduce these properties [23–25]. The discrepancies may be due to the different sources, compositions, and treatments of CBA, as well as the different mix proportions, curing conditions, and testing methods of concrete.

Therefore, there is a research gap in the literature on the properties and effects of CBA as a cement substitute in concrete, especially after undergoing different treatments. These treatments can alter the physical and chemical characteristics of CBA, affecting its performance and compatibility with concrete. They can also reduce the environmental impact of CBA disposal by transforming it into a more valuable and useful material. The aim of this research is to bridge this crucial knowledge gap by thoroughly exploring the effects of two distinct treatments—flotation and burning—on CBA, with a particular emphasis on the use of finer particles (100 microns). Flotation, a method that leverages air bubbles and water, segregates these lighter, finer CBA particles from their heavier, coarser counterparts. Conversely, the burning process incinerates organic matter and carbon content within CBA through the application of high temperatures and oxygen. Furthermore, this study delves into the potential of finely processed CBA to serve as a substitute for traditional cement in concrete, examining a range of replacement ratios (5%, 10%, 15%, and 20%).

1.2. Literature Review

CBA, a by-product of coal combustion in thermal power plants, is influenced by coal type, combustion conditions, and collection methods. In 2015, the ACAA reported that 40.13 percent of the coal ash production, equivalent to 12 million tons of CBA, was generated [11]. CBA exhibits diverse sizes (0.075 to 19 mm) and shapes (spherical, angular, or irregular). The ratio of fly ash to bottom ash, dependent on coal type and combustion temperature, typically ranges from 25% to 90% [16, 26]. Key concrete production parameters like specific gravity, water absorption, and fineness modulus are influenced by CBA's size and shape variations. The specific gravity of CBA ranges from 1.39 to 2.66, which is lower than that of natural aggregates, and water absorption ranges from 3.7% to 20%, with the fineness modulus ranging from 2.2 to 3.0 [1, 13, 23, 27]. CBA's chemical composition, comprising silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3), accounts for 50% to 80% of its mass [25]. These components contribute to pozzolanic reactions in concrete. However, impurities like carbon (1% to 20%), sulfur (0.1% to 2%), and chlorine (0.01% to 0.1%) vary, impacting CBA's reactivity [17, 24, 28]. High carbon content reduces specific gravity and increases water absorption, affecting mix design and workability. Sulfur content may lead to sulfate attack, damaging concrete structures, while chlorine content can cause chloride attack, potentially corroding steel reinforcement in concrete [8, 27, 29]. Careful consideration of CBA's variability is crucial for its effective use in concrete applications.

The impact of CBA on the workability of freshly made concrete is highlighted by its influence on the surface area, shape, water content, and texture of the added materials. The use of CBA as an alternative to Portland Cement (PC) notably affects concrete's fresh properties by enhancing inter-particle friction, which restricts the free flow of concrete. Specifically, concrete with 10% Ground CBA showed a decrease in slump values by about 10%, indicating reduced workability compared to control concrete due to the Ground CBA's additional water absorption and its uneven surface texture [11]. Conversely, other investigations noted an improvement in workability with increased Ground CBA content, though explanations for these findings were not fully discussed [30].

Grinding can also reduce the water absorption and increase the specific gravity of CBA, which can affect the mix design and the workability of concrete. Singh et al. reported that grinding CBA for 60 minutes reduced the particle size from 4.75 mm to 75 μm and increased the pozzolanic activity index from 55% to 85%. Ground CBA in concrete significantly enhances resistance to chloride attack, reducing chloride migration and diffusion. Concrete with 10% CBA shows 1.7 times lower chloride migration than with Fly Ash (FA), and 25% CBA achieves 3.8 times lower diffusion than with 25% FA. The chloride penetration depth decreases from 76 mm in control concrete to 17 mm with increased CBA content, indicating improved chloride resistance with CBA use [17, 30].

Pulverizing is a process that crushes and grinds the CBA particles into a fine powder using high pressure and impact. Pulverizing can increase the fineness and pozzolanicity of CBA, which can improve the reactivity and strength of concrete. Pulverizing can also reduce the water absorption and increase the specific gravity of CBA, affecting the mix design and workability of concrete. Jamaluddin et al. reported that pulverizing CBA for 30 minutes reduced the particle size from 4.75 mm to 45 μm [13, 27].

The compressive strength of concrete with CBA replacement varies with CBA content and curing time. At low replacement levels (3.7%), compressive strength increased by 6%, while higher levels (up to 43.7%) reduced strength by 8% to 30% after 28–90 days, compared to control concrete. However, extended curing showed strength improvements, attributed to CBA's pozzolanic activity. Certain studies found that 15%–20% CBA replacements could equal or surpass control strength at later curing stages, indicating a complex relationship between CBA's physical properties, replacement percentage, and concrete's compressive strength over time [30].

Flexural strength results from CBA in concrete show variable outcomes. Up to a 15% CBA substitution, improvements are noted, with flexural strength increasing by 23% at a 30% replacement level when mixed with Aluminum powder. However, high-volume substitutions (70%) lead to decreased strength, although adding lime can mitigate this effect, enhancing strength at all curing periods. The impact of CBA on flexural strength is thus dependent on the level of substitution and the addition of other materials [23, 28, 30]. On the other hand, Jamaluddin et al. demonstrated that self-compacting concrete (SCC) incorporating CBA as a partial fine aggregate replacement exhibited decreased flexural strength, particularly as the water to cement ratio increased from 0.35 to 0.45. The reduction in flexural strength was observed with the increase in CBA content up to 30% volumetric replacement of natural sand. This suggests that while CBA can be used in SCC, its inclusion at higher percentages may adversely affect the concrete's structural performance, especially in terms of its flexural capabilities [13].

Khan et al. research highlights the potential of ground CBA as a supplementary cementitious material to improve the durability of concrete against acid and sulfate attacks [31]. The findings suggest that not only does the replacement level of CBA influence the concrete's resistance to such attacks, but also that ground CBA can enhance the long-term performance of concrete by reducing the penetrability of harmful agents. Resistance to sulfate attack in concrete with a 10% replacement of Portland Cement (PC) by Ground CBA was evaluated over curing periods of 28 to 90 days. Results indicated that mixes with Ground CBA demonstrated comparable or improved resistance against sulfate deterioration compared to control mixes without CBA.

1.3. Motivation and Objective

Several researchers have emphasized that CBA is a toxic material posing risks to human health and safety, as noted in the literature review. To enhance the quality of concrete while promoting a greener and more sustainable world, an innovative and environmentally friendly method has been developed for reusing or recycling industrial waste, such as CBA, in concrete mixtures. Key factors considered to improve the mechanical properties of concrete include the amount of cement replacement material, the treatment method applied to the CBA, and the curing times. The microstructure and chemical composition of CBA are also crucial elements for concrete bonding that must be considered. The durability of ordinary Portland cement (OPC) in harsh environmental conditions—such as those encountered in wastewater treatment plants, underground structures, and coastal structures—significantly impacts the performance of concrete structures. Therefore, enhancing concrete's permeability might accelerate damage by facilitating quicker penetration of harmful substances.

This study aims to enhance the mechanical and durability properties of concrete, including its compressive, tensile, and flexural strengths, alongside evaluating slump test results. It will also examine concrete's resilience against environmental challenges like sulfate and chloride attacks to fully utilize CBA as a sustainable cement alternative. Given the inconsistent findings from previous research on CBA's impact—particularly regarding the effects of flotation, burning treatments, and the incorporation of finer particles (100 microns)—this research seeks to address these discrepancies. It focuses on a thorough assessment of CBA's role as a cement substitute, aiming to clarify its application for improved concrete sustainability and durability.

The purpose of this study is to illustrate the importance of evaluating the effects of different CBA replacement percentages on the fresh properties of concrete. It aims to assess the impact of CBA percentages as a replacement for cement on the characteristics of freshly poured and hardened concrete. Furthermore, the study seeks to determine the impact of carbon treatments, such as burning and flotation, on CBA-enhanced concrete, focusing on the mechanical characteristics of both fresh and hardened concrete. Additionally, it involves evaluating the impact of various CBA treatments on the strength and durability development of concrete incorporating CBA.

2. Material and Methods

The quality of Concrete Bottom Ash (CBA) concrete, as illustrated in Figure 1, is analyzed by examining the chemical and mechanical properties of CBA as a substitute for cement, as well as the microstructure of the ash particles. This study typically begins with a literature review, gathering data from various publications and scholarly articles, before proceeding to experimental testing. To enhance the pozzolanic reaction, CBA will undergo two types of treatments in this study: burning therapy and flotation treatment. The mechanical characteristics of CBA and the microstructure of each treatment will be examined using varied CBA proportions of 5%, 10%, 15%, and 20% to identify the most optimal and efficient percentage for CBA concrete proportions as a cement replacement material. The mechanical properties to be evaluated include splitting tensile, compressive strength, and flexural strength tests. On the other hand, X-ray fluorescence (XRF) tests and scanning electron microscopy (SEM) are used to examine the microstructure and chemical composition of CBA. Additionally, after every 28 and 56 days for various mixes, the following tests for chemical properties will be carried out: compression test, water absorption test, sulfate penetration test, and chloride penetration test.

