sustainability

Article

The Implementation of a Binary Blend of Waste Glass Powder and Coal Bottom Ash as a Partial Cement Replacement toward More Sustainable Mortar Production

Stephen Babajide Olabimtan and Mohammad Ali Mosaberpanah *

Civil Engineering Department, Cyprus International University, North Cyprus, Nicosia 99258, Turkey; stephenbabajide1@gmail.com
* Correspondence: mmosaberpanah@ciu.edu.tr

Abstract: One way the sustainability and efficiency of concrete production can be improved is by incorporating waste by-products into the mix. This can help reduce the use of natural resources, such as river sand, and prevent the pollution of valuable land. Two specific examples of waste by-products that can be used in the concrete industry are waste glass powder and coal bottom ash. This study presents an experimental investigation that analyzes the influence of adding glass powder and waste bottom ash from 0% to 20% with a 5% interval to produce high-performance mortar for rheological, mechanical, and durability properties cured under different conditions (wet and dry) and temperatures (20 °C), and at several curative processes at 7 and 28 days. The water/cement ratio is a constant 0.35. According to the research findings, blending glass powder and coal bottom ash in the production of mortar results in a significant improvement in performance, particularly in terms compressive and flexural strength (3.4–20.8%) (1.7–20.3%), while employing a 10% WGP and 10% CBA binary blend provides a large increase in the flexural strength (10.6%). In the fire resistance test, 15% WGP and 5% CBA has the maximum bond strength at 200 °C (2.6%). In SEM pictures of WGP and CBA, it is found that the two materials have a low porosity compared to the control cement mortar. Furthermore, the study finds that 10% glass powder and 10% coal bottom ash combined with cement paste is the best percentage of waste by-products to use in the creation of high-performance mortar. This ratio was discovered to be the most successful in terms of increasing mechanical, rheological, and durability qualities.

Keywords: cement replacement; waste glass powder; coal bottom ash; waste materials

check for updates

Citation: Babajide Olabimtan, S.; Mosaberpanah, M.A. The Implementation of a Binary Blend of Waste Glass Powder and Coal Bottom Ash as a Partial Cement Replacement toward More Sustainable Mortar Production. *Sustainability* **2023**, *15*, 8776. https://doi.org/10.3390/su15118776

Academic Editors: Natt Makul and Gritsada Sua-Iam

Received: 25 April 2023
Revised: 17 May 2023
Accepted: 25 May 2023
Published: 29 May 2023

1. Introduction

Concrete has been a prevalent building material throughout the course of history and continues to be a fundamental element in modern civil engineering projects [1]. Its significance can be seen in its wide usage across infrastructure development, as it is an essential component in the construction industry. The durability and strength of concrete make it an ideal material for a wide range of structures such as bridges, roads, dams, buildings, and many more. Due to its versatility and cost-effectiveness, concrete has become a staple material in the construction industry. It continues to be a fundamental element in the design, construction, and maintenance of various structures, making it a significant material in the development of infrastructure. According to Kumar et al. [2], after water, it is the substance that is the most used on Earth. The most common materials used in concrete are cement, (fine) sand, (coarse) gravel aggregates, and water. Waste deposition has recently become a major consideration. Improving the eco-friendly proper disposal of industrial debris has become a universal challenge in maintaining a cleaner and greener environment. Seeking to preserve a cleaner and greener environment, ecologically acceptable solutions for the safe discharge of industrial waste are increasingly a global issue. The construction industry's growth has accelerated the demand for concrete and its component, notably ordinary Portland cement (OPC). Its increasing level of industrial and domestic debris is the source of numerous environmental concerns and burdens. Resource depletion, pollution, and waste management are just a few of the environmental problems that recycling is essential for solving. The use of natural resources, landfill waste, and carbon emissions can all be decreased by recycling waste materials in building. Researchers have looked into employing recycled components in concrete production to improve construction performance and reuse waste. Many waste and recyclable materials have been discovered to have pozzolanic attributes, which have significance when replacing cement in concrete. Pulverized fuel ash (FA), also known as flue ash or coal ash, and silica fume (SF), also known as micro silica [3], as well as other less frequently used materials such as marble dust [4–6], rice husk ash [7], glass powder [8,9], brick dust [10], and chemosphere [8,11] are examples of these materials.

The principal cause for the generation of these wastes is the massive growth rate of population development in industrial areas. Manufacturing by-products, often known as industrial waste, have been intensively researched as a viable alternative to Portland cement in concrete. The demand for innovative materials rises in line with the general demand for low-cost, environmentally friendly construction materials. In 2005, the worldwide value of waste glass manufacturing was 130 million tons, with the EU, China, and the United States producing approximately 33 million tons, 32 million tons, and 20 million tons, respectively [12]. Glass is not compostable; therefore, it has adverse hazards and can be costly to dispose in a landfill. When cement replacement is substituted with crushed waste glass for concrete manufacturing, it can provide significant energy, environmental, and economic advantages by boosting the reactions between glass and cement hydration. Waste glass has also been considered an additional component in the formation of concrete. An excellent pozzolan has the potential to reduce ASR (alkali silica reaction) while also using a proportion of lime [13].

Glass is made by liquefying a combination of silicon dioxide, washing soda, and calcite ($CaCO_3$) at an elevated heat, followed afterwards by temperature-controlled cooling. Waste glass is largely generated from bottles, jars, windows, windshields, bulbs, cathode ray tubes, etc. Glass is a renowned type of material across the globe. This material was found as early as 5000 BC and has been manufactured for a wide range of uses. Glass is a one hundred percent renewable source that can be reprocessed permanently without reduction in quality [14]. Quaxz et al. [15] explore the hazards of waste glass (WG) and emphasize the importance of economically and environmentally friendly recycling. They investigate the physical and chemical properties of WG and review the existing literature on its use as a substitute for aggregates in concrete. The study aims to demonstrate the potential of recycled WG in concrete and to provide practical guidance while identifying research gaps and outlining future objectives for further investigation. The variances in chemical levels of various types of glass, as well as the challenges in categorizing multiple-color glass, make reuse problematic [16]. Based on its chemical characteristics, it is composed mainly of amorphous silica (SiO_2), which is the primary component of glass. In addition, waste glass contains various other oxides such as alumina (Al_2O_3,CaO, MgO, Na_2O, and K_2O). Glassware is classified as soda-lime glass, borosilicate glass, lead glass, and alumina silicate glass, among others. Soda-lime glass is extensively used in the production of bottles, floats, and sheets, and it accounts for more than 80% of the weight in waste glass [17]. To process scrap glass to be employed as aggregates in concrete, it is crushed to a certain size. In recent years, waste glass has indeed been tested as a part substitute for coarse aggregates, sand, and cement in concrete and mortar. The lack of a designated storage area for waste glass poses a risk of soil and water pollution, as it can undergo oxidation. To address this environmental concern, the utilization of recycled glass in concrete production can make a significant contribution toward reducing such problems, as highlighted in several studies [18–21]. According to Aliabdo et al. [4], 75 μm glass powder is an excellent choice for substituting as well as applying to cement. Rheological properties are widely recognized as the utmost efficient approach for determining the load-bearing capacity of cementitious composites. GP was replaced by cement up to 25% by unit weight in this investigation, with 90% passing (#200 sieve). Wang et al. [22] showed that employing glass powder as an alternative to OPC produces positive results for the durability parameter up to a 10% replacement quantity, with improved microstructure of blended mortar at 28 days. According to Taha et al. [23], integrating ground glass into concrete lowers overall moisture absorption and controls water and ion migration inside the concrete/mortar by preventing the continuance of the pores and micro-cracks. Due to its well-known pozzolanic qualities, waste glass powder, in contrast, is a substance that shows outstanding potential as a cement substitute. Therefore, there is a lot of interest in the synergistic performance of finely ground waste glass powder when used in conjunction with other pozzolanic materials in the field of sustainable construction [24].

According to the guidelines established by ASTM C618-19, waste glass is characterized by notable calcium content and an amorphous structure, which endows it with the potential to be ground into a fine powder suitable for use as either a pozzolanic material or a cement additive. This is owing to the ability of the waste glass to react chemically with the surrounding environment when combined with water, thus forming a cementitious compound. Therefore, through the process of pulverization, waste glass powder (WGP) can be obtained and employed as a constituent in the production of concrete [25,26]. Zeybek et al. [27] found that replacing 20% of cement with waste glass powder (WGP) in concrete is optimal. However, combining WGP with crushed glass particles initially improved but later decreased mechanical properties due to reduced workability. They recommend using 10% WGP as the replacement level, resulting in stronger strength and better workability due to the merging of waste glass particles. It is also important to dwell in the alkali silica reaction. There is a possibility of an alkali–silica aggregate reaction when employing micro powdered glass in cement-based materials. This is a chemical reaction that can occur between the alkalis found in cement and certain reactive minerals in the aggregate. Over time, this reaction can cause concrete to swell and crack, resulting in decreased durability and significant structural difficulties, according to Özkılıç et al. [28]. Their study examined the impact of adding waste glass aggregate (WGA) with fly ash in different proportions to geopolymer concrete (GPC) with varying molarity values of NaOH concentration. The results indicated that the optimal mix includes 10% glass aggregate and NaOH molarity of 16 for sustainable GPC with desirable properties. The study also developed strength models and an equation to predict compressive strength. SEM analysis was carried out on GPC examples containing WGA. This study provides valuable insights for designing and optimizing sustainable GPC utilizing waste materials. Another recent study by Çelik et al. [29] examined the impact of waste glass powder (WGP) on the workability and setting time of geopolymer concrete (GPC). WGP was shown to reduce workability and slump values, whereas high NaOH molarity enhanced capacity but decreased setting time and workability. According to the findings, 10% WGP mixed with M13 NaOH provides the optimal balance of fresh and hardening qualities for long-term GPC.

When a large volume of coal is burned to create electricity in a thermal power plant, coal bottom ash is produced. Power stations create a lot of coal powder which is some of the most prevalent industrialized waste. According to Cheriaf et al. [30], the production of 1.2 million metric tons of bottom ash from 2.9 million metric tons of coal makes it a significant source of energy. The application of green and recycled by-products in the building industry has now become a problem for the engineering and construction community. As a result of the degradation of non-renewable materials in the building sector, the building industry is being required to reconsider the use of industrial effluents as supplemental resources.

CBA (coal bottom ash) is indeed wastage debris caused by the burning of pulverized coal that significantly contributes to industrial solid waste. In recent years, bottom ash from coal has been employed as an alternate for fine aggregate in concrete. According to [31], CBA with a high degree of fineness is thought to have advantageous pozzolanic characteristics. Bottom ash has been demonstrated to be a cost-effective resource due to its good engineering qualities and constructability. Sarawak, Sabah, and East Malaysia are the three Malaysian regions in which coal may be extracted. It produces electricity at the power plant by being burned in a furnace with a boiler. Abu Bakar et al. [32] stated that coal bottom ash is frequently rough, highly porous, gelatinous, light, and gritty, with a cement-like appearance. Additionally, they showed that the presence of SiO_2 and Al_2O_3 in coal bottom ash induces pozzolanic activity During the hydration of cement, it also reacts with calcium hydroxide Ca $(OH)_2$ to create cementitious compounds (CSH) and calcium aluminate hydrate (CAH). Coal is considered a major source of energy in Malaysia [33,34].