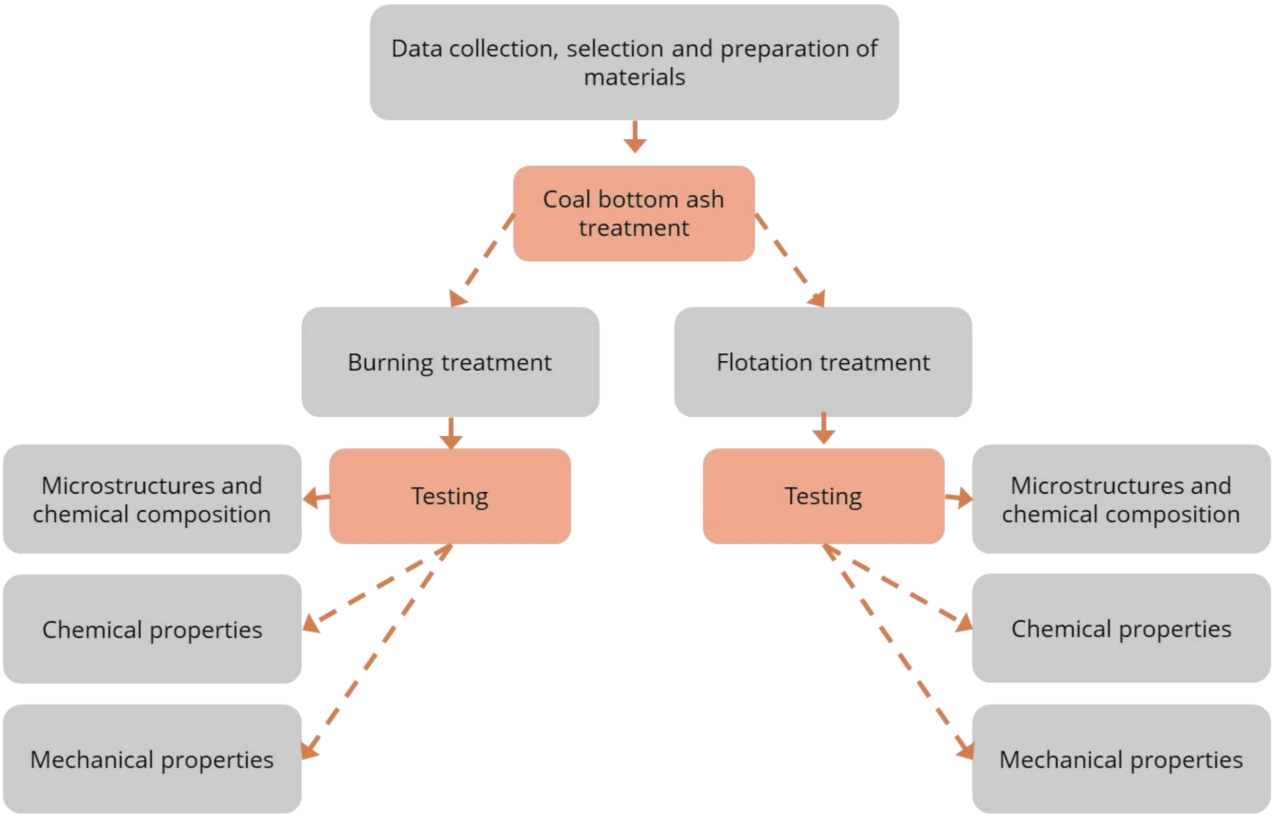

Figure 1. Flowchart of methodology

Throughout this research, nine cubes for each mix of CBA as a cement replacement material—5%, 10%, 15%, and 20%, as well as the control mix, with three cubes for varying curing times of 7, 28, and 56 days—were subjected to compression tests. Additionally, only a 28-day curing period is used for the flexural test on three prism specimens for each combination. Similar to the splitting tensile test, six specimens are prepared for each combination for curing times of 7 and 28 days. Additionally, the samples' chemical properties will be determined by a 5% concentration of chloride and sulfate solution, which other researchers have identified as appropriate. Three samples from each mixture will be evaluated to obtain an average result. The two different treatment techniques used in this investigation, flotation and burning, are depicted in Figure 1.

2.1.1. Burning Treatment

According to Ibrahim et al. [32], this treatment procedure begins with burning the CBA at a temperature of 110 ± 5 for 24 hours before grinding it in a Los Angeles machine for two hours. The particles formed from such a process are then employed in the experiment and have passed a sieve size of 100 microns as shown in Figure 2.

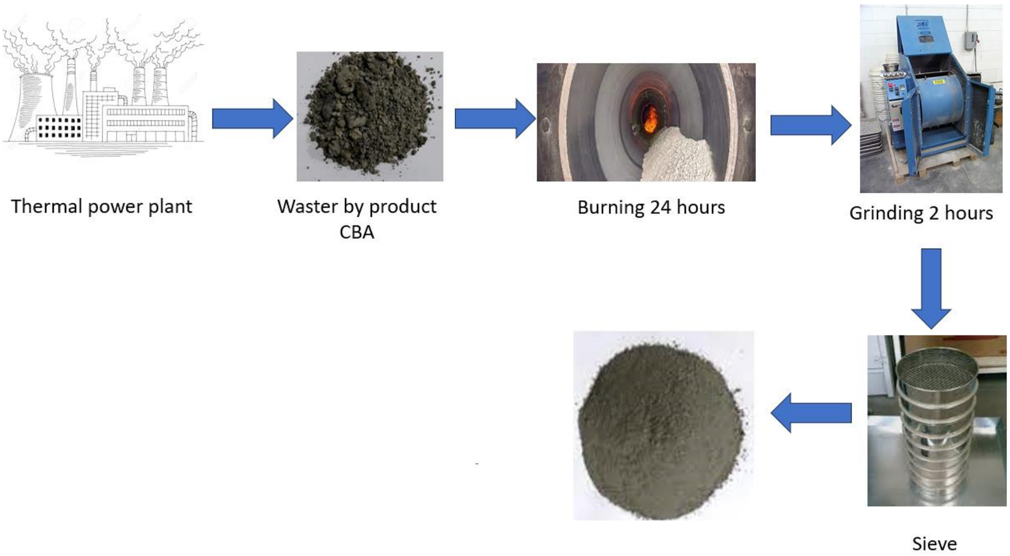

Figure 2. Flotation treatment

2.1.2. Flotation Treatment

According to Um et al. [17]. during the column flotation, air was injected at a flow rate of 10 L/min with a pH of 8. Each sample, weighing between 6.5 and 52 g/L, was subjected to the flotation procedure. 500 g/ton of kerosene and 80 g/ton of MIBC (Methyl Isobutyl Carbinol) were employed as reagents. After being ground for two hours in a Los Angeles machine and passing through a 100-micron sieve size, it will be employed in the experiment as shown in Figure 3.

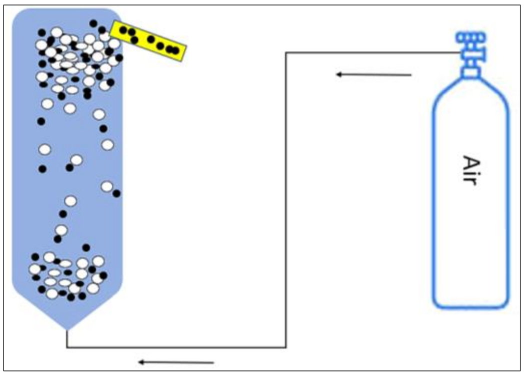

Figure 3. Flotation treatment

2.1.3. Chemical Compositions

The XRF test results, displayed in Table 1, demonstrate that CBA qualifies as a Class F natural pozzolan according to ASTM C 618 [33], containing SiO_2, Al_2O_3, and Fe_2O_3 at levels totalling 70%. With less than 9% lime (CaO) content, raw CBA exhibits very low pozzolanic (lime) properties. To form cementitious mixtures, CBA requires a cementing agent, such as quicklime, hydrated lime, or Portland cement, which reacts with water. In terms of treated CBA, the main differences include a 20% reduction in the percentage of SiO_2 following the burning treatment compared to the flotation treatment. Conversely, Fe_2O_3 increases by 40% in the flotation treatment compared to the burning treatment. However, the higher percentage of silicates (SiO_2) in the burning treatment enhances the hydration reaction in concrete compared to the flotation treatment.

Table 1. Results from the XRF

Element	Burning	Flotation	RAW
SiO_2	40.72%	32.52%	43.61%
AL_2O_3	13.79%	10.96%	14.47%
Fe_2O_3	9.55 %	15.95 %	10.99%
CaO	8.00 %	16.63 %	8.82%
K_2O	0.77 %	0.71 %	0.85%
Na_2O	0.64 %	0.63 %	0.83%

2.1.4. Cement

In this study, Ordinary Portland Cement (OPC) type I is used, classified according to ASTM C150 / C150M [34] and supplied by a local manufacturer.

2.1.5. Coarse Aggregates and Fine Aggregate

Following ASTM C33 [35] standard practice, the coarse aggregates used in this study had a maximum size of a pass-through 20mm sieve. According to ASTM C33 [19] standard practice, the fine aggregates used in this study had a maximum size of pass-through 4.75mm sieve.

2.1. Specimen Mix Design

As can be seen in Table 2, the mix design method employed in this study was based on (DOE) to design concrete grade G35. The water content is fixed at 225 kg/m^3 and the water-to-cement/binder ratio is 0.55. 5%, 10%, 15%, and 20% of the cement is replaced with CBA.

Table 2. Mixture proportions of the binary blended-based CBA

Description	Notation	Rep by weight %	Cement kg/m^2	CBA kg/m^2	Fine aggregate kg/m^2	Coarse aggregate kg/m^2	Water kg/m^2
Control mix concrete	M1	0	409	0	486	1250	225
Concrete Mix with CBA	M2	5%	388.55	20.45	486	1250	225
Concrete Mix with CBA	M3	10%	368.1	40.9	486	1250	225
Concrete Mix with CBA	M4	15%	347.65	61.35	486	1250	225
Concrete Mix with CBA	M5	20%	327.2	81.8	486	1250	225

2.1.1. Molds Preparation

The summary of the total number, and dimensions of the samples is tabulated where (OPC s referring to control mix) in Tables 3 and 4.

Table 3. Specimen details for every mix

Sample	Name	Specimen	Dimensions (mm)	Test Age
1	Compression	Cube	100x100x100	7 days
2	Compression	Cube	100x100x101	28 days
3	Compression	Cube	100x100x102	56 days
4	Flexural	Prism	100x100x500	28 days
5	Splitting tensile	Cylinders	dia 100x200	7 days
6	Splitting tensile	Cylinders	dia 100x201	28 days

Table 4. Number of samples for every mix

	Compressive test MPa			Flexural Strength MPa	Splitting tensile MPa		Total
Curing time	**7 days**	**28 days**	**56 days**	**28 days**	**7 days**	**28 days**	
100% OPC	3	12	12	3	3	3	
5% CBA 95% OPC	3	12	12	3	3	3	
10% CBA 90% OPC	3	12	12	3	3	3	
15% CBA 85% OPC	3	12	12	3	3	3	
20% CBA 80% OPC	3	12	12	3	3	3	
Total	**15**	**60**	**60**	**15**	**15**	**15**	**180**

2.2. Tests for Mechanical Properties of Concrete

2.2.1. Compression Test

This concrete is properly poured into molds and tamped to prevent any voids. The molds are removed after 24 hours, and the test specimens are then submerged in water to cure. The top surfaces of these specimens should be level and smooth. After 7, 28, and 56 days of curing, these specimens are tested by a compression testing machine to determine the pozzolanic reaction of CBA. The load should be gradually added until the specimens fail. The compressive strength of the concrete is calculated by dividing the load at failure by the specimen's area, in accordance with ASTM C109/C109M [36]. Compression tests are performed on cubic specimens with an edge length of 100 mm. Before testing, the cubes should be dried in the sun. Three specimens per mix are tested, and their average strength is computed. When testing cubes, the specimen must be positioned in the machine so that the load is applied to the opposite sides as they were cast. The specimen's axes must align precisely with the plate's center of thrust. The compression test is conducted on a laboratory universal testing machine with a load rate of 6 KN/s and a capacity of 5000 KN.

2.2.2. Flexural Test

The flexural test on concrete can be conducted using either a four-point load test, as used in this experiment according to ASTM C78 [37], or a center point load test according to ASTM C293 [38]. The sample is placed on two supporting pins set a certain distance apart, with two loading pins placed at an equal distance around the center, as shown in Figures. The test should be conducted immediately after removing the specimen from the curing condition to prevent surface drying, which decreases flexural strength. The machine used has a capacity of 5000KN, and the load rate of the experiment is 1.57 KN/s, as shown in Figures 4 and 5.

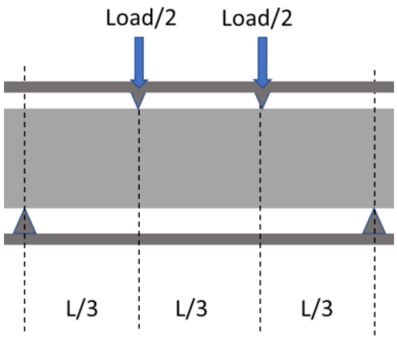

Figure 4. Four-point load test

Figure 5. Four point's flexural test

2.2.3. Splitting Tensile Test

The splitting tensile strength test on a concrete cylinder, adhering to ASTM C496 [39], is used to determine the tensile strength of concrete. The equipment utilized for this test has a capacity of 5000KN, with a load rate set at 1.57 KN/s. After curing, ensure the specimen's surface is completely dry, conforming to ASTM C496. The machine should apply the load steadily until the specimen breaks, as depicted in Figures 6 and 7.

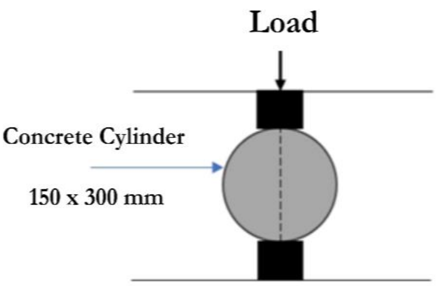

Figure 6. Splitting tensile test

Figure 7. Splitting tensile sample after fail

2.3. Tests for Chemical Properties of Concrete

2.3.1. Water Absorption Test

The concrete cubes required 28 and 56 days to cure after casting. A saturated water absorption (SWA) test was conducted according to ASTM C 642-81 [40], 28 and 56 days after curing. The samples were removed from the curing tank, dried at 105°C for 24 hours in the oven, cooled to room temperature, and then precisely weighed (dry weight) as W_1. Then, the dried samples were submerged in water. After wiping the surface with a dry cloth at predetermined intervals of 12 hours, specimen weights were recorded. A constant weight, W_2, was obtained in two consecutive observations after at least 48 hours. The percentage of water absorption was calculated using the formula below:

$$\text{Water absorbed} = (W_1 - W_2 / W_2) \times 100 \quad (1)$$

2.3.2. Sulphate Penetration Test

According to Mangi et al. [27], sodium sulphate (Na_2SO_4) solution was made. Ten grams of sodium sulphate were dissolved in 100 ml of solution to make a 5% Na_2SO_4 solution, which was mixed with water by percentage by weight (w/v). The cubes were then submerged in this solution after curing for 28 days. After being in the solution for 28, 56 days, the cubes were removed and dried on the surface. The cubes' surfaces were scrubbed and cleaned, and the final weights were determined as shown in Figure 8.

The formula for weight percent (w/v) is: [Mass of solute (g) / Volume of solution (ml)] × 100 (2)

Figure 8. samples under 5% Na2SO4 solution

2.3.3. Chloride Penetration Test

According to Mangi et al. [27], sodium chloride (NaCl) solution was made. Ten grams of sodium chloride were dissolved in 100 ml of water to create a 5% sodium chloride solution. This mixture was done using percentage by weight (w/v). The cubes were then submerged in this solution after curing for 28 days. After 28, 56 days, the cubes were removed from this solution and the surface dried. After cleaning and scrubbing the cubes' surface, the specimen's final surface dry weights were determined.

3. Results and Discussion

3.1. Microstructure

The microstructure of the three samples of the CBA of (raw, burning and flotation) shows that CBA has a porous surface. Many voids were observed due to their angular, rough textured and irregular shaped particles. Also, the raw material has several impurities such as dust on the surface compared to the treated sample as shown in Figure 9.

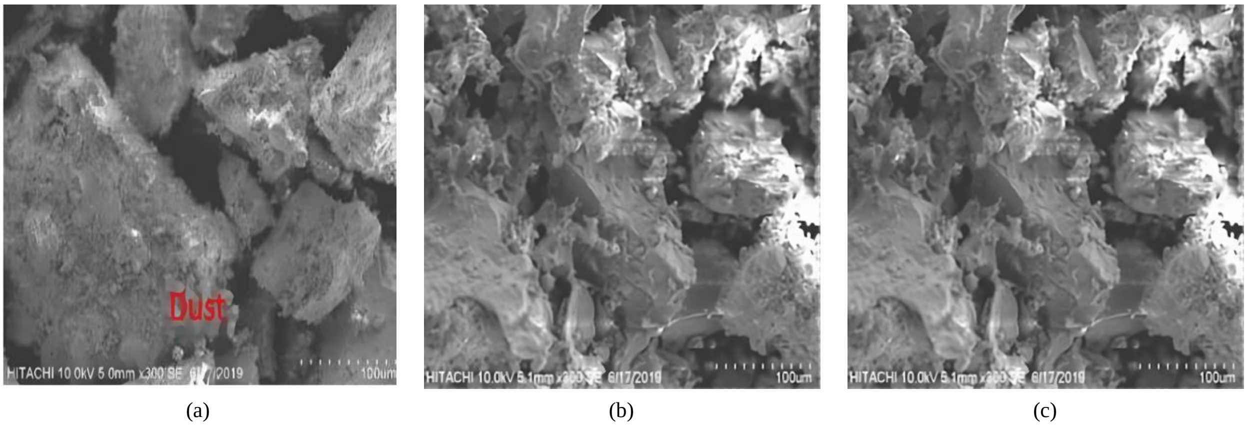

Figure 9. Raw CBA (a) Burning (b) Flotation (c) at 100 µm

3.2. Mechanical Properties

The mechanical properties of normal and CBA concrete are discussed in this section which includes the results of a compression strength, flexural strength and splitting tensile strength of the rubberized concrete.

3.2.1. Slump Test

The data in Figure 10 shows that the slump value of concrete decreases as the CBA percentage increases, for both burning and flotation treatment methods. This trend can be attributed to the high-water absorption ratio of CBA, which results from its porous surface and numerous voids. Additionally, the uneven surface texture of the CBA particles also plays a role in diminishing slump values. Notably, the treatment method applied to the CBA whether burning or flotation does not markedly influence the concrete's workability; the decline in slump values follows a similar trajectory for both treatments. The slope of this decline for each treatment method is roughly equivalent, indicating that the workability of concrete incorporating CBA is not significantly altered by the method of CBA treatment.

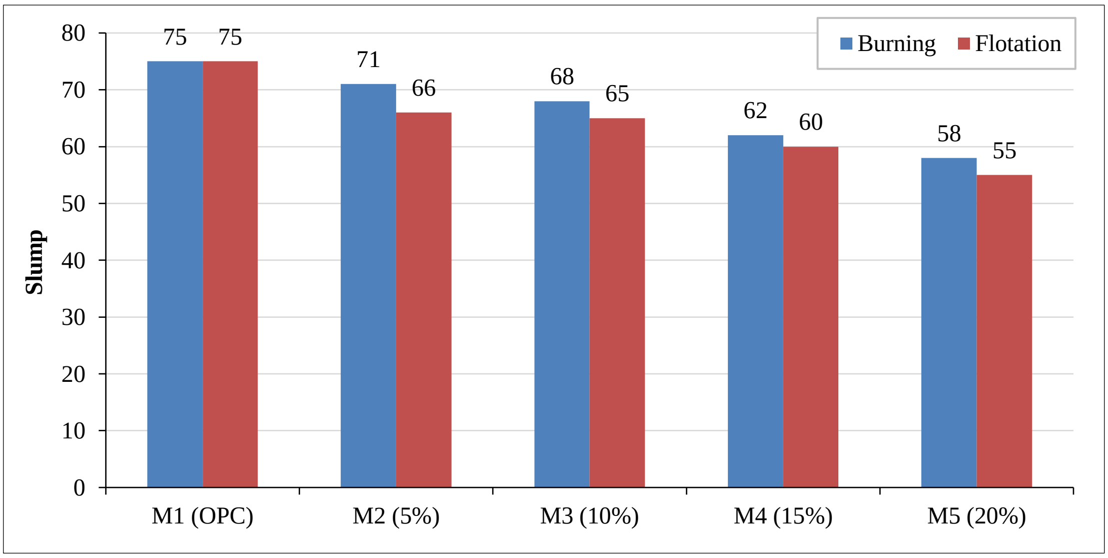

Figure 10. Slump test of CBA mixes after burning and flotation treatment

3.2.2. Compressive Strength

At 7, 28, and 56 days, all mixes underwent compression testing. Except for 10% CBA by burning treatment, all concrete samples produced with CBA replacement are generally lower than the control mix. Additionally, the findings show that burning CBA concrete rather than flotation treatment is preferred because it exhibits exceptional improvement, as shown in Figures 11 and 12.