Singh and Siddique [35] investigated coal bottom ash in the laboratory. Coal bottom ash is a dark grey material that contains angular particles of varied shapes. Coal bottom ash is wastage of coal combustion in a thermal plant at 1400–1500 °C, which creates bottom ash of varied sizes that may be classified as fine or coarse particles in high-strength concrete [36]. According to a recent study, replacing fine aggregate with CBA can lower tensile strength by up to 30%, whereas cement additives can boost compressive strength. Flexural strength is increased at lower CBA replacement levels, but it can be decreased by 25% when typical fine aggregate is replaced. Additionally, the porous nature of CBA can increase water absorption, but some cement additives may be able to increase the rate [37]. Karalar et al. [38] also conducted a recent study investigating the effect of different ratios of bottom ash as fine aggregate on the cracking and flexural behavior of reinforced concrete beams. The study utilized various concrete series with different aggregate sizes and supplemented them with bottom ash and aggregate particles, replacing fine aggregates at ratios of 25%, 50%, 75%, and 100%. Results showed that using 75% BARs provided the best displacement capacity, while 100% BARs decreased deflection capacity. The abrasive nature of MSW-BA mortars in challenging environments was investigated, and it was discovered that the reaction of bottom ash's metallic aluminum with OH- ions produced hydrogen gas, resulting in increased porosity and decreased performance. Leaching of highly soluble chemicals in high humidity settings significantly hindered performance, especially when recycled aggregates were being employed. However, bottom ash alkali activation led to quick carbonation and increased strength [39].

Aramraks [40] revealed the moisture requirements of concrete mixes including between 50 and 100 percent coal bottom ash as a sand replacement. Aggarwal [41] explored how well bottom ash performed in place of fine aggregate to produce concrete with a strength of 33.3 MPa, but found that the amount of bottom ash in the concrete actually reduced. When compared to sand particles, Raju et al. [42] observed that replacing bottom ash by up to 50% enhances moisture content. Porous aggregates absorb more water, making them more workable. Bottom ash has an excellent permeability rate, and an earlier study indicated that bottom ash water absorption has an impact on concrete workability. The compressive strength of concrete comprises bottom ash, which is used to partially substitute cement in concrete or mortar, resulting in a slightly lower compressive strength than conventional concrete. The porosity of the hydrated paste influences the strength contributions of concretes [43].

Prior studies and findings reached the conclusion that the utilization of waste glass powder in cement-based composites yields promising outcomes in terms of overall performance. Nonetheless, scant attention has been given to the implementation of a binary blend that comprises both waste glass powder and coal bottom ash in cement mortar and the resultant effects on the production of a more sustainable mortar. Considering the recent developments in the field, the available literature suggests conducting an in-depth investigation into the influence of the aforementioned materials (i.e., waste glass powder and coal bottom ash) on cement mortar. An evaluation of the overall efficacy of the mortar would entail examining various aspects, such as its mechanical properties (including compressive and flexural strength), as well as its durability properties (such as fire resistance, acid attack, dry shrinkage, and water absorption). Additionally, studying the microstructure of the materials would be imperative to gain a comprehensive understanding of their nomenclature.

2. Materials and Methods

2.1. The Raw Materials

2.1.1. Cement

The research implements Type 1 cement, as specified, in compliance with the American Society for Testing and Materials guidelines; the raw material blends were made with 42.5-grade cement [44].

2.1.2. Waste Glass Powder

Waste glass powder with a diameter of less than 90 µm was used, which was produced from different color bottles, which are commonly known as beer bottles. Figure 1 shows the meticulous process of how the bottles were collected from dumpsites, campus restaurants, and wine shops; subsequently, all the bottles were soaked, washed, and rinsed to remove any paper labels, dust, or other unwanted materials. They were crushed and grounded by a crushing machine called the Los Angeles Machine after drying. Figure 2 also shows the SEM image of WGP. The waste glass powder used had a particle size of 75 µm to match the particle size range of the binder (cement) in order to achieve a homogeneous structure with minimal voids.

Figure 1. (**a**) Bottles picked from different places and brought to the laboratory. (**b**) Bottles are soaked, washed, and cleaned to remove label papers and dust. (**c**) Bottles are broken so they can be easily crushed by the Los Angeles Machine. (**d**) Glass powder after having been crushed and sieved to a particle size of 75 µm.

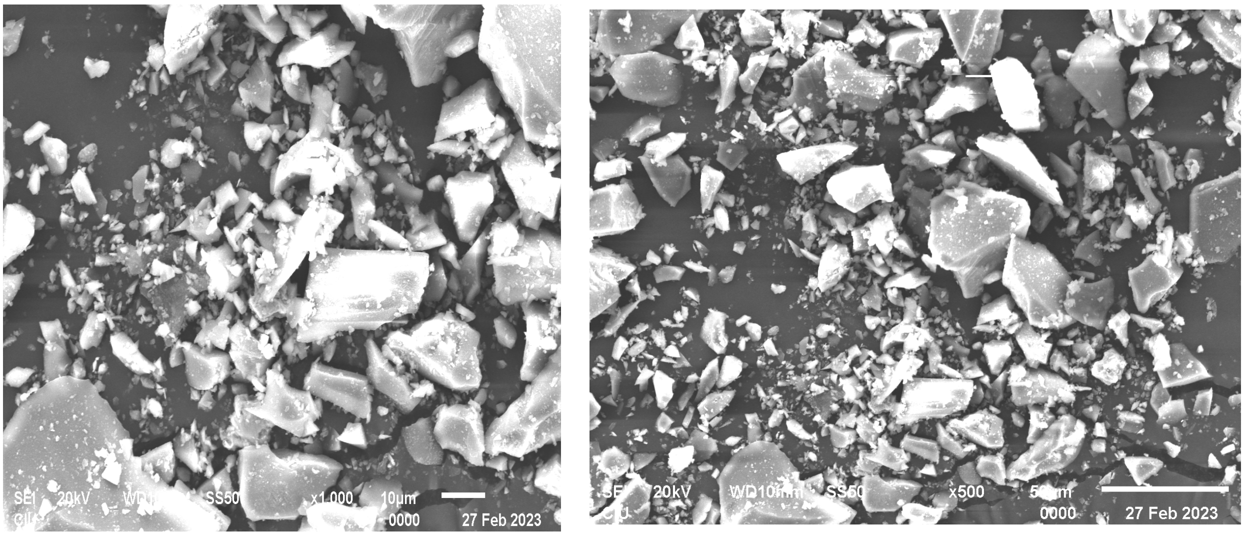


Figure 2. SEM image of waste glass powder particles.

2.1.3. Coal Bottom Ash

The used coal bottom ash in this course of research was treated as dry bottom ash (DBA), which was obtained by drying raw bottom ash at room temperature for 24 h. This coal was collected from the thermal plant of Gurdag Trading and Brick Industry Limited located at Hospolat Sanayi Bolgesi No 3, Lefkosa, North Cyprus. Figures 3 and 4 depict the ground coal bottom ash collected and its SEM image. The coal bottom ash used had a particle size of 75 µm to match the particle size range of the binder (cement) in order to achieve a homogeneous structure with few voids.

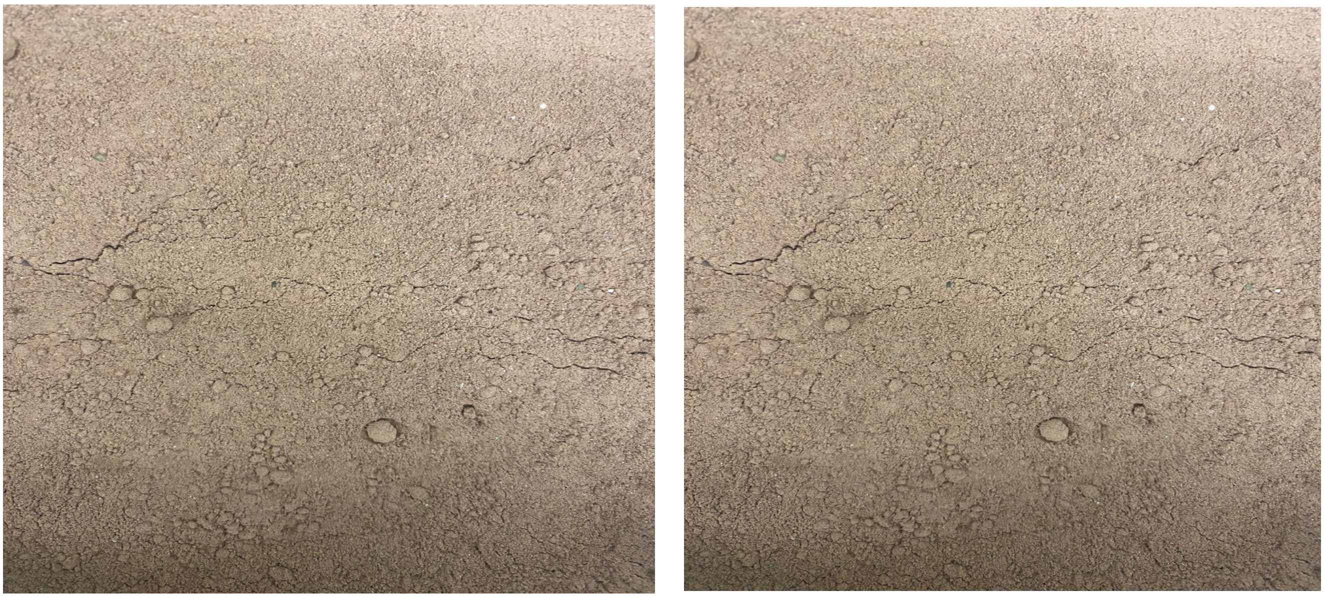


Figure 3. The grounded coal bottom ash after collection.

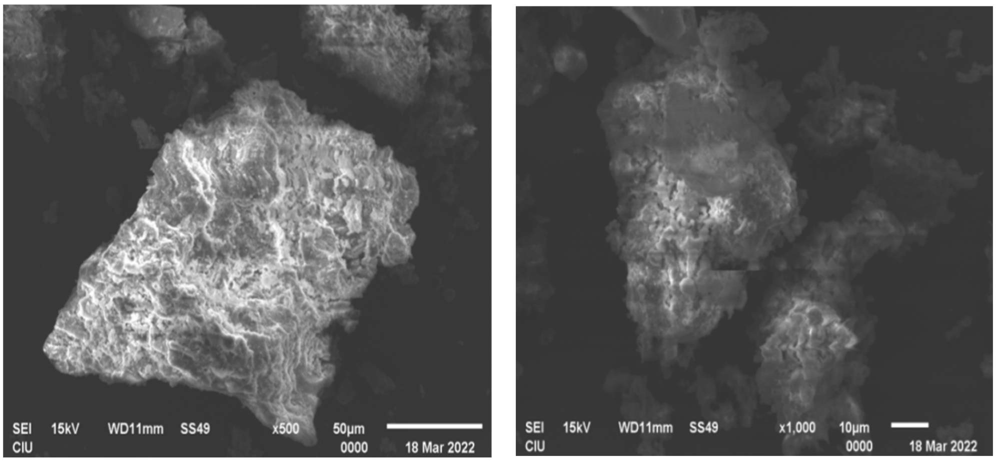


Figure 4. SEM image of coal bottom ash particles.

2.1.4. Fine Aggregate

Fine aggregate is classified as a particle that passes through the sieve at 4.75 mm. The main role of sand in a concrete mix is to fill the voids between coarse aggregates. Particle size distribution, specific gravity, and water absorption of river sand and coal bottom ash are shown in ASTM C33/C33M-18 [45]. Specifically, finely ground limestone served as the study's fine aggregate, and specifications are given in Table 1. As depicted in Figure 5 the sand was sieved to obtain the desired particle size distribution in conformance with ASTM C136/C136M-19 [46] (sieve chart). Based on the most recent ASTMC128-15 [47], the sand was utilized in an immersed dry condition to limit the water absorbed in the course of mixing.

Table 1. Outline of the sand's characteristics.