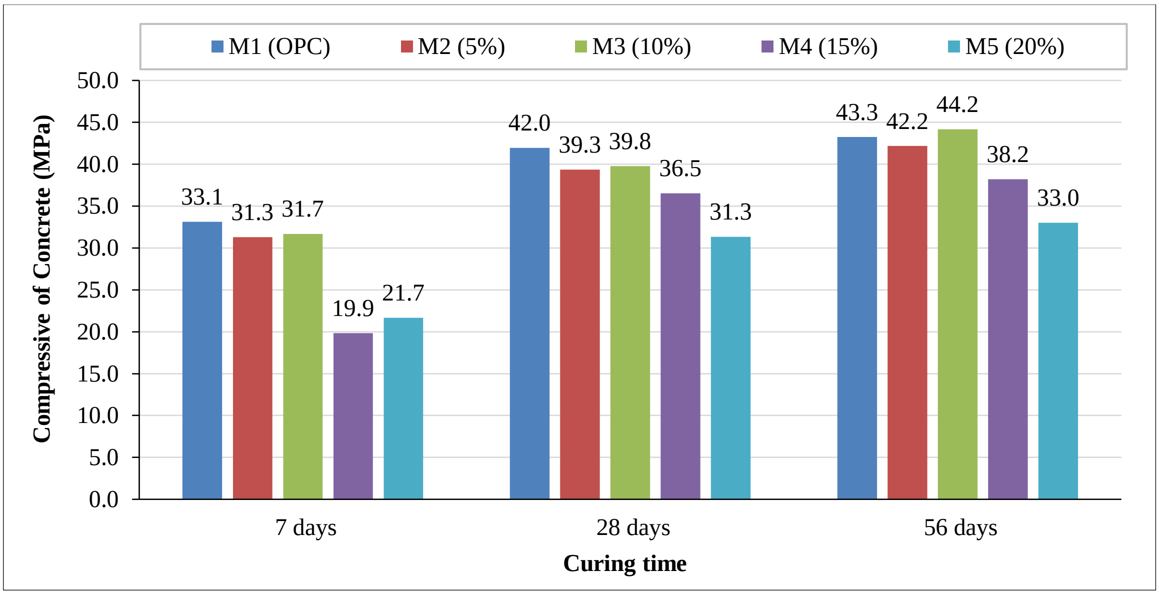

Figure 11. Compressive Strength of CBA mixes after Burning Treatment

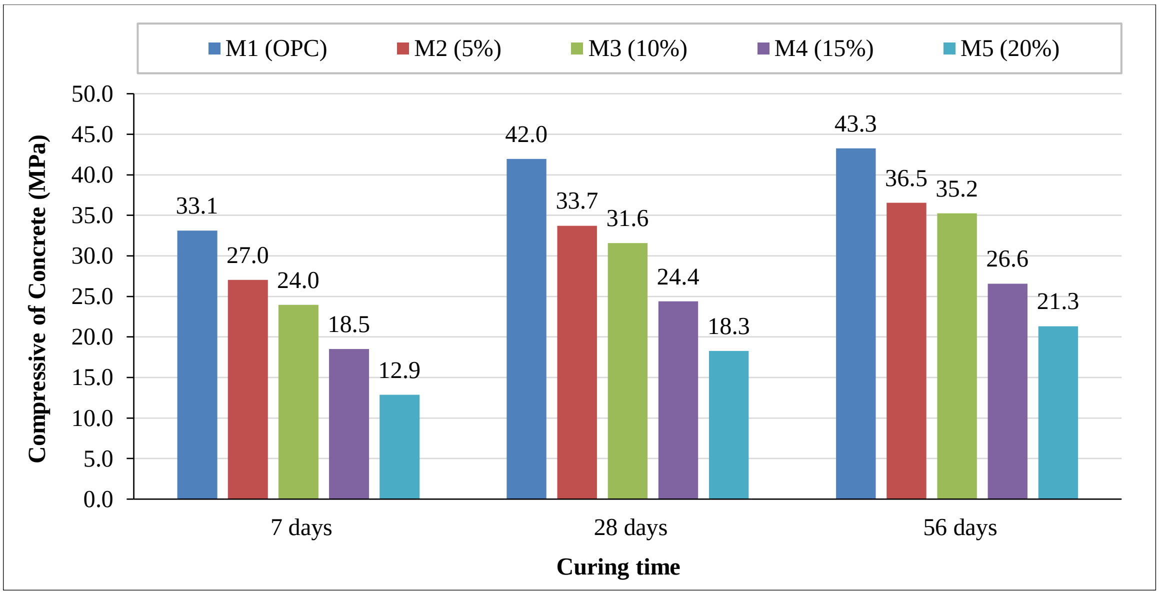

Figure 12. Compressive Strength of CBA mixes after Flotation Treatment

Additionally, the compressive strength of CBA treated by burning improves as CBA percentage rises until 10% before declining. However, the results show that, except for 20% CBA sample, CBA concrete reached the design strength of 35MPa after 28 days of curing. Figure 11 illustrates the strength starting to decline below the control mix at 56 days with a compressive strength of 10% CBA exceeding the control mix by 2%. As shown in Figure 12 the CBA samples that are treated by flotation present a drop in the strength as the CBA percentage increase and it never reach the control mix strength in any of the curing times. Some observations from Flotation Compression test results are that it took CBA concrete of 5% and 10% 56 days of curing to reach the design strength 35 MPa then the strength start to drop for 15% and 20%.

From Figure 11 and Figure 12 the huge difference between the burning and flotation treatment as most of the sample reached the designed strength at 28 days by burning treatment as for the flotation treatment it took it 56 days. However, that difference is indicated in the chemical compositions between the two of treatment methods as percentage of SiO_2 in the burning treatment is more than the flotation treatment by 20%. The difference in the chemical composition made burning treatment improve the concrete compressive strength by improving the hydration process, as SiO_2 is one of its main components. Also, the chemical composition helped to explain the slope of increasing strength at 10% of CBA then decreasing for 15% and 20% that is due the bottom ash requires a cementing agent such as Portland cement to reacts with water, if that percentage exceeded the CBA cannot be active in the hydration process. Beyond a 10% threshold, excess CBA does not contribute actively to the hydration process, thereby limiting further strength improvements.

3.2.3. Splitting Tensile Test

By conducting the test on cylinder specimens at 7 and 28 days after curing, the splitting tensile test is used to determine the tensile strength of the concrete. The split tensile of the CBA increased for the two treatment methods up to 10% CBA before starting to decline for 15% and 20%, according to the results shown in Figures 13 and 14. The control sample also produced strengths of 7.75 MPa after 7 days and 11.72 MPa after 28 days. Where burning treatment CBA concrete of 10% which resulted in 7.88 MPa and 13.02 MPa exceed the control mix at 7 day and 28 days, respectively shown in Figure 13. As for the Flotation treatment the 10% CBA concrete exceeded the control mix at 7 days split tensile strength but at 28 days it decreases by 8.3% compared to the control mix. Because of the slow hydration process that is caused by less silicate compared to burning CBA sample as shown in Figure 14. The improvement in split tensile strength, particularly with burning treatment, underscores the chemical composition and particle shape of CBA as key factors enhancing concrete's bonding and paste quality. This detailed analysis confirms the nuanced role of CBA in concrete's tensile strength, emphasizing the importance of treatment method and CBA content in achieving optimal concrete performance.

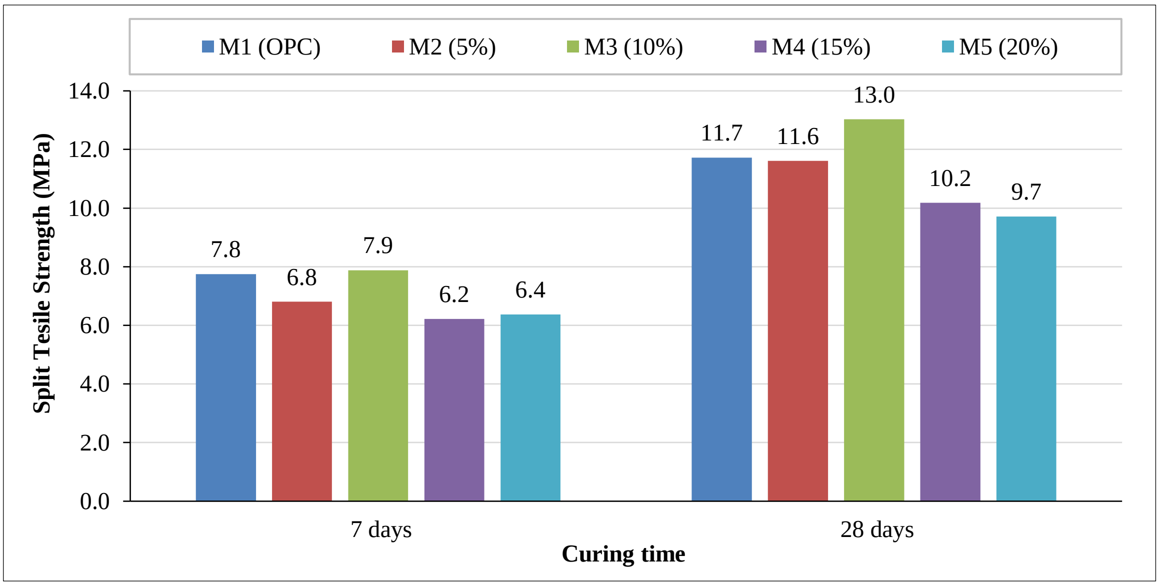

Figure 13. Split Tensile Strength of CBA mixes after Burning Treatment

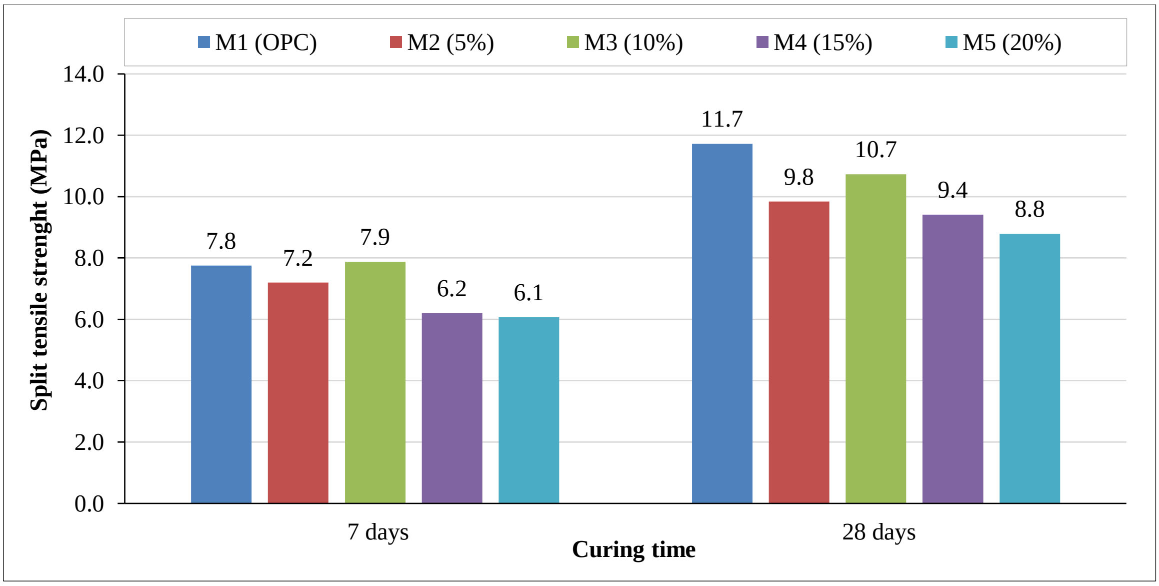

Figure 14. Split Tensile Strength of CBA mixes after Flotation Treatment

3.2.4. Flexural Strength

The specimens used for the four-point bending flexural tests were prepared 28 days after curing. Normal concrete mix is denoted by M1, and CBA concrete is denoted by M2 to M5. Figures 15 and 16 display the results, which demonstrate that the CBA concrete outperformed the control mix in terms of flexural strength.

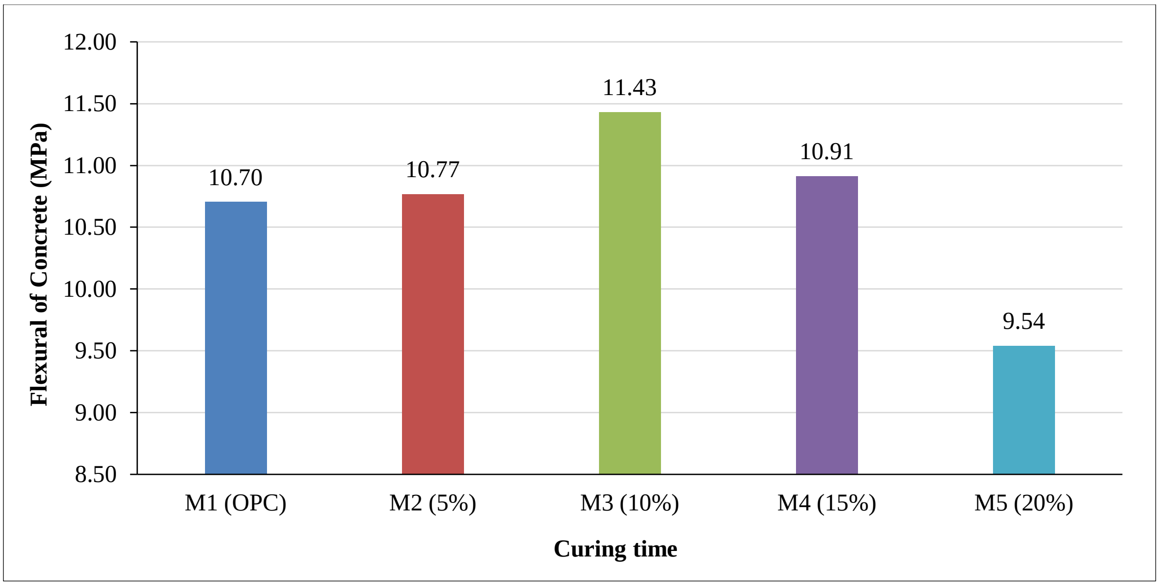

Figure 15. Flexural Strength of CBA mixes after Burning Treatment

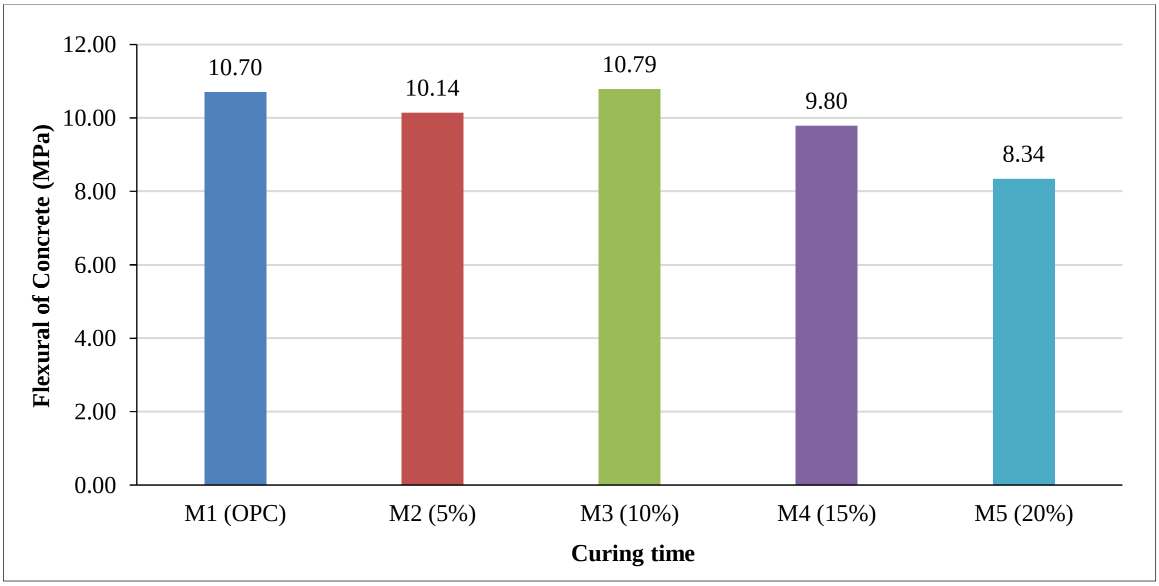

Figure 16. Flexural Strength of CBA mixes after Flotation Treatment

Figure 15 shows CBA concrete by burning treatment rise in the strength until 10% then reduction for 15% and 20%. The CBA concrete produced better results by 7% in flexural strength than normal concrete by producing 11.43 MPa average strength for 10% CBA compared to the control mix average of 10.7 MPa. The specimens were capable of withstanding measurable post failure load. As for the flotation treatment sample shown in Figure 16 the flexural strength has the same behavior as the burning treatment as the strength increases until 10% CBA then it stars to decline. The CBA concrete gave better flexural strength by 0.7% than the control mix by a small margin. That indicated in the CBA 10% by 10.78 MPa compared to control mix of 10.7 MPa. Furthermore, this analysis underscores the CBA's ability to withstand significant post-failure loads and its contribution to the spread of cracks within the tension region of the beam specimens. The CBA particles not only supported additional loads during crack formation but also expanded the failure surface area, attributing to their large deformation capacity and high compressive strength.

The flotation treatment samples mirrored the burning treatment's performance, improving strength up to 10% CBA before declining. However, the flexural strength improvement over the control mix was marginal at 0.7%, indicating a nuanced impact of CBA treatment methods on flexural strength. This enhancement in flexural strength, despite being slight with flotation treatment, suggests that the CBA's chemical composition and particle shape significantly contribute to the concrete mix's bonding and paste quality. The distinction between burning and flotation treatment outcomes emphasizes the critical role of CBA's silicate content in the hydration process, influencing the flexural strength development in concrete.

3.3. Chemical Properties

3.3.1. Saturated Water Absorption

The water absorption of burned CBA at 28 days of all the mixes contain CBA M2, M3, and M4 was found less than the control mix M1 except M5 which was higher than control mix, while the burned CBA at 56 days for the mixes M2 and M3 were found less than M1 and the rest of mixes were found higher than M1. The volume of water absorption in the concrete corresponds with the degree of porosity. Consequently, the result revealed that the concrete contains 5% and 10% of burned CBA will be able to enhance the degree of porosity of concrete more than control mix M1 for 28 and 56 days, as presented in Figure 17.

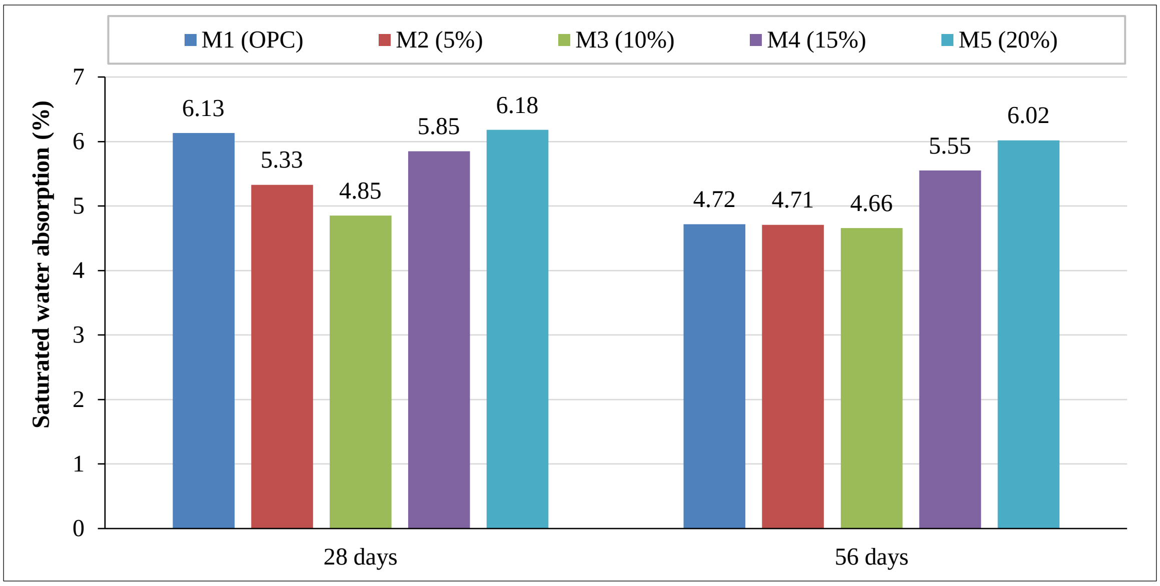

Figure 17. Saturated water absorption of all mixes subjected to burning treatment

On the contrary, the result of the CBA that treated with flotation revealed that at 28 days the water absorption of the mixes M2 and M3 was lesser than M1, while at 56 days all mixes M2, M3, M4, and M5 was higher than control mix M1. Hence, the degree of porosity for control mix superior on all the mixes contain CBA that treated with flotation, because the flotation treatment failed to enhance the degree of porosity for all mixes for short-term period, as presented in Figure 18. The expected drop in capillary absorption coefficients was noticed due to a reduction in overall porosity levels due to optimal particle packing and distribution. This suggests that while flotation treatment may initially improve porosity, its long-term effects do not sustain reduced water absorption, potentially due to the slower hydration process within the concrete matrix.

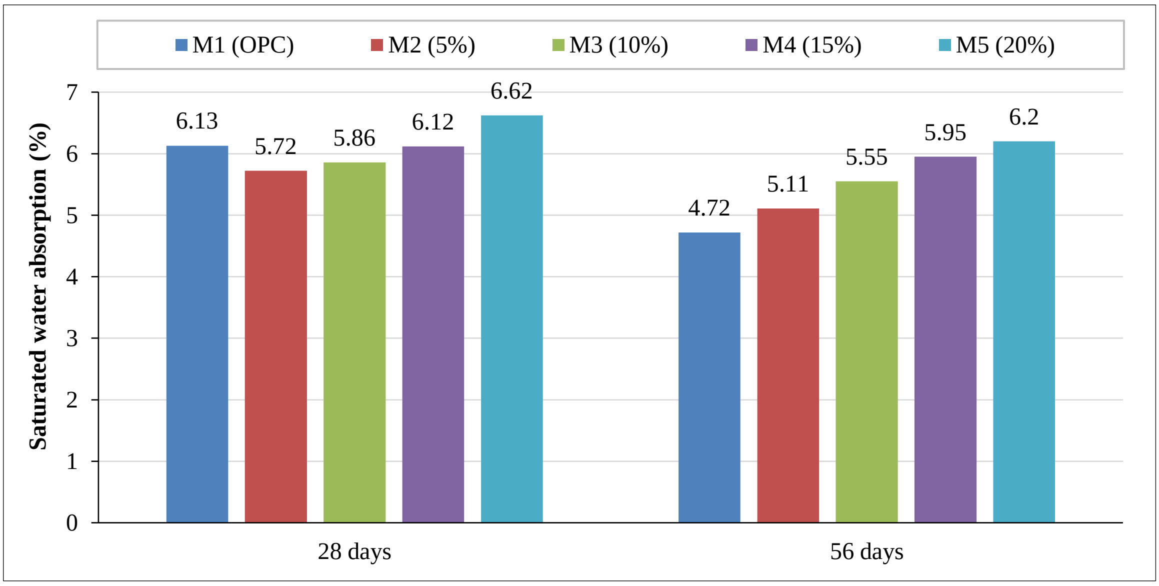

Figure 18. Saturated water absorption of all mixes subjected to flotation treatment

3.3.2. Compressive Strength of Concrete Submerged in 5% NaCl

The study investigated the effectiveness of concrete exposed for 28 and 56 days to a 5% sodium chloride (NaCl) solution under burning and flotation conditions. The findings indicated that the strength development of concrete mixes M2, M3, M4, and M5 was slower under 5% sodium chloride (NaCl) exposure conditions compared to the control mix M1. This slower development is attributed to the chloride solution producing chloro aluminate, which can cause deterioration at later ages. Additionally, the inclusion of CBA, containing amorphous silica, reacts with this chloro aluminate at later stages. The leaching of calcium hydroxide, $CaOH_2$, created by cement hydration and the formation of C-S-H (calcium silicate hydrate) gel, crucial in concrete, leads to a reduction in calcium hydroxide present due to the reaction between amorphous silica and calcium hydroxide. Thus, the presence of chloride solution impacts pore sizes and disrupts the hydration process, affecting the external appearance of concrete. Moreover, chloride ions influence the pore size distribution, critical for the properties of hardened concrete, resulting in potential harm or alterations, as depicted in Figures 19 and 20.