Properties	Value
Specific gravity (SSD)	2.66
Moisture absorption (%)	1.32
Bulk density (Kg/m^3)	1728
Loss bulk density (Kg/m^3)	1576
Fineness modulus	2.79
Moisture content (%)	0.1

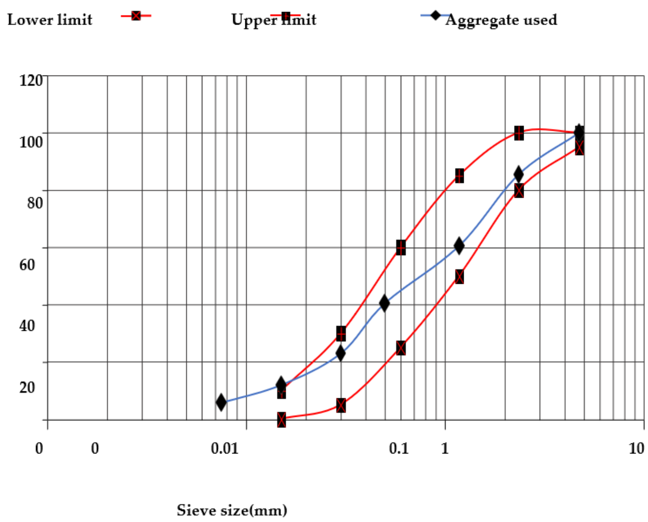


Figure 5. The grain size distribution of sand.

2.1.5. XRD, Elemental Composition of Waste Glass Powder

The X-ray diffraction technique was employed to examine the crystalline phase in waste glass powder. A Rigaku powder diffractometer utilizing K Cu wavelength radiation was used for this analysis, which covered a range of 2° to 90° positions (2θ, Cu-Kα). The samples were dried and sifted through a 75 µm sieve before scanning. The data collected from this technique. Figure 6 revealed the composition of coesite, which is also known as silicon dioxide SiO_2, for which waste glass powder has the highest peak.

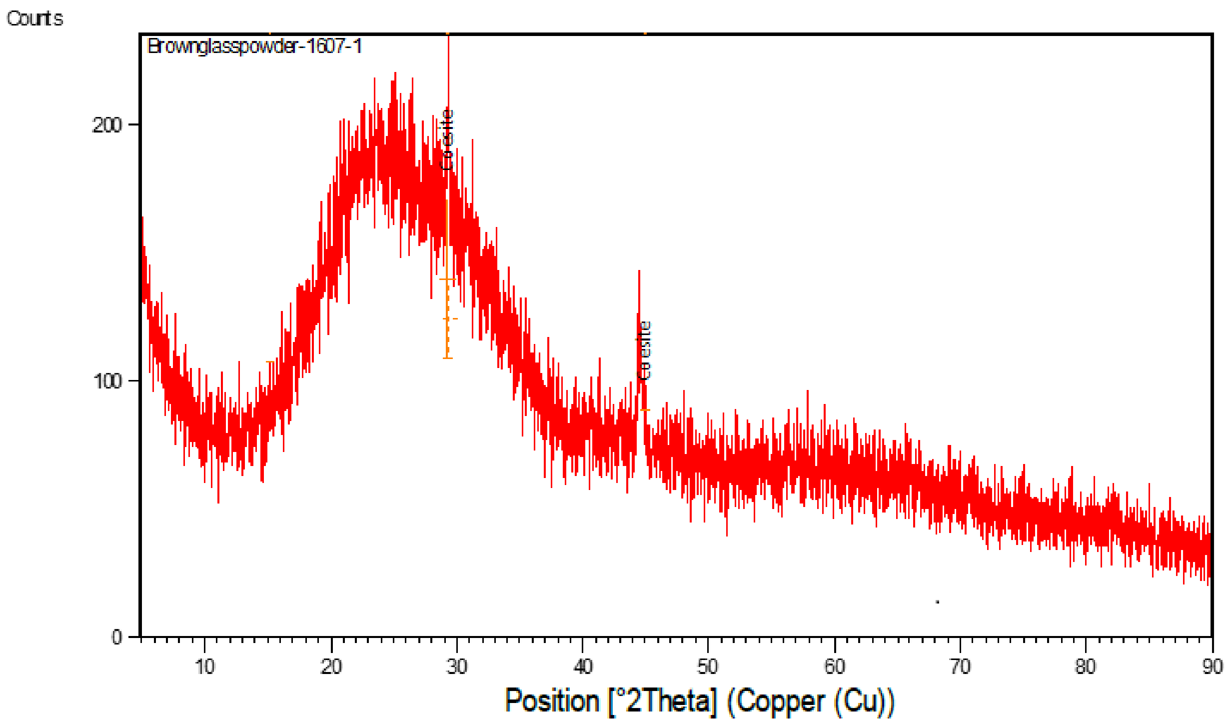


Figure 6. XRD analysis of waste glass powder.

2.2. Methods

2.2.1. Mix Proportions

Six different combinations were generated using the design of the experimental approach to investigate the effects of substituting cement with waste glass powder and coal bottom ash in a high-performance mortar. This collection of mixes includes a control mix. A design blend of waste glass powder and coal bottom ash is utilized to form a composite material with superior qualities over the individual components. Tables 2 and 3 show the proportional mix design and the altered SP dosage. ASTM C270-19a [48] displays the names of the mixed materials used in the study, which are abbreviated as CM, WGP20, WGP15-CBA5, WGP10-CBA10, WGP5-CBA15, and CBA20. The abbreviations CM, WGP, and CBA refer to control mix, waste glass powder, and coal bottom ash, respectively. The use of a design mixture for waste glass powder and coal bottom ash can offer a sustainable option for waste management while also producing a material with improved qualities.

Table 2. Nomenclature of mortars and cement replacement detail.

Nomenclature	Cement (%)	WGP (%)	CBA (%)
Control Mix	100	0	0
WGP 20%-CBA 0%	80	20	0
WGP 15%-CBA 5%	80	15	5
WGP 10%-CBA 10%	80	10	10
WGP 5%-CBA 15%	80	5	5
WGP 0%-CBA 20%	80	0	20

Table 3. The structure of the mixes.

Mix ID	W/B	Cement (Kg/m^3)	Sand (Kg/m^3)	Water (Kg/m^3)	GP (Kg/m^3)	CBA (Kg/m^3)	SP (Kg/m^3)
CM	0.35	684	1538	239	0	0	10.26
WGP20-CBA 0	0.35	547.2	1538	239	136.8	0	10.26
WGP15-CBA 5	0.35	547.2	1538	239	102.6	34.2	10.26
WGP10-CBA10	0.35	547.2	1538	239	68.4	68.4	10.26
WGP5-CBA 15	0.35	547.2	1538	239	34.2	102.6	10.26
WGP0-CBA20	0.35	547.2	1538	239	0	136.8	10.26

Note: CM: control mix; WGP: waste glass powder; CBA: coal bottom ash; W/B: water binder ratio; SP: superplasticizer.

2.2.2. Specimen Preparation

As required by ASTM C305-20 [49], mortar mixtures were created. For a short while, fine aggregates, binders, coal bottom ash (CBA), waste glass powder (WGP), and cement were dry mixed. To handle larger amounts, moist mixes were utilized. Intervals of 14–15 min were required for mixing. For multiple testing, the mixture was put into steel molds of particular sizes. Steel molds approximately 50 mm × 50 mm × 5 mm were utilized for compressive strength, water absorption, fire resistance, acid attack, and packing density testing. Short-length prism molds with the dimensions 40 mm × 40 mm × 40 mm were utilized for the flexural strength tests. Long-length prism molds that were 25 mm × 25 mm × 300 mm were used for drying shrinkage tests. To prevent surface voids and simple demolding, all of the casting forms (cubes and prisms) utilized were composed of metal and were thoroughly lubricated. Figure 7 shows the mortar mixer, a machine used to mix cement-based composite materials. It ensures consistency and accuracy in the results by blending ingredients such as cement, sand, water, and additives used in making construction mortar. Figure 8 shows the casted blend in the mold. All of the cast specimens are left at room temperature for 24 h or one hour after demolding to set or harden.

Figure 7. Mortar mixer.

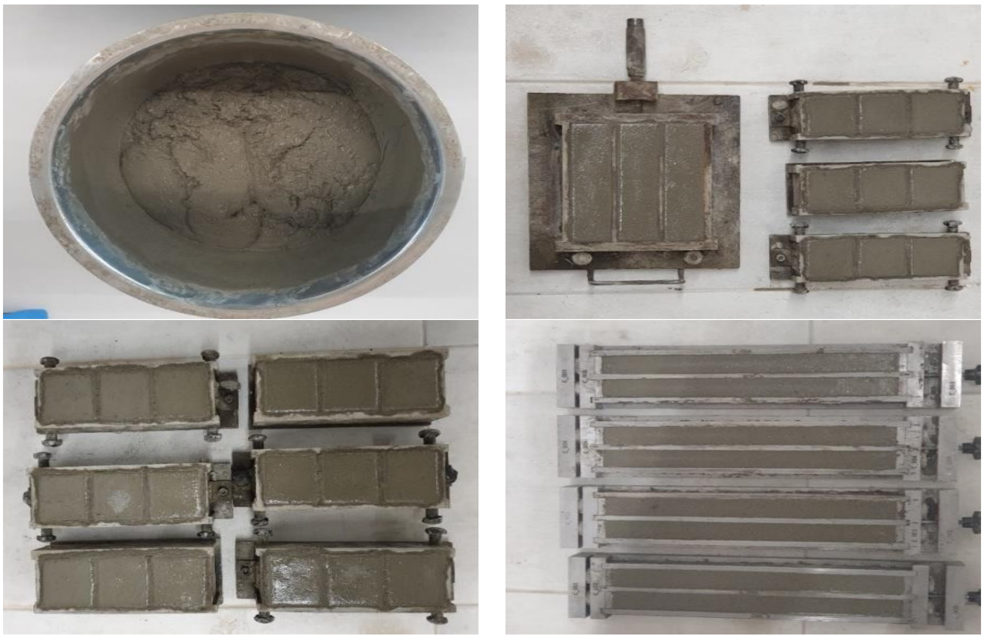


Figure 8. Casted mixes.

2.2.3. Curing

To attain the aimed-for mechanical and durability attributes, produced specimens were removed from the mold after 24 h and treated to curing. In the water bath and oven, drying and ambient curing conditions were applied for the appropriate time of softening, spanning between 7 and 28 days. The illustration of how the samples were cured according to the guidelines outlined in ASTM C511-21 [50] for 7 days and 28 days are seen in Figure 9. This gives a clear insight into how the materials are cured under ambient curing conditions.

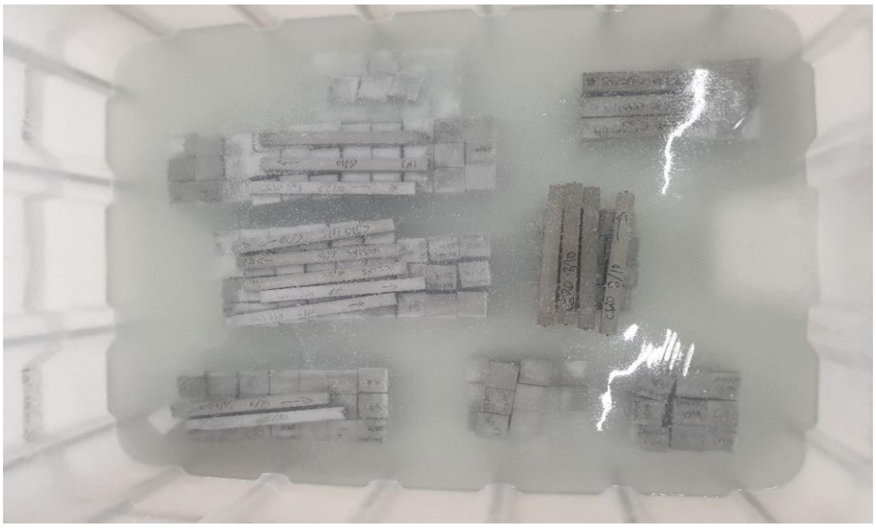


Figure 9. Cured specimens in lime water.