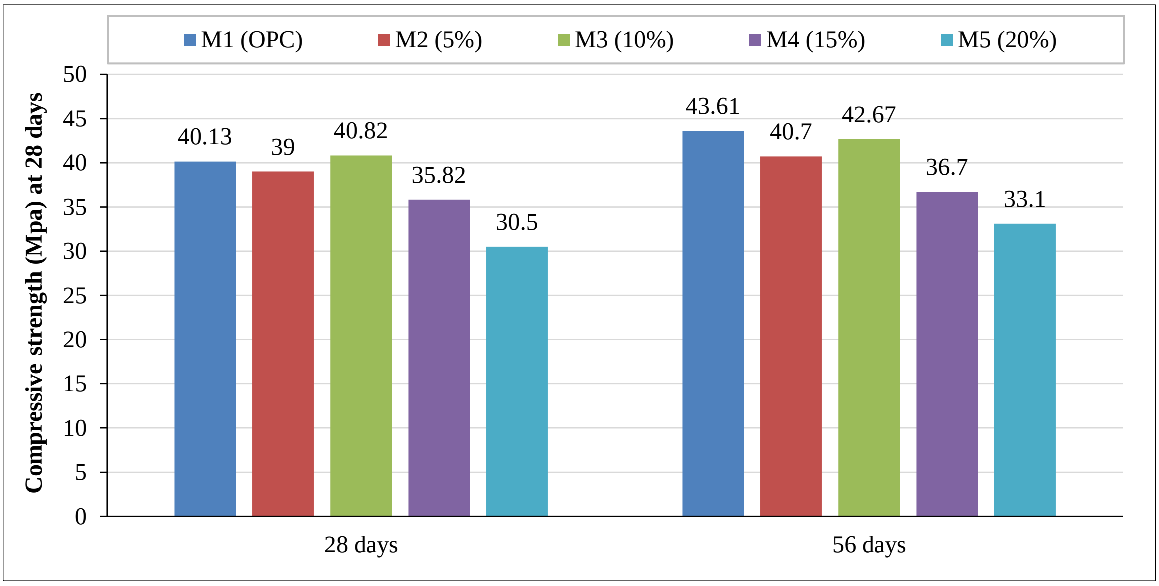

Figure 19. Compressive strength of concrete submerged in 5% NaCl Burning treatment

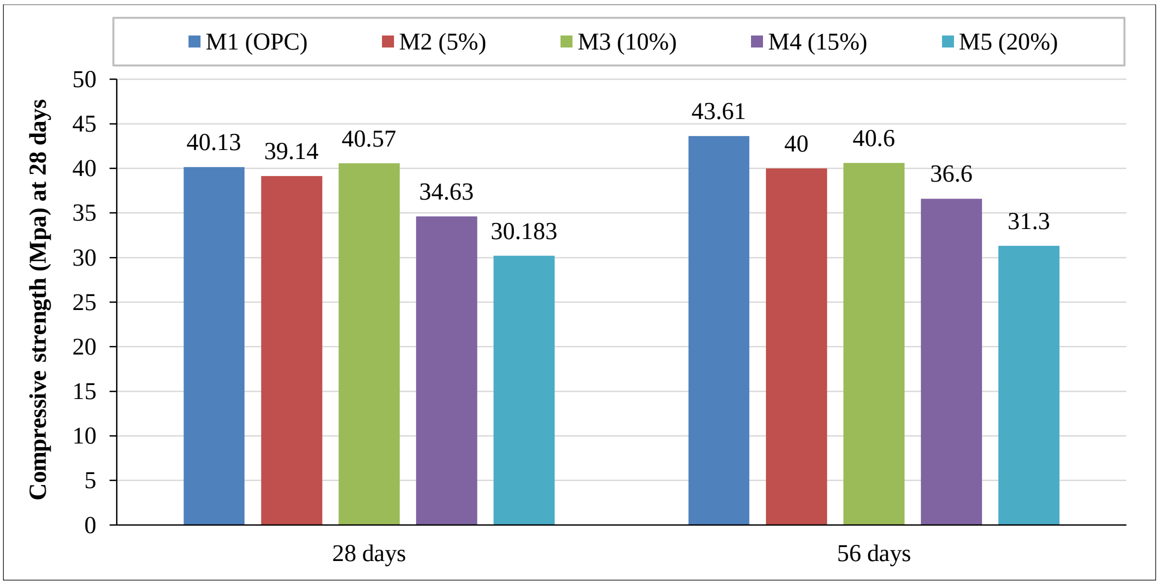

Figure 20. Compressive strength of concrete submerged in 5% NaCl Flotation treatment

3.3.3. Compressive Strength of Concrete Submerged in 5% Na_2SO_4

Figures 21 and 22 depict the performance of concrete containing CBA for burning and flotation treatment while submerged in a 5% Na_2SO_4 exposure condition. Except for mixes M4 and M5, which have lower strengths than the control mix, the results showed that the concrete containing CBA for mixes M2 and M3 was comparable with the control mix M1 for 28 days. Because, under short-term exposure conditions, sodium sulphate solution has no discernible effect on concrete with or without CBA.

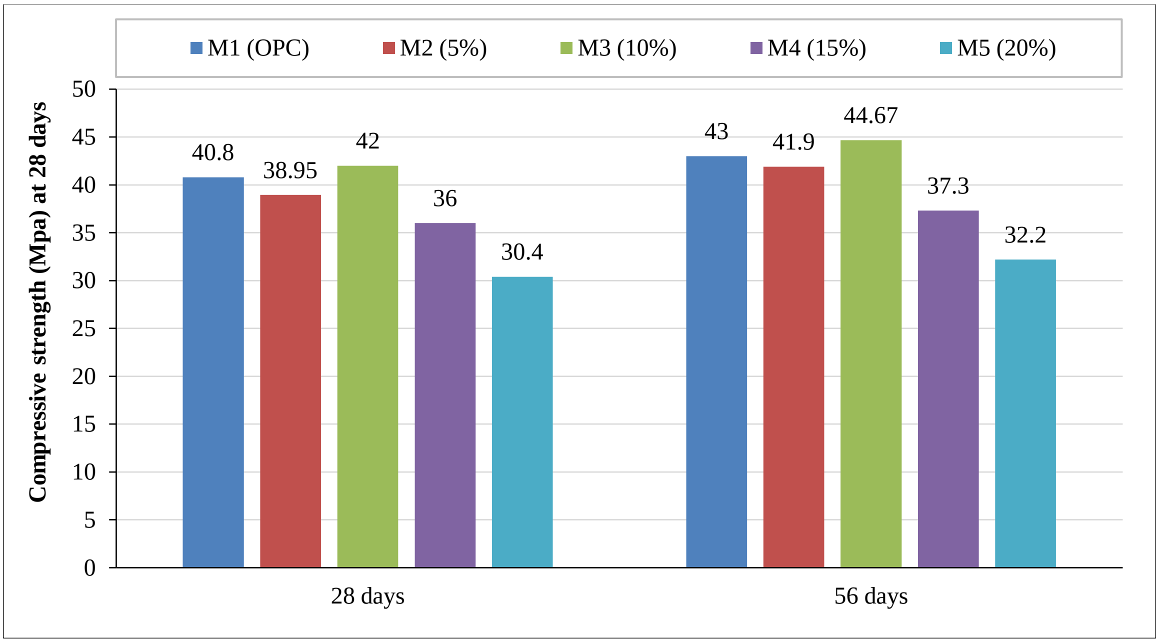

Figure 21. Compressive strength of concrete submerged in 5% Na_2SO_4 Burning treatment

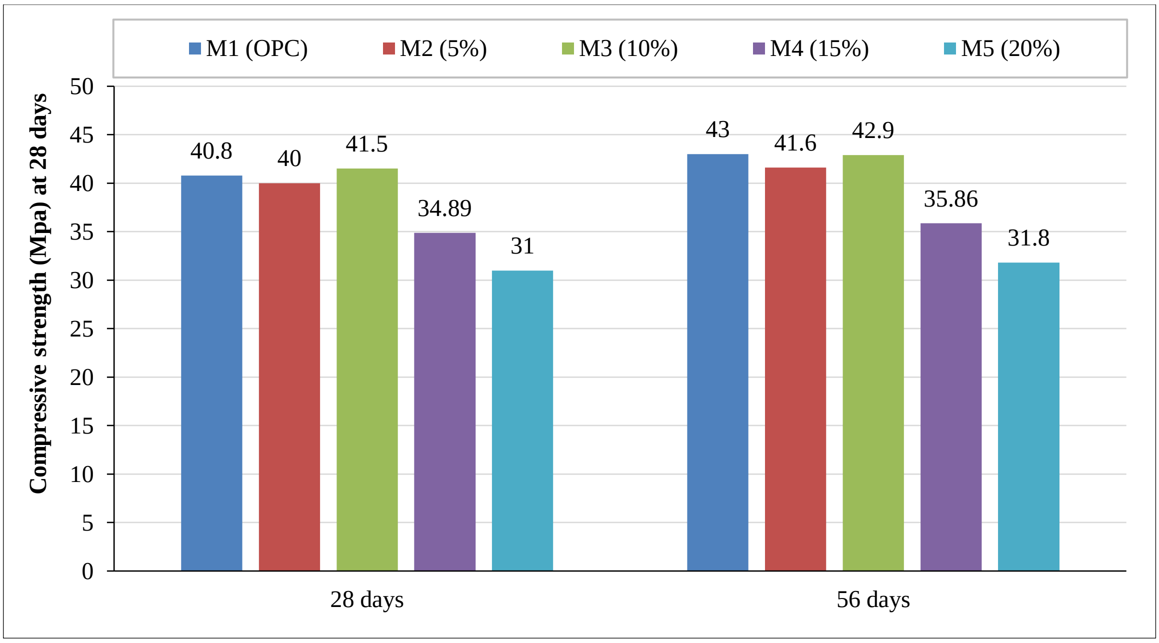

Figure 22. Compressive strength of concrete submerged in 5% Na_2SO_4 Flotation treatment

On the other hand, for mixes M3 and M2, the performance of concrete containing CBA was found to be superior to control mixes M1 and M2, respectively, for 56 days. Because the process of the Na_2SO_4 reaction was previously known as the sulfate ions that were present in the pores of the concrete, a chemical reaction between cement hydration and sulfate ions and sodium sulphate reacting with $CaOH_2$ to create gypsum and ettringite may occur in the pores of the concrete. Additionally, the pozzolanic reaction consumed calcium hydroxide, making the concrete denser and preventing the development of ettringite through sulfate attack. However, because the CBA contains less calcium oxide, it may be able to lessen the sulphate attack.

3.3.4. Sodium Chloride Penetration

Figures 23 and 24 show the findings for the weight change of concrete immersed in 5% NaCl solution for the burning and flotation treatment specimens at 28 and 56 days. The outcome reveals that M5 experienced the highest weight gain, while M1 experienced the lowest weight gain under the same conditions. Additionally, the M2, M3, and M4 mixes have gained more weight than M1. Because the presence of CBA in concrete for all mixes could not be able to reduce the hydration process and reduce salts penetrability in the concrete, the result shows that the concrete with lower effective was noticed in all mixes of concrete with CBA than the control mix. As a result, less weight gain was observed in control mix M1. Furthermore, the adverse effects of a NaCl solution on concrete mixes caused a compromised formation of calcium silicate hydrate (C-S-H) gel, which led to affecting pore sizes and disrupts the hydration process.

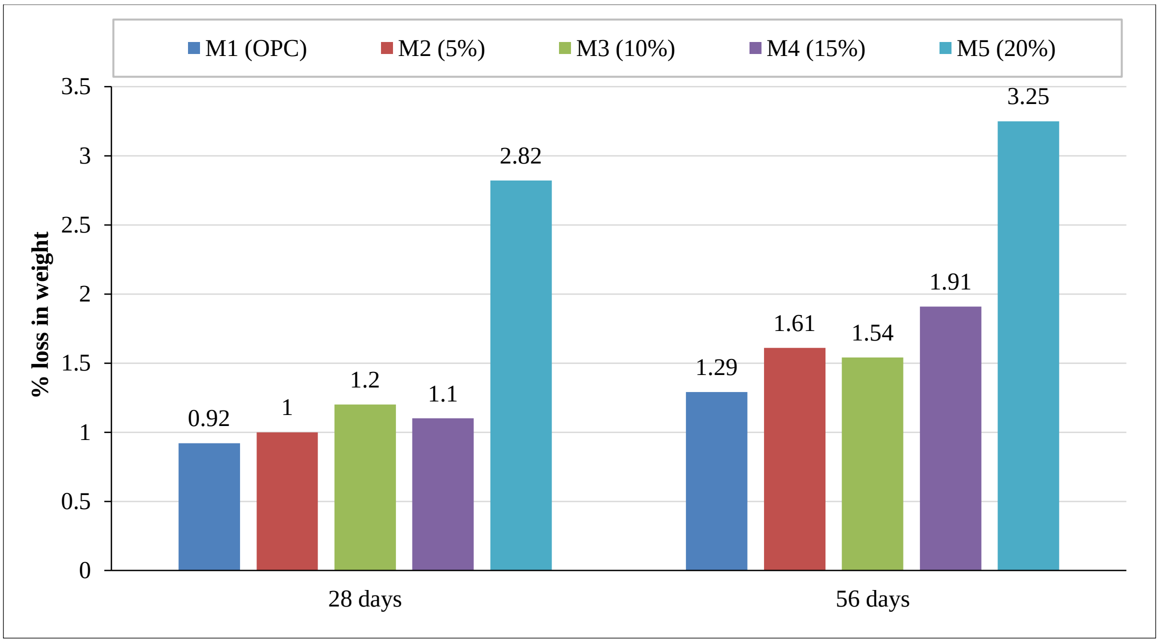

Figure 23. Change in weight for concrete submerged in 5% NaCl Burning treatment

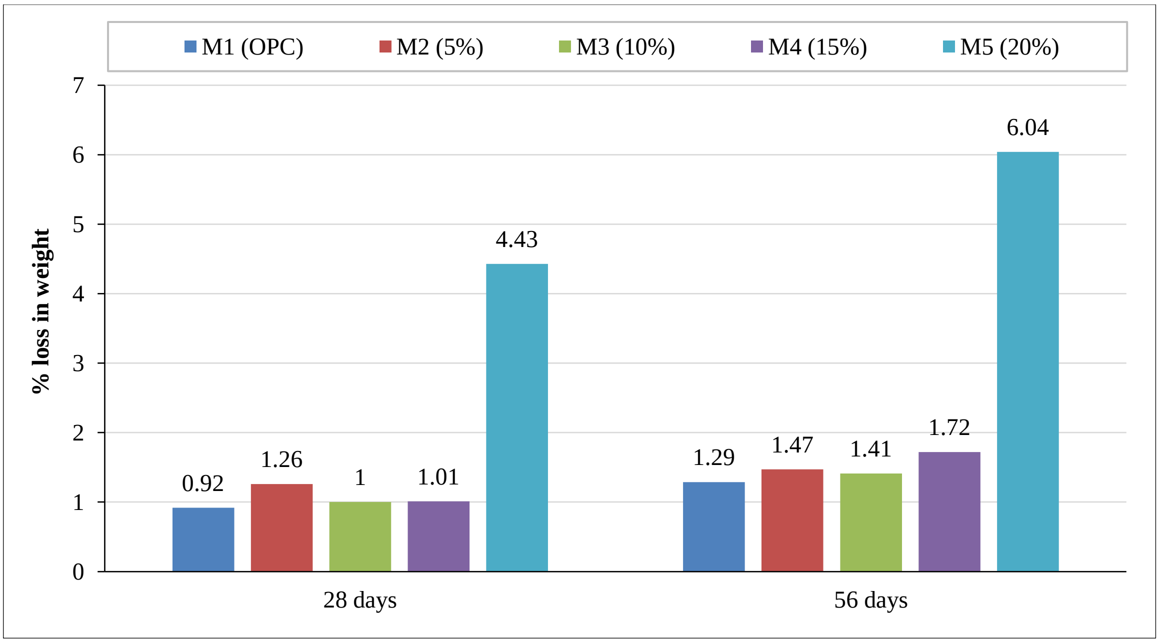

Figure 24. Change in weight for concrete submerged in 5% NaCl Flotation treatment

3.3.5. Sodium Sulphate Penetration

The impact of immersing concrete samples in a 5% Na_2SO_4 solution on weight change was evaluated for specimens subjected to burning and flotation treatments at 28 and 56 days, as depicted in Figures 24 and 25. The data indicate that mix M1 exhibited the highest weight gain, whereas mixes M3 and M2 experienced lower weight gains under identical conditions. Furthermore, while mixes M4 and M5 also gained less weight than M1, they were less effective in reducing weight gain compared to M3 and M2. The observed lower weight gain in mixes M3 and M2, relative to the control mix M1, suggests that the incorporation of CBA in these mixes could effectively reduce the hydration process and decrease the concrete's permeability to salts. This inclusion of CBA appears to have partially clogged the voids within the concrete matrix, thereby potentially enhancing the strength development in the concrete mix.

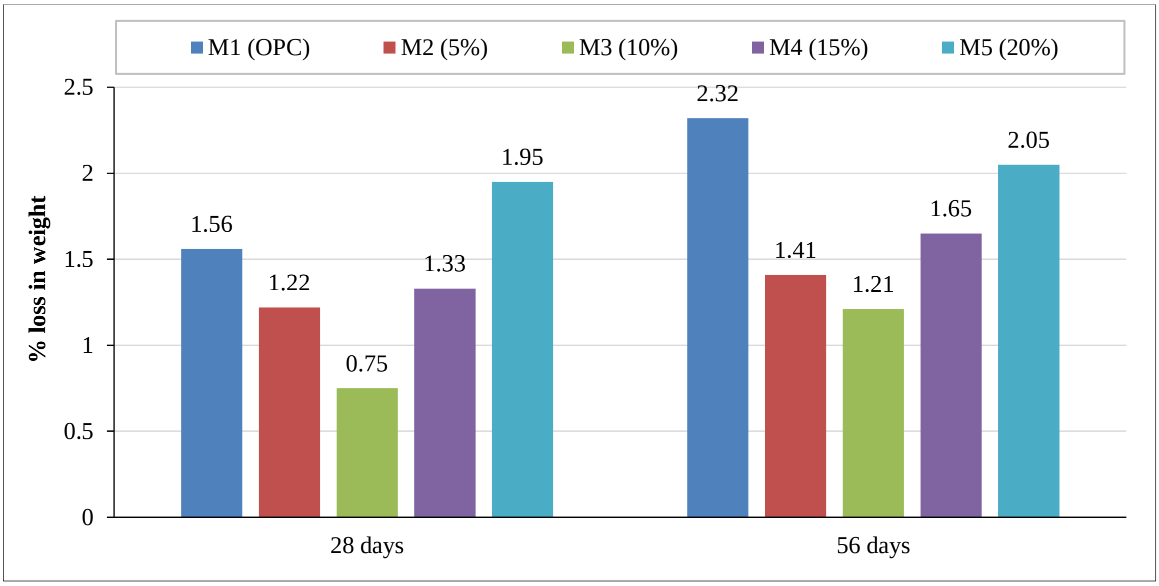

Figure 25. Change in weight for concrete submerged in 5% Na_2SO_4 Burning treatment

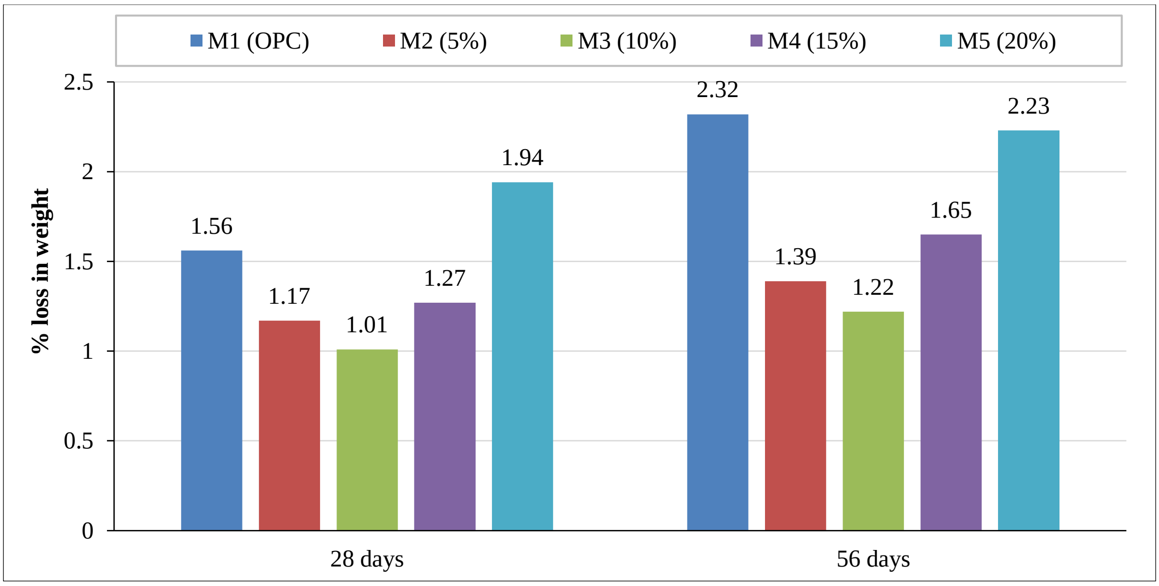

Figure 26. Change in weight for concrete submerged in 5% Na_2SO_4 Flotation treatment

4. Conclusions

The study and experimental results discussed in the previous chapter have led to the following conclusions:

- The slump decreases as the CBA percentage increases because CBA has a high-water absorption capacity.
- The compressive strength of concrete using burnt CBA showed an improvement compared to the control mix and flotation CBA concrete. This improvement is attributed to the high SiO_2 content in its chemical composition.
- Flexural and split tensile test results indicated an increase in strength for burnt CBA concrete compared to normal concrete. This is due to additional pozzolanic reactions within the concrete, which enhance the quality of the cement paste and interfacial transition zones.
- The chemical compositions of the two treatments show that the burning treatment provides more significant improvements in the mechanical properties of concrete compared to the flotation treatment. This improvement is due to the high SiO_2 content observed in the burning treatment, which enhances pozzolanic reactions.
- The durability performance of concrete containing a 10% increment of burnt CBA shows more enhancement and effectiveness than other mixes and is comparable to OPC concrete.
- The inclusion of a 10% increment of CBA in concrete can reduce the hydration process and increase porosity, leading to decreased salt penetrability in concrete compared to OPC concrete.

- Concrete containing CBA provides sufficient compressive strength, higher than the control mix with a 10% increment of CBA, when exposed to a 5% Na_2SO_4 solution. Moreover, it is not adversely affected under Na_2SO_4 solution exposure. However, under a 5% sodium chloride (NaCl) solution, the pozzolanic reaction becomes slower and requires more time to recover.
- The burning treatment proves to be more effective in enhancing the durability and strength of CBA concrete than the flotation treatment.
- The microstructure of treated coal bottom ash reveals particles that are denser and less porous, which could be comparable to OPC particles.

5. Declarations

5.1. Author Contributions

Conceptualization, F.N.A.A.A. and A.M.; methodology, A.M.; software, O.M.M.E.; validation, O.M.M.E., M.A., and H.A.D.; formal analysis, A.M.; investigation, A.M.; data curation, A.M.; writing—original draft preparation, A.I.; writing—review and editing, H.A.M. and M.A.; visualization, O.M.M.E.; supervision, F.N.A.A.A.; project administration, M.A.; funding acquisition, H.A.D. 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 the article.

5.3. Funding

The Article Processing Charges (APC) of this project are funded by the TRC research project BFP/RGP/EI/23/073, University of Nizwa, Oman.