2.2.4. Flowability

To ascertain the flow of each mortar blend created, a flowability test was carried out. ASTM CC1437-20 [51] was followed in performing this test. This test reveals the new mortar's consistency (or, to put it another way, workability). Figure 10 shows the flowability test of the various blended materials.

Figure 10. Flow mortar paste.

2.2.5. Compressive Strength

The ability to withstand loads is a crucial characteristic of concrete materials that is affected by inherent strength properties. Using a compression testing machine, as illustrated in Figure 11, shows the compressive strength. In addition, the materials in Figure 12 that were exposed to compressive forces utilizing WGP and CBA were damaged because the applied stress exceeded their maximum strength capacity, resulting in cracking, fracturing, or deformation. According to ASTM C109/C109M-21 [52], the compressive strength test was achieved. The method used for this test is described below:

1. The bottom and upper platens of the compressive strength machine were cleaned to have uniform contact with the placed specimen.
2. The mortar was placed at the approximate center of the bottom platen of the machine. The sides of the specimens facing the upper and bottom platens of the machine were the ones in contact with plane surfaces of the mold.
3. The load rate of the machine was kept at 1 kN/s.
4. When the samples were crushed, the machine automatically calculated their compressive strength.

Figure 11. Compressive and flexural strength machine.

Figure 12. Damaged materials after undergoing compressive strength testing.

2.2.6. Flexural Strength

The capacity of cementitious composites to resist bending loads is known as flexural strength. The binding strength between the components of the mortar may also be estimated using this test. Through the use of a flexural testing machine, the behavior of the cement mortar replaced with WGP and CBA subjected to three-point loading was investigated. The technique chosen for this test is given below. The flexural testing device's two clean roller supports were used to support the 28-day specimen. When the specimen was cast, the sides of the specimen that faced the roller supports were in touch with the steel mold. The midway loading roller of the machine in line with ASTM C34821 [53] was then made to apply a load at the rate of 2 kN/s.

2.2.7. Water Absorption

Water absorption is a crucial feature to assess for cement-based composites, particularly when they are submerged in water, because it influences the adaptive capacity of cement-based composites. This test was carried out in accordance with the requirements established according to ASTM C642-21 [54]. This test was carried out as follows:

1. The concrete samples were oven-dried for 72 h at 105 ± 5 °C to attain a consistent density after the exact curing days. Samples were weighed after drying.
2. Subsequently, the specimens were immersed in water for 28 days.
3. Specimens were weighed again after 28 days to ascertain water absorption according to water absorption = $\frac{Ww - Wd}{Wd} \times 100$
4. where Dw = dry weight of the specimen, and Ww = wet weight of the specimen. After the failure of the specimen, the machine provided its flexural strength.

2.2.8. Sulfuric Acid Resistance

To determine the impact of the corrosivity of mortar mixes, an acidic resistance test was conducted. The test was carried out in accordance with ASTM C267-20 [55]. The mixes' resistance to sulfuric acid was determined utilizing weight, aesthetic appearance, and persistent strength properties. The experiment was conducted using the following techniques. Specimens were weighted and wiped to SSD state after curing for 28 days. At room temperature, a 5% sulfuric acid solution was prepared. The specimens were submerged in the solvent for two to four weeks. The mixture was changed once each week to keep the acid content consistent. When the desired substantial effect had been achieved, the material was taken out of the acid solution, cleaned, and wiped to SSD before being examined for any remaining degradation.

2.2.9. Fire Resistance

To assess how well the combinations would function in an elevated environment, such as a fire disaster, a fire-resistance test was conducted. Three sets of temperatures (200, 400, and 600 °C) were chosen as the target temperature that the materials were tested against, and the test was conducted in accordance with ASTM [56] rules using an electric furnace. Figure 13 shows the furnace. The materials were preheated at 105 °C for 24 h to lessen the pressure drop of interstitial water before the test was conducted at 28 days.

1. Subsequently, specimens were transferred to the furnace chamber. To ensure consistent heat dispersion, a buffer in both the materials and the vents was kept.
2. With a heating rate of 9 °C/min, the temperature was raised from 25 °C to the desired target degree, and it was maintained there for two hours.
3. The furnace was turned off, and the specimens were allowed to naturally cool inside the furnace for 24 h.
4. Concrete specimens that had been cooled were examined for latent strength.

Figure 13. Electric muffle furnace.

2.2.10. Drying Shrinkage

A significant occurrence in cementitious composites called drying shrinkage results from the loss or evaporation of capillary water from the cemented matrix, which causes contraction (or fissures and shrinking). This study examined how WGP and CBA were affected. The atmosphere, the rate and temperature of the hydration process, the variety of pozzolanic materials utilized, and other variables all affect the pace at which moisture evaporation occurs from a material [57]. The cement mortar was examined according to the guidelines assessed using ASTM C596-18 [58]. The test was carried out according to the following:

1. The normal drying equipment rod's length was measured to establish a reference.
2. The samples were then removed from the curing chambers for measurement. Their length was compared to a standard close to ten times to preserve the test's accuracy.
3. Tests were performed on each specimen 1, 3, 7, 14, 21, and 28 days after casting.
4. A change in length and percentage change in length were then measured for each specimen.

$$\Delta Lx = \frac{CRD - initail\ CRD}{G}$$

where ΔLx = drying shrinkage (%), CRD = the variance of the benchmark bar's frequency and specimen at aging, and G = gauge length.

2.2.11. Microstructure

Utilizing a JSM6610LV Scanning Electron Microscope (SEM), overall microstructural characteristics were tested to determine the impact of enhancing GP and CBA in the cement mix and their impact on filling, gaps, granular size, and ITZ (interfacial transition zone).

3. Results and Discussions

3.1. Flowability

The capacity to pour and compact freshly mixed concrete or mortar while maintaining homogeneity depends on the flowability or workability of cement-based composites, which is a critical factor. The mixture's flowability is affected by a number of variables, including W/C, aggregate properties, and admixtures [59,60]. Due to their pore volume, penetrability, and particle sizes, mineral admixtures and pozzolanic materials have a major impact on flowability. The mortar samples were made with a consistent water-to-binder ratio of 0.35 for the flow tests. A little improvement in mortar flow was seen when waste glass powder and coal bottom ash were used in place of some of the cement. In Figure 14, 20% WGP is shown to have the highest flowability of 180 mm due to its lightweight surface area, which increased flowability. It is possible that the cleaner nature of glass material is what causes the waste glass powder to boost mortar flow [61]. The flowability, however, is significantly improved when 10% WGP and 10% CBA are used. According to the data, all of the mixes' flowabilities fall between 159 mm and 180 mm.

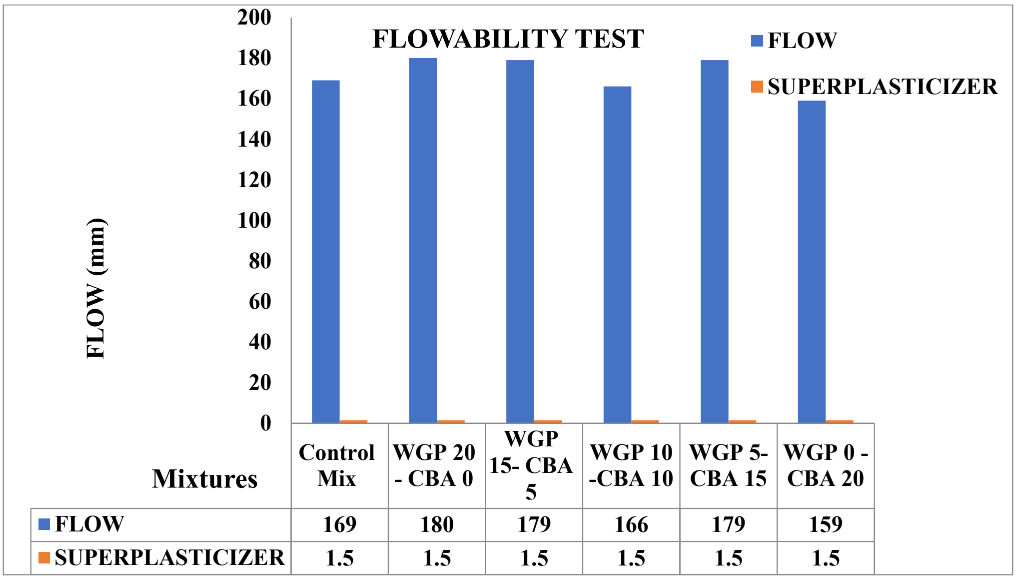


Figure 14. The flowability of the mixtures.

3.2. Density

When the combined specimens were in a saturated surface dry (SSD) condition, it was discovered that their density ranged from 2328 to 2404 kg per cubic meter at 28 days. Mortar was noticeably adversely affected by waste glass powder and coal bottom ash, resulting in a modest increase in density relative to the reference mix. This enabled the mortar's components to be compacted more firmly and allowed for the closure of gaps and holes. The GP and CBA particles acted as fillers and enhanced C-S-H formation. As shown, in Figure 15. Furthermore, the density decreased as CBA concentration rose [62,63]. For instance, when 5% WGP and 15% CBA were combined, the density decreased by 3%. This drop may have been caused by additional factors. Because of the influence of WGP and CBA on the hydration process, increasing the replacement amount of CBA up to 20% reduced the production of C-S-H. The incorporation of 10% WGP and 10% CBA mixes stabilized the density reduction. Furthermore, a modest improvement in density was reported in 10% WGP and 10% CBA combinations, demonstrating that adding 10% of glass powder and 10% of coal bottom ash to cement mortar improved overall density due to the previously described impact of these two precursors on concrete/mortar microstructure.

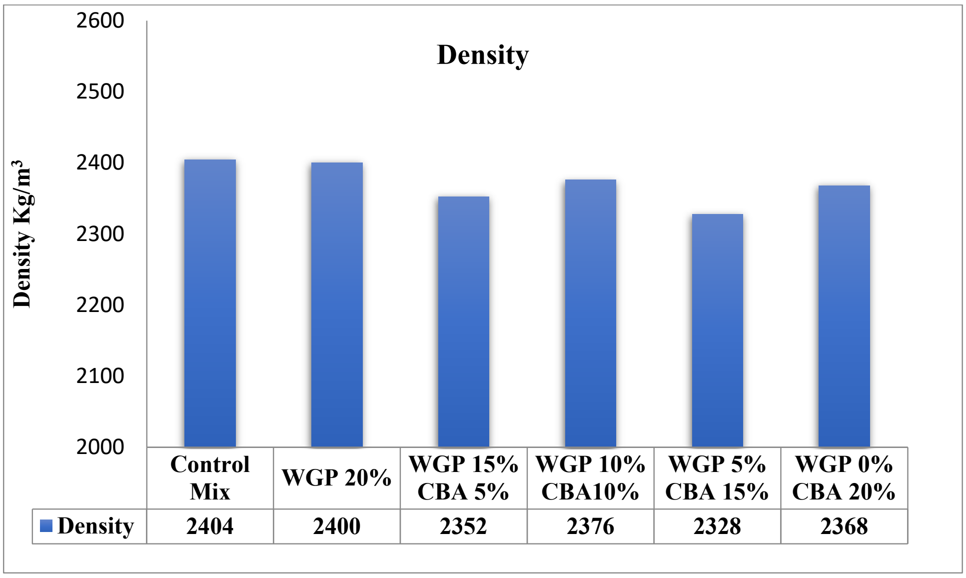


Figure 15. The density of the mixtures at 28 days.

3.3. Absorption of Water

The pendency of WGP and CBA particles at an elevated temperature of 20 °C that filled the gaps and the microporosity with the increased C-S-H created by the cementitious material reduced the water absorption of the mixes comprising WGP and CBA, as shown in Figure 16. Furthermore, the application of WGP and CBA, which clogged capillary pores and limited the passage of water, resulted in a denser and more compacted structure. It is observed in Figure 16 that although permeability rises with constant temperature, as in the control mix, WGP20-CBA0, WGP15-CBA5, WGP10-CBA10, CBA15-WGP5, and CBA20-WGP0 showed water absorption levels.

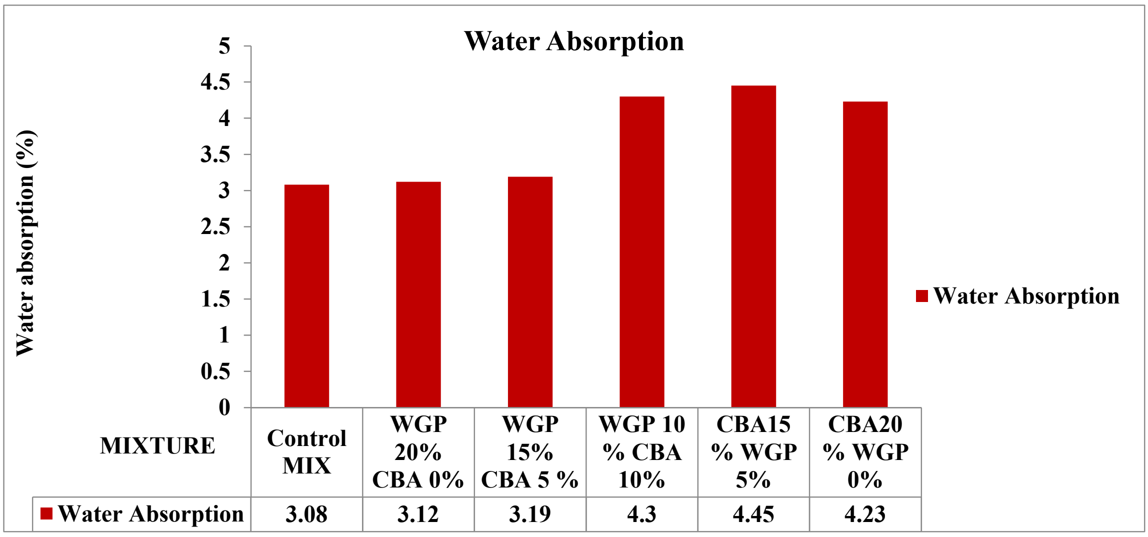


Figure 16. The values of the mixes for moisture absorption.

Figure 17 demonstrates a linkage involving moisture content and concrete strength. In the data in the figure, there is an inverse connection between strength properties and moisture content. In contrast to mixes with lower compressive strength and a greater absorption, such as 10% WGP, 10% CBA, 15% CBA, and 5% WGP, mixes with higher compressive strength, such as 20% WGP, 15% WGP, 5% CBA, and 20% CBA, have a more compact structure and less accessible voids.

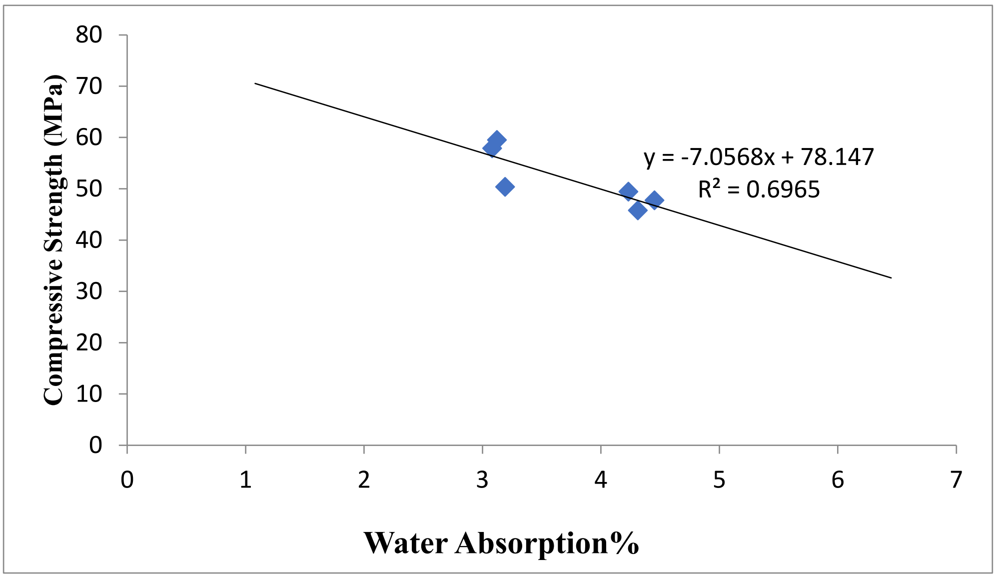


Figure 17. Correlation of compressive strength versus water absorption.

3.4. Compressive Strength

Figure 18 depicts compressive strength evaluations at 7 and 28 days for various combinations of WGP and CBA. The control mixture exhibited strengths of 52.25 MPa after 7 days and 57.93 MPa after 28 days. At 28 days, adding 20% glass powder enhanced strength by 2.7%, whereas adding 20% coal bottom ash decreased strength by 14.5%. Mixtures containing 15% WGP and 5% CBA, 10% WGP and 10% CBA, and 5% WGP and 15% CBA exhibited slightly lower compressive strength than the control mix, with reductions of 13%, 20.8%, and 17%, respectively. However, waste glass powder at 20% became slightly higher in strength than the control mix; this can be attributed to the fact that the hydration process of glass powder as a cementitious material is slow at the beginning and gets rapidly faster later [64]. The delayed initial hydration process of the waste glass powder, followed by a quick increase in strength, is what causes the increase in compressive strength of concrete mixes with 20% waste glass powder. The improvement in strength is further facilitated by the absence of coal bottom ash. However, if waste glass powder makes up more than 20% of the cement, the strength might decrease. The discrepancy in the particle size distribution of the WGP and CBA, which can affect the packing density and the available surface area for hydration, may be one of several factors causing the closed range strength compared to the control mix with 15% WGP and 5% CBA. The waste glass powder's pozzolanic reaction, which strengthens the concrete's interlocking structure, is responsible for the strength increase. The improvement in strength is attributed to the following reasons:

1. As a result, of the chemical change in the cement particles, heat was generated, which may have increased the chemical reaction (pozzolanic) activities of GP particles [65].
2. By increasing hydration processes due to its strong pozzolanic activity, WGP can improve the rapid strengthening of cement-based materials, from 3 to 7 days.
3. In mortar/concrete, a small proportion of glass powder acting or used as filler helps to reduce the total void in the mortar [66].

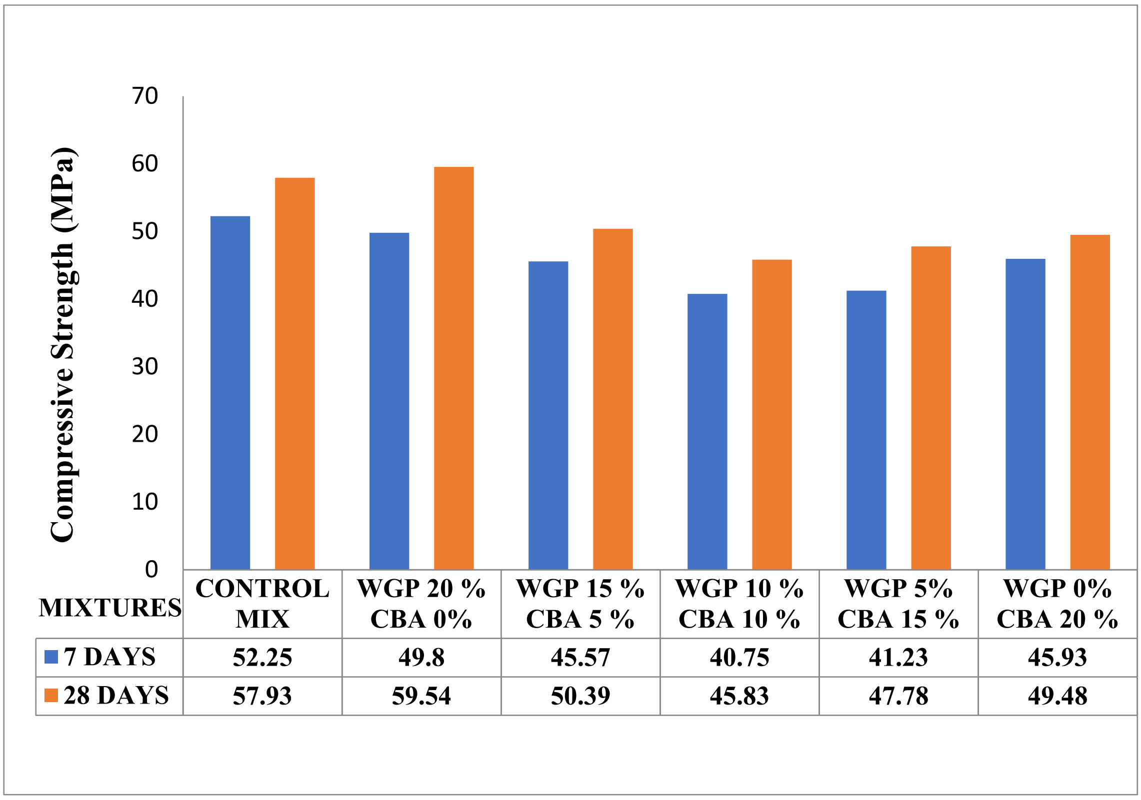
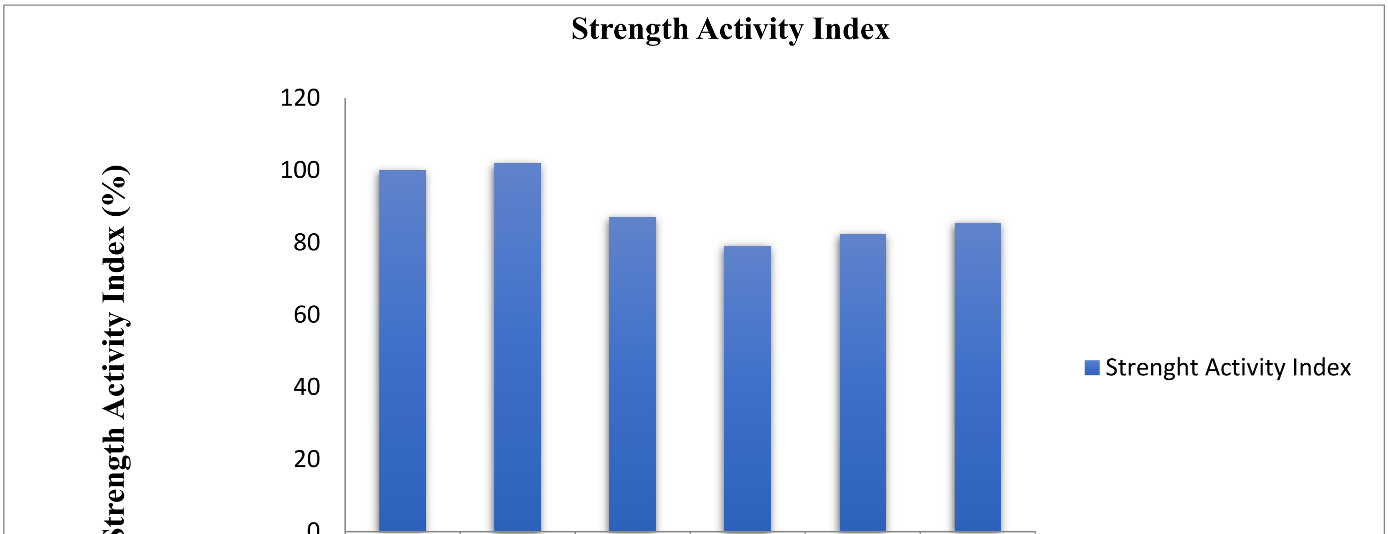


Figure 18. The compressive strength of the mixtures.