5.4. Acknowledgements

Experimental work was carried out at Construction Material Laboratory, Universiti Putra Malaysia, Author is thankful to the academic advisors and mentors for supervising this research, and also, the authors would like to thank the University of Nizwa for its financial support.

5.5. Conflicts of Interest

The authors declare no conflict of interest.

6. References

[1] El-Bitouri, Y. (2023). Rheological Behavior of Cement Paste: A Phenomenological State of the Art. Eng (Switzerland), 4(3), 1891–1904. doi:10.3390/eng4030107.

[2] Alaneme, G. U., Iro, U. I., Milad, A., Olaiya, B. C., Otu, O. N., Chibuisi, U. P., & Agada, J. (2023). Mechanical Properties Optimization and Simulation of Soil–Saw Dust Ash Blend Using Extreme Vertex Design (EVD) Method. International Journal of Pavement Research and Technology, 1–27. doi:10.1007/s42947-023-00272-4.

[3] Arafa, S., Milad, A., Yusoff, N. I. M., Al-Ansari, N., & Yaseen, Z. M. (2021). Investigation into the permeability and strength of pervious geopolymer concrete containing coated biomass aggregate material. Journal of Materials Research and Technology, 15, 2075–2087. doi:10.1016/j.jmrt.2021.09.045.

[4] Elbasir, O. M. M., Johari, M. A. M., Ahmad, Z. A., Mashaan, N. S., & Milad, A. (2023). The Compressive Strength and Microstructure of Alkali-Activated Mortars Utilizing By-Product-Based Binary-Blended Precursors. Applied Mechanics, 4(3), 885–898. doi:10.3390/applmech4030046.

[5] Dehwah, H. A. F. (2007). Effect of sulfate concentration and associated cation type on concrete deterioration and morphological changes in cement hydrates. Construction and Building Materials, 21(1), 29–39. doi:10.1016/j.conbuildmat.2005.07.010.

[6] Abdul Kadir, A., & Hassan, M. I. H. (2015). Leachability of Self-Compacting Concrete (SCC) Incorporated with Fly Ash and Bottom Ash by Using Synthetic Precipitation Leaching Procedure (SPLP). Applied Mechanics and Materials, 773–774, 1375–1379. doi:10.4028/www.scientific.net/amm.773-774.1375.

[7] Sandhya, B., & Reshma, E. K. (2013). A study on mechanical properties of cement concrete by partial replacement of fine aggregates with bottom ash. International Journal of students research in Technology & Management, 1(4), 416-430.

[8] Qaidi, S., Najm, H. M., Abed, S. M., Ahmed, H. U., Al Dughaishi, H., Al Lawati, J., Sabri, M. M., Alkhatib, F., & Milad, A. (2022). Fly Ash-Based Geopolymer Composites: A Review of the Compressive Strength and Microstructure Analysis. Materials, 15(20), 7098. doi:10.3390/ma15207098.

[9] Kadam, M. P., & Patil, Y. D. (2015). Effect of sieved coal bottom ash as a sand replacement on the properties of cement concrete. Magazine of Concrete Research, 67(5), 227–234. doi:10.1680/macr.14.00179.

[10] Rafieizonooz, M., Salim, M. R., Mirza, J., Hussin, M. W., Salmiati, Khan, R., & Khankhaje, E. (2017). Toxicity characteristics and durability of concrete containing coal ash as substitute for cement and river sand. Construction and Building Materials, 143, 234–246. doi:10.1016/j.conbuildmat.2017.03.151.

[11] An American recycling success story. (2015). Beneficial use of Coal Bottom Combustion Products. American Coal Ash Association (ACAA), Denver, United States.

[12] Dewi, S. J., Ramadhansyah, P. J., Norhidayah, A. H., Md. Maniruzzaman, A. A., Hainin, M. R., & Che Norazman, C. W. (2014). Performance of RHA Blended Cement Concrete under Sodium Chloride via Wetting and Drying. Applied Mechanics and Materials, 554, 106–110. doi:10.4028/www.scientific.net/amm.554.106.

[13] Jamaluddin, N., Hamzah, A. F., Wan Ibrahim, M. H., Jaya, R. P., Arshad, M. F., Zainal Abidin, N. E., & Dahalan, N. H. (2016). Fresh Properties and Flexural Strength of Self-Compacting Concrete Integrating Coal Bottom Ash. MATEC Web of Conferences, 47, 01010. doi:10.1051/matecconf/20164701010.

[14] Ibe Iro, U., Alaneme, G. U., Milad, A., Olaiya, B. C., Otu, O. N., Isu, E. U., & Amuzie, M. N. (2022). Optimization and Simulation of Saw Dust Ash Concrete Using Extreme Vertex Design Method. Advances in Materials Science and Engineering, 5082139. doi:10.1155/2022/5082139.

[15] Kadir, A. A., Hassan, M. I. H., & Abdullah, M. M. A. B. (2016). Investigation on Leaching Behaviour of Fly Ash and Bottom Ash Replacement in Self-Compacting Concrete. IOP Conference Series: Materials Science and Engineering, 133(1), 012036. doi:10.1088/1757-899X/133/1/012036.

[16] Ewa, D. E., Ukpata, J. O., Otu, O. N., Memon, Z. A., Alaneme, G. U., & Milad, A. (2023). Scheffe's Simplex Optimization of Flexural Strength of Quarry Dust and Sawdust Ash Pervious Concrete for Sustainable Pavement Construction. Materials, 16(2), 598. doi:10.3390/ma16020598.

[17] Um, N.-I., Ahn, J.-W., Han, G.-C., Lee, S.-J., Kim, H.-S., & Cho, H. (2008). Flotation process in coal bottom ash and their effect on the removal of unburned carbon. Geosystem Engineering, 11(4), 75–80. doi:10.1080/12269328.2008.10541289.

[18] Qaidi, S., Najm, H. M., Abed, S. M., Özkılıç, Y. O., Al Dughaishi, H., Alosta, M., Sabri, M. M. S., Alkhatib, F., & Milad, A. (2022). Concrete Containing Waste Glass as an Environmentally Friendly Aggregate: A Review on Fresh and Mechanical Characteristics. Materials, 15(18), 6222. doi:10.3390/ma15186222.

[19] ASTM C33/C33M-18. (2023). Standard Specification for Concrete Aggregates. ASTM International, Pennsylvania, United States. doi:10.1520/C0033_C0033M-18.

[20] Meena, A., Singh, N., & Singh, S. P. (2023). High-volume fly ash Self Consolidating Concrete with coal bottom ash and recycled concrete aggregates: Fresh, mechanical and microstructural properties. Journal of Building Engineering, 63, 105447. doi:10.1016/j.jobe.2022.105447.

[21] Singh, G., & ShriRam. (2023). Microstructural and other properties of copper slag–coal bottom ash incorporated concrete using fly ash as cement replacement. Innovative Infrastructure Solutions, 8(2), 78. doi:10.1007/s41062-023-01051-7.

[22] Muthusamy, K., Wong, W. H., Mohamad, N., Rajan, J., Budiea, A. M. A., P.P. Abdul Majeed, A., & Kırgız, M. S. (2023). Properties of concrete containing coal bottom ash as hydraulic binder substitution. In Advance Upcycling of By-products in Binder and Binder-Based Materials: Woodhead Publishing, 243–250. Woodhead Publishing. doi:10.1016/B978-0-323-90791-0.00002-0.

[23] Sorum, M. G., & Kalita, A. (2023). Effect of Bio-Cementation with Rice Husk Ash on Permeability of Silty Sand. Civil Engineering Journal, 9(11), 2854-2867. doi:10.28991/CEJ-2023-09-11-016.

[24] Singh, M., & Siddique, R. (2016). Effect of coal bottom ash as partial replacement of sand on workability and strength properties of concrete. Journal of Cleaner Production, 112, 620–630. doi:10.1016/j.jclepro.2015.08.001.

[25] Rafieizonooz, M., Mirza, J., Salim, M. R., Hussin, M. W., & Khankhaje, E. (2016). Investigation of coal bottom ash and fly ash in concrete as replacement for sand and cement. Construction and Building Materials, 116, 15-24. doi:10.1016/j.conbuildmat.2016.04.080.

[26] Milad, A., Ali, A. S. B., Babalghaith, A. M., Memon, Z. A., Mashaan, N. S., Arafa, S., & Nur, N. I. (2021). Utilisation of waste-based geopolymer in asphalt pavement modification and construction; a review. Sustainability (Switzerland), 13(6), 3330. doi:10.3390/su13063330.

[27] Mangi, S. A., Wan Ibrahim, M. H., Jamaluddin, N., Arshad, M. F., & Putra Jaya, R. (2019). Short-term effects of sulphate and chloride on the concrete containing coal bottom ash as supplementary cementitious material. Engineering Science and Technology, an International Journal, 22(2), 515–522. doi:10.1016/j.jestch.2018.09.001.

[28] Benson, C. H., & Bradshaw, S. (2011). User guideline for coal bottom ash and boiler slag in green infrastructure construction. University of Wisconsin, Madison, United States.

[29] Alawi, A., Milad, A., Barbieri, D., Alosta, M., Alaneme, G. U., & Imran Latif, Q. B. alias. (2023). Eco-Friendly Geopolymer Composites Prepared from Agro-Industrial Wastes: A State-of-the-Art Review. CivilEng (Switzerland), 4(2), 433–453. doi:10.3390/civileng4020025.

[30] Singh, N., Shehnazdeep, & Bhardwaj, A. (2020). Reviewing the role of coal bottom ash as an alternative of cement. Construction and Building Materials, 233, 117276. doi:10.1016/j.conbuildmat.2019.117276.

[31] Khan, R. A., & Ganesh, A. (2016). The effect of coal bottom ash (CBA) on mechanical and durability characteristics of concrete. Journal of building materials and structures, 3(1), 31-42. doi:10.34118/jbms.v3i1.22.

[32] Ibrahim, A. H., Choong, K. K., Megat Johari, M. A., Md Noor, S. I., Zainal, N. L., & Ariffin, K. S. (2015). Effects of Coal Bottom Ash on the Compressive Strength of Portland Cement Mortar. Applied Mechanics and Materials, 802, 149–154. doi:10.4028/www.scientific.net/amm.802.149.

[33] ASTM C618-19. (2022). Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. ASTM International, Pennsylvania, United States. doi:10.1520/C0618-19.

[34] ASTM C150 / C150M-19a. (2020). Standard Specification for Portland Cement. ASTM International, Pennsylvania, United States. doi:10.1520/C0150_C0150M-19A.

[35] ASTM C33-03. (2010). Standard Specification for Concrete Aggregates. ASTM International, Pennsylvania, United States. doi:10.1520/C0033-03.

[36] ASTM C109 / C109M-16. (2016). Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens). ASTM International, Pennsylvania, United States. doi:10.1520/C0109_C0109M-16.

[37] ASTM C78 / C78M-18. (2021). Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading). ASTM International, Pennsylvania, United States. doi:10.1520/C0078_C0078M-18.

[38] ASTM C293/C293M-16. (2016). Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Center-Point Loading). ASTM International, Pennsylvania, United States. doi:10.1520/C0293_C0293M-16.

[39] ASTM C496 / C496M-17. (2017). Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens, ASTM International, Pennsylvania, United States. doi:10.1520/C0496_C0496M-17.

[40] ASTM C642-21. (2022). Standard Test Method for Density, Absorption, and Voids in Hardened Concrete. ASTM International, Pennsylvania, United States. doi:10.1520/C0642-21.