By employing CBA as a cement substitute, a 14% reduction in strength was observed when replacing 20% of the cement with CBA without the addition of waste glass powder. Enhancing the concentration of CBA in the mortar by up to 20% results in a significant drop in strength. This reduction maybe ascribed to the following reason:

1. The compressive strength of concrete comprises coal bottom ash, which is used to partially substitute cement in concrete or mortar, resulting in a slightly lower compressive strength than conventional concrete [67].
2. The porosity of the moist paste affects the strength contributions of concretes. The porosity is thus governed by the water/cement ratio and the cracks that present at the interface of its aggregates and hydrated paste.
3. Coal bottom ash, on the other hand, can also be used as a filler, helping to reduce voids in mortar or concrete [68].

Figure 19 depicts the strength activity index (SAI) of the investigated mixes according to the ASTM C618-19 [69] specification. The pozzolanic performance of GP may be estimated with SAI, which is the ratio of the strength of the mortar containing glass powder and coal bottom ash to the strength of the equivalent control mortar at the same age. According to ASTM C618-19, for all material to be qualified as a pozzolan, the SAI should be greater than 75%. SAI is used to measure the pozzolanic rate of cement replacement materials by determining the relative compressive strength of the mixtures in comparison to the reference mix. It can be seen from Figure 19 that all of the mixtures are above the 75% limit compared to the control mixture. However, 20% WGP, 15% WGP, and 5% CBA combinations produced 102 percent, 86.98 percent, and 85.4 percent, respectively, demonstrating that utilizing a 20% WGP replacement is appropriate for compressive strength.

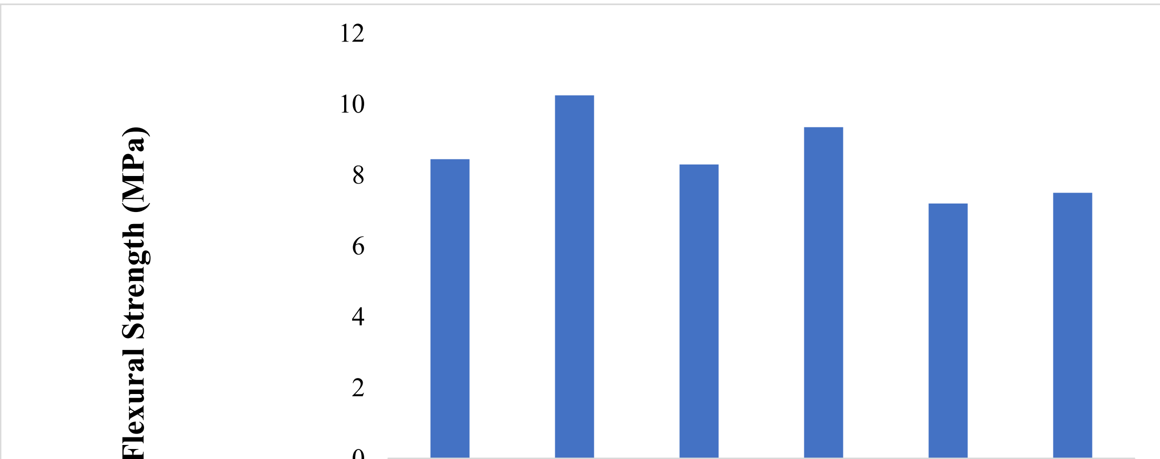


	Control Mix	GP 20% CBA 0%	GP15% CBA 5%	GP 10% CBA10 %	GP 5% CBA15 %	CBA20 % GP 0%
Strenght Activity Index	100	102	86.98	79.1	82.4	85.4

Figure 19. Strength activity index of the mixtures.

3.5. Flexural Strength

Flexural strength detailing the incorporation of WGP and CBA mixtures at both temperature and curing age of 28 days is given in Figure 20. After 28 days of curing, the control mix had a flexural strength of 8.45 MPa at 20 °C. WGP at 20% showed improved flexural strength compared to the control mix. It is glaring that a 10% WGP and 10% CBA blended material provides greater strength compared to the control mix. This is shown in Figure 20 below. The increase can be explained by various factors. The flexural strength increment is based on the higher pozzolanic activity of WGP and coal bottom ash and tightened bonding between the particles.



MIXTURES	Control Mix	WGP 20 - CBA 0	WGP15 - CBA 5	WGP 10 - CBA 10	WGP 5 - CBA 15	WGP 0 - CBA 20
Flexural strength 28 DAYS	8.45	10.25	8.3	9.35	7.2	7.5

Figure 20. Flexural strength.

1. Using WGP as a partial substitution of cement up to 20% reinforced the flexural strength of concrete because glass powder particles have an angular structure that makes it harder for concrete or mortar to resist bending.
2. Furthermore, when the portion of CBA in the mix increased, the flexural strength of concrete decreased. It worth noting that 10% WGP and 10% CBA have greater strength compared to the control mix. It has been demonstrated experimentally that a 10% cement substitution with coal bottom ash is optimal.
3. Variations in the shape of coal bottom ash concrete led to a reduction in aggregate evaluation as the coal bottom ash mix ratios increased. This signifies the concrete's cracked section contains coal bottom ash aggregates.
4. It was established that the reduction in the flexural strength of coal bottom ash concrete could be attributed to the splitting of the bottom ash concrete, which happens rapidly compared to conventional aggregate, which has difficulty penetrating.
5. The flexural strength test on the effect of coal bottom ash in concrete revealed that flexural strength decreases when natural fine aggregate has been substituted with coal bottom ash concrete [70].

Figure 21 represents the correlation between flexural strength and compressive strength for all mixes. The relationship graph reveals that compressive strength is connected with flexural strength; higher compressive strength increases flexural strength. However, this relation is not necessarily true, as can be noted in the graph, where the value of the coefficient of determination (R^2) is 0.250 and not close to 1; for instance, the WGP20 and WGP10CBA10 mixtures exhibited higher flexural strength but less compressive strength in comparison to the reference mix because of the aforementioned reasons.

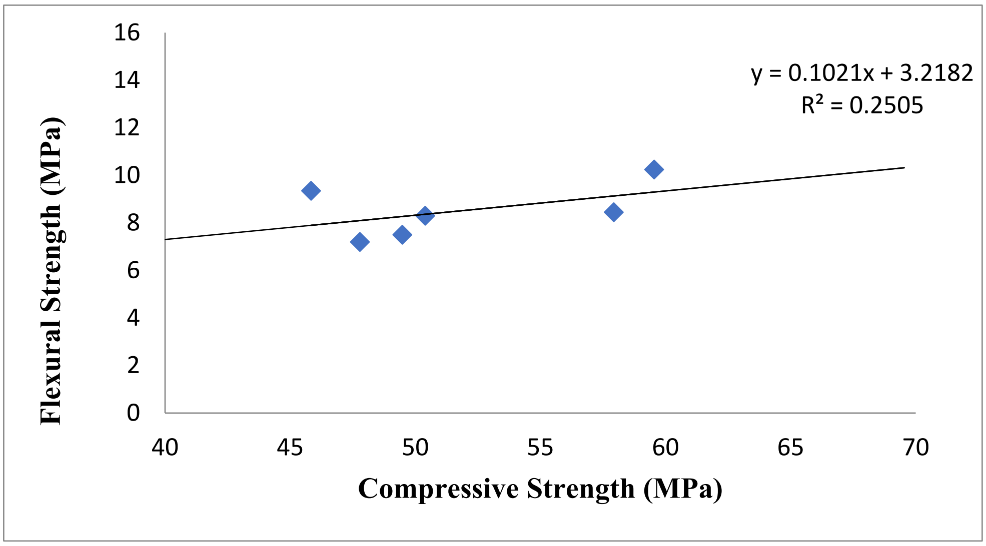
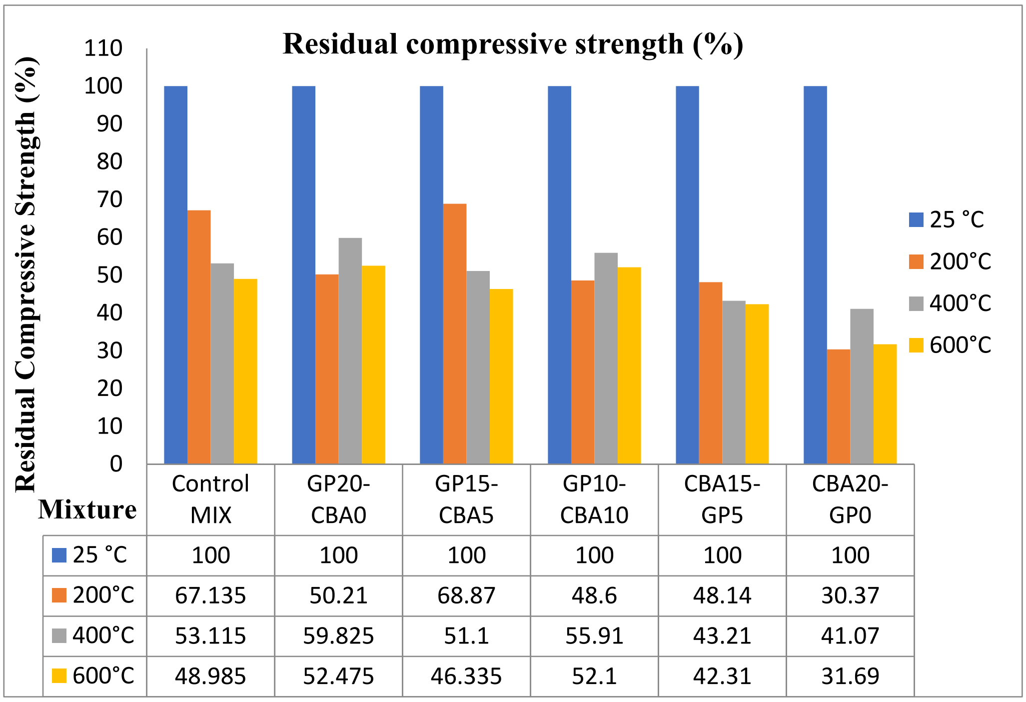


Figure 21. Correlation of flexural strength versus compressive strength.

3.6. Fire Resistance

Figure 22 illustrates the resistance to high temperatures of the studied mortar combinations including WGP and CBA. In general, the temperature used for fire resistance testing is determined by a number of criteria, including the intended usage and the materials being tested. Fire resistance testing often entails subjecting the material to high temperatures for a set length of time and evaluating its behavior, such as its capacity to endure heat while maintaining structural integrity. Based on the ASTM E119 [56] standard guidelines and recommendations for assessing the fire resistance of materials, the mixes were subjected to three temperature ranges (200, 400, and 600 °C) and at 200 °C, a noticeable improvement in strength was observed in all the combinations, with 15% WGP and 5% CBA with a maximum bond strength increase of 68.87 MPa. Mixes had the utmost strength improvement in comparison to the compressive strength of the control mix at 28 days unexposed to temperature, with an over 2.6% increase, and the lowest strength development was recorded to be 30.37 MPa, which was 20% coal bottom ash. The reason for this remarkable development was the loss of water, resulting in an increase in adhesion between the planes of breakdown. Therefore, more compressive strength was required to damage the specimen. Furthermore, strength growth occurred in some specimens when the temperature was elevated to 400 °C. It was noticed that WGP15-CBA5 start decreasing in strength. However, 20% WGP, 10% WGP, 10% CBA, and 20% CBA gained more strength, 25%, 27%, 28%, and 54%, respectively. All mixes exhibit a significant decrease in compressive strength at 600 °C, which is attributed to the breakdown of C-S-H and the dehydration of calcium hydroxide. Internal stresses within the mortar lead to the formation of micro cracks, which can weaken the bond between its components. These cracks result from the expansion of the mortar's volume, generating internal tensions that erode the cohesion between the different elements of the material.

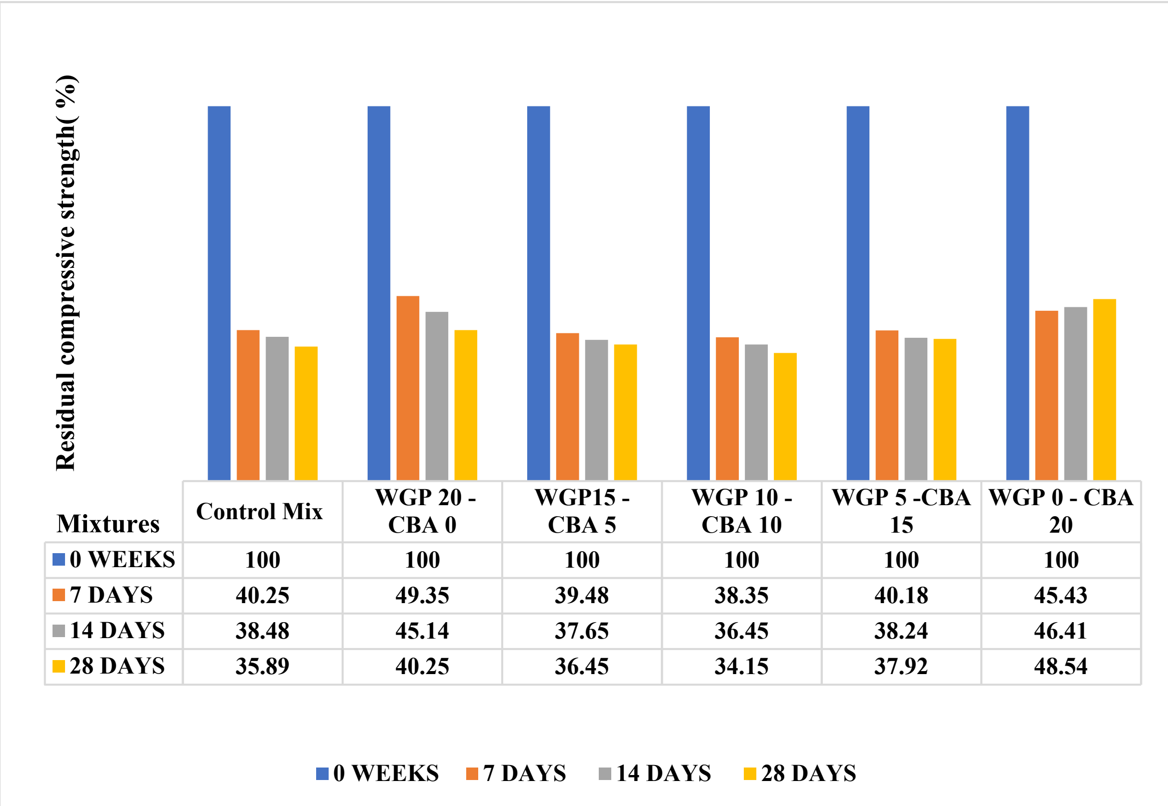


Mixture	Control MIX	GP20-CBA0	GP15-CBA5	GP10-CBA10	CBA15-GP5	CBA20-GP0
25 °C	100	100	100	100	100	100
200°C	67.135	50.21	68.87	48.6	48.14	30.37
400°C	53.115	59.825	51.1	55.91	43.21	41.07
600°C	48.985	52.475	46.335	52.1	42.31	31.69

Figure 22. Residual compressive strength after exposure to high temperatures.

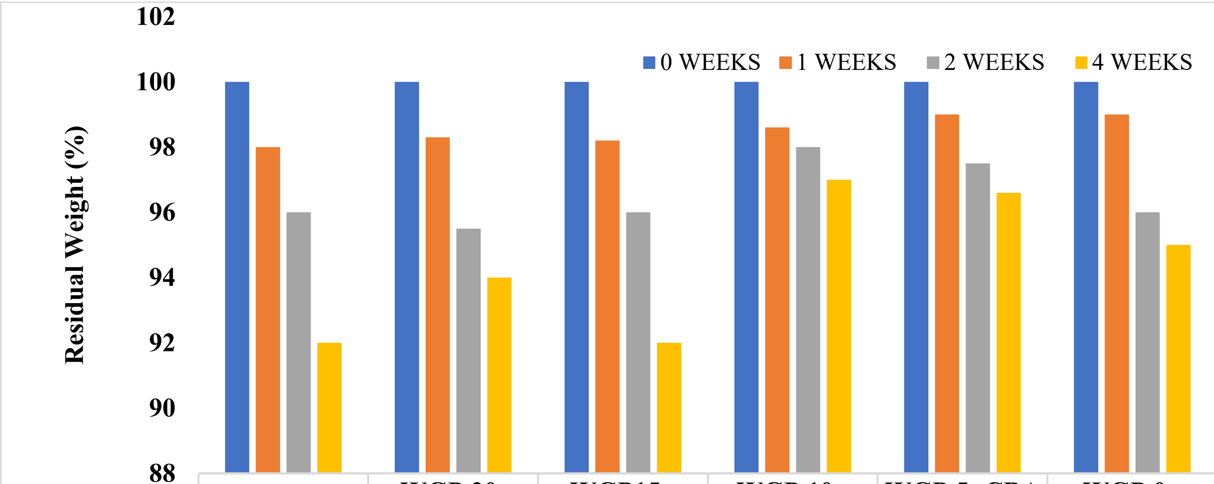
3.7. Sulfuric Acid Attack

Examining the impact of adding glass powder and coal bottom ash as a substitute for cement on mortar rigidity from sulfuric acid attack is vital in a bid to strengthen the durability of cementitious composites exposed to acidic conditions. Figure 23 shows the performance of the combinations of WGP and CBA following exposure to a dilute solution of 5% sulfuric acid, after which the specimens' weight and relative compressive strength were measured. Elevated absorbency calcium compounds, including gypsum, were created as a result of the interaction between the acid and the calcium hydroxide in cement. These formed salts that spread throughout the cementitious composite, causing stress and integration that caused concrete and mortar to spall and lose mass and strength. As shown in Figure 23, the control combination seems to have the minimum compressive strength and weight of all the mixes after 4 weeks of immersion in a 5% sulfuric acid solution, with a strength bond of 35.89 MPa and an accumulated density of 92.0 percent. The inclusion of WGP and CBA of various percentages perhaps enhanced the strength and weight in all immersion durations. This improvement could be due to the filler action of CBA particles, which culminated in voids in the mortar and a decrease in overall opacity. When the mixtures were exposed to water containing a 5% sulfuric acid (H_2SO_4) solution, Figures 23 and 24 reveals how all of the mixtures had reduced compressive strength and weight. The control mix had the weakest resistance to the H_2SO_4 attack, with a reduction in compressive strength loss after 7, 14, and 28 days at 20 °C; the percent compared to 7 days was 4.9 percent. In mortar with 20% WGP and 20% CBA, mass loss decreased gradually with a replacement dosage. These results confirm the higher resistance of mortars containing GP and coal bottom ash, especially with a high percentage of GP and CBA replacement levels. According to the literature, gypsum and ettringite are the two main cementitious materials showing potential against attack by sulfuric acid [71,72]. However, Figures 25–27 show the visual inspection of the materials exposed to sulfuric acid, demonstrating the deterioration of the samples and the impact of a sulfuric acid attack on the surface of the samples. These two materials are commonly connected with deformation, cracking, and spalling, as well as shrinkage, because the amount of deterioration is significantly influenced by the CH concentration of the moist mortar mix. The consumption by the WGP pozzolanic process may account for the decreased mass shrinkage in WGP mortars. By speeding up the hydration process and closing the pores and gaps, a blend of waste glass powder (WGP) and coal bottom ash (CBA) improved the volume fraction of the mortar. This prevented the acidic solution from penetrating the mortar.



Mixtures	Control Mix	WGP 20 - CBA 0	WGP15 - CBA 5	WGP 10 - CBA 10	WGP 5 -CBA 15	WGP 0 - CBA 20
0 WEEKS	100	100	100	100	100	100
7 DAYS	40.25	49.35	39.48	38.35	40.18	45.43
14 DAYS	38.48	45.14	37.65	36.45	38.24	46.41
28 DAYS	35.89	40.25	36.45	34.15	37.92	48.54

Figure 23. Residual compressive strength of the mixtures after sulfuric acid exposure.



MIXTURES	Control Mix	WGP 20 - CBA 0	WGP15 - CBA 5	WGP 10 - CBA 10	WGP 5 -CBA 15	WGP 0 - CBA 20
0 WEEKS	100	100	100	100	100	100
1 WEEKS	98	98.3	98.2	98.6	99	99
2 WEEKS	96	95.5	96	98	97.5	96
4 WEEKS	92	94	92	97	96.6	95

Figure 24. Residual weight of the mixtures after sulfuric acid exposure.

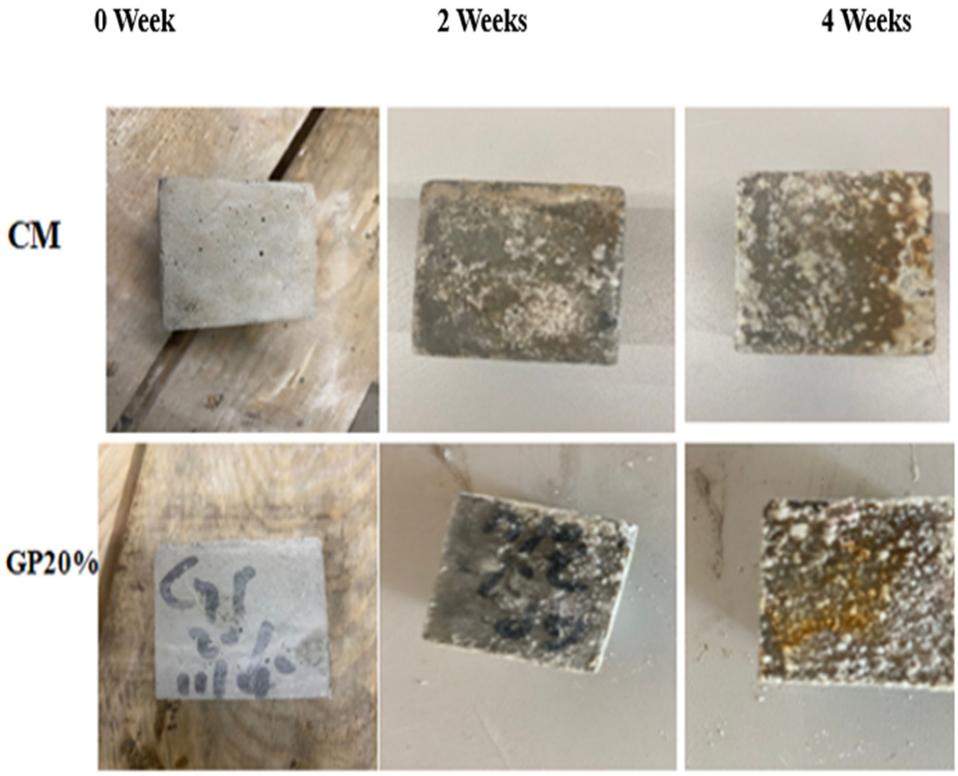


Figure 25. The impact of sulfuric acid attack on the surface degradation of control mix and GP20% on the samples.

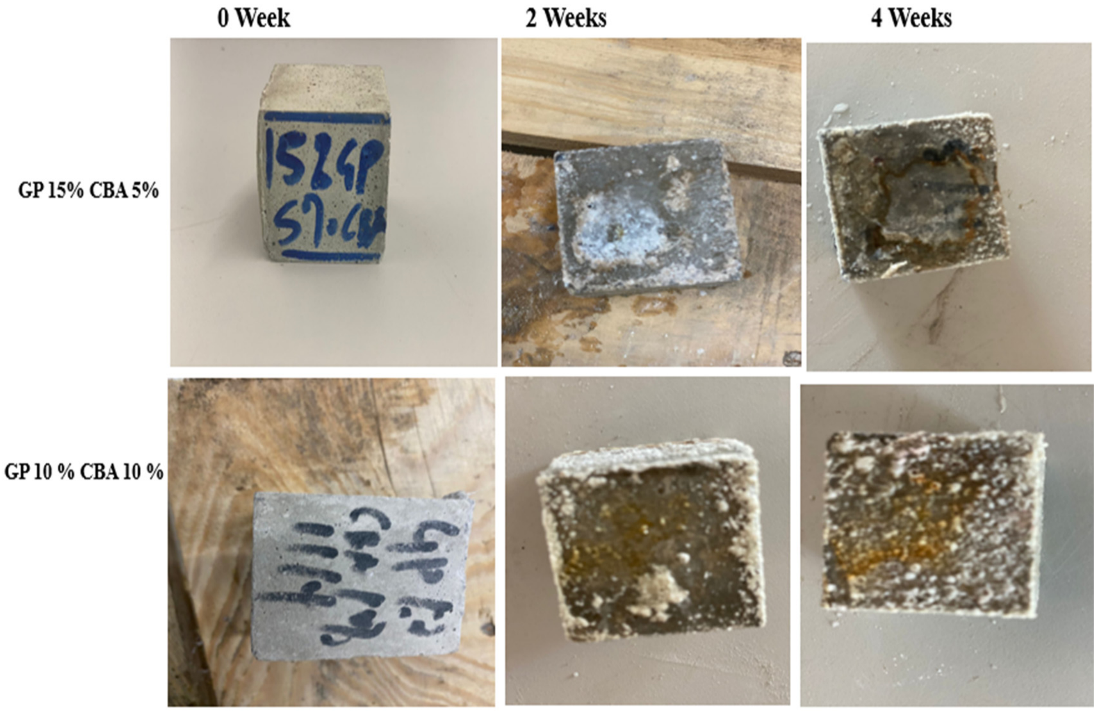


Figure 26. The impact of sulfuric acid attack on the surface degradation of GP15% CBA 5% and GP 10% CBA 10% samples.

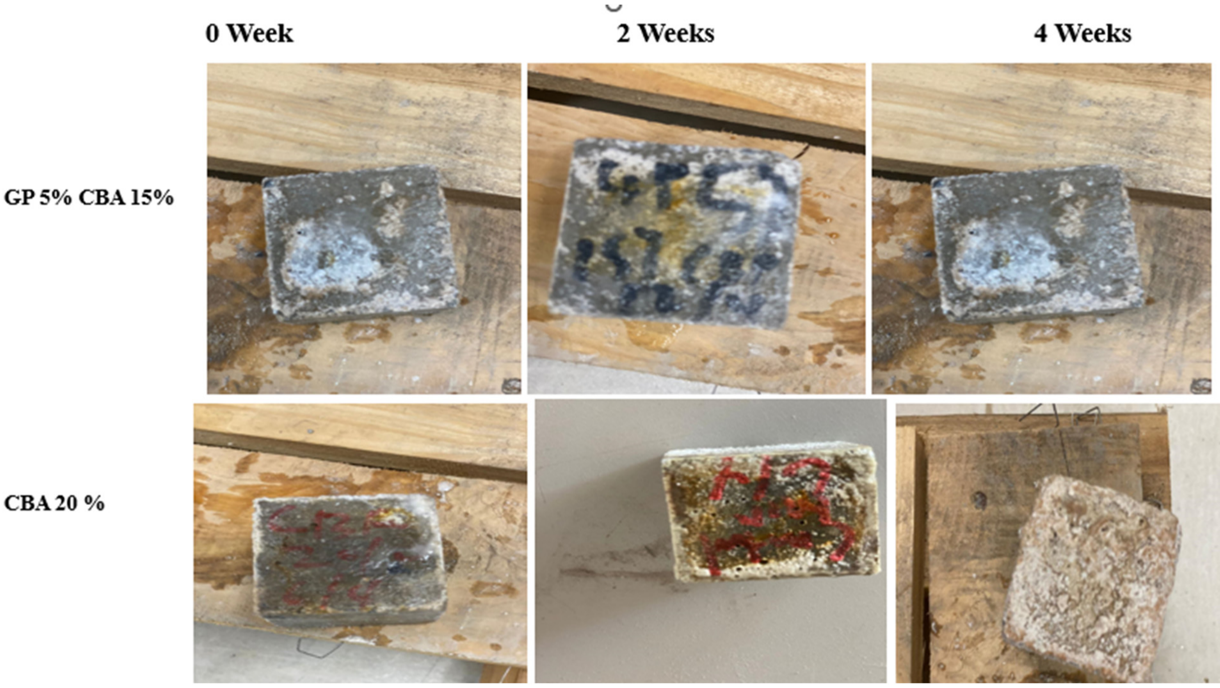


Figure 27. The impact of sulfuric acid attack on the surface degradation of GP 5% CBA 15% and CBA 20% samples.

3.8. Dry Shrinkage

Due to particle alteration (contraction) brought on by water loss in the pore space, cement-based composites undergo autogenous shrinkage. This occurrence is dependent on a number of factors, including the W/C proportion, mixing %, curing, physical climate conditions, heat generated during hydration, and ambient temperature [73]. Excessive shrinkage results in the formation of fissures, subjecting the concrete/mortar to chemical exposure. Figure 28 shows the impact of dry shrinkage on all mixtures analyzed at temperature of 20 °C in water and drying curing conditions. The following attributes, however, caused the incorporation of WGP and CBA at 20 °C temperature, and curing conditions dropped in contrast to the control mix. Its properties seem to be more visible in WGP because waste glass powder produces the least drying shrinkage.

1. The cementitious interaction of WGP and CBA results in array pore modification which exhibits drying shrinkage.
2. The quantity of lime required for a quick hydration rate, which lowers dry shrinkage, is reduced by replacing cement with WGP and CBA.

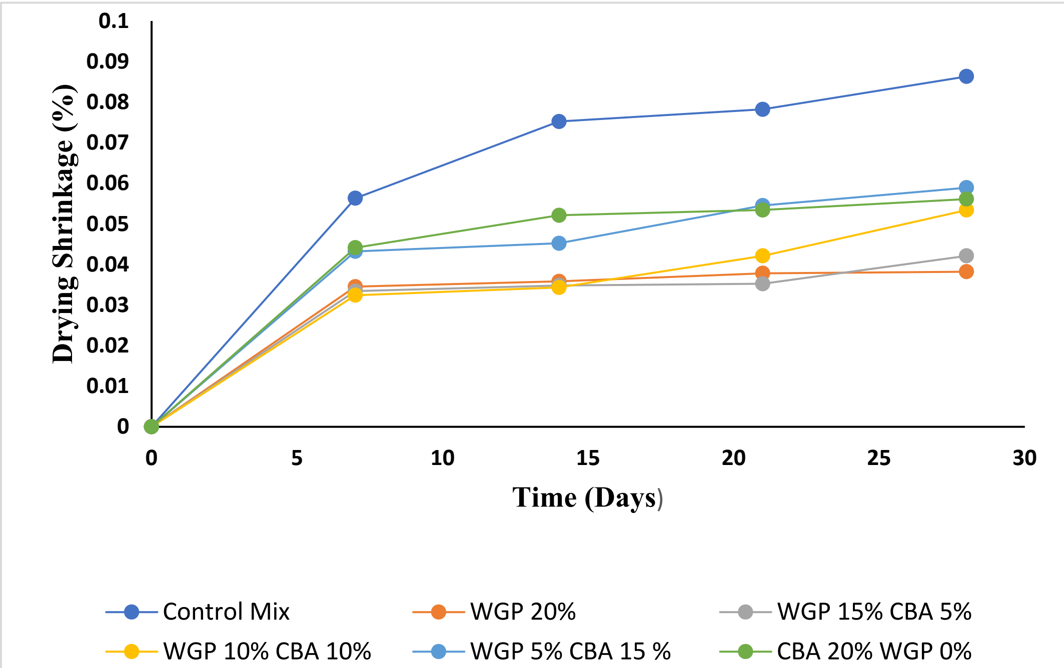
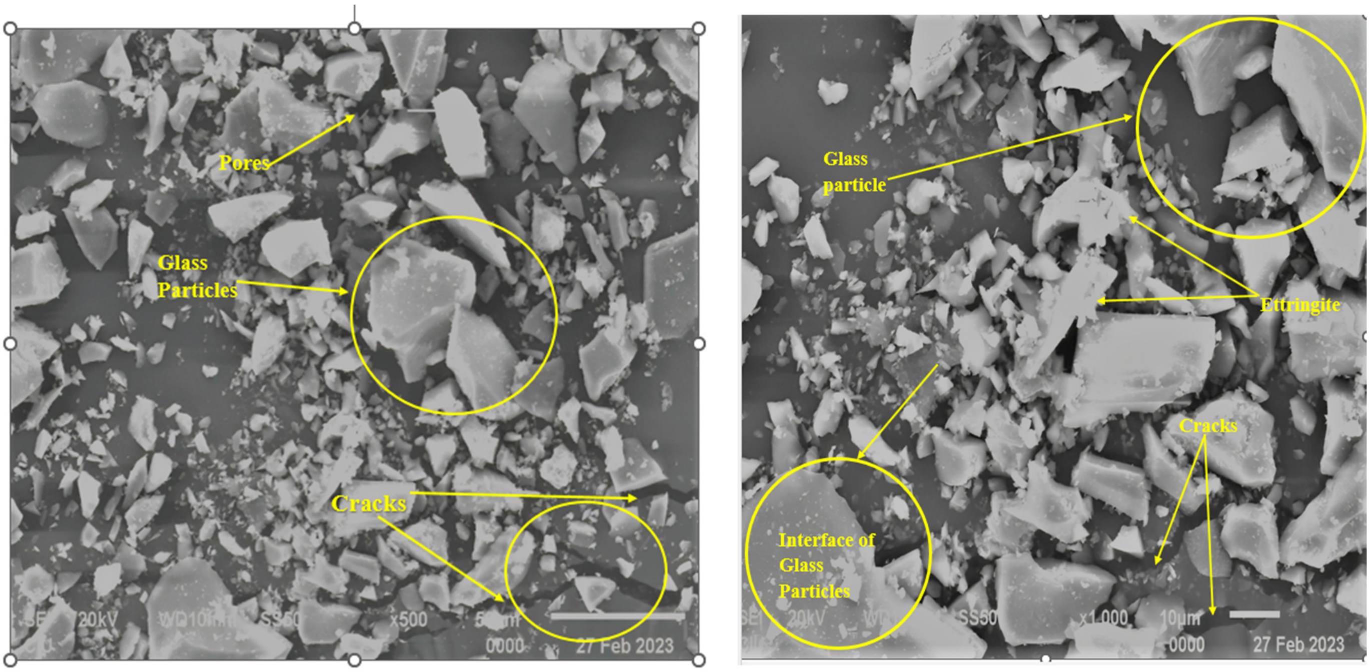


Figure 28. The drying shrinkage values of the mixtures.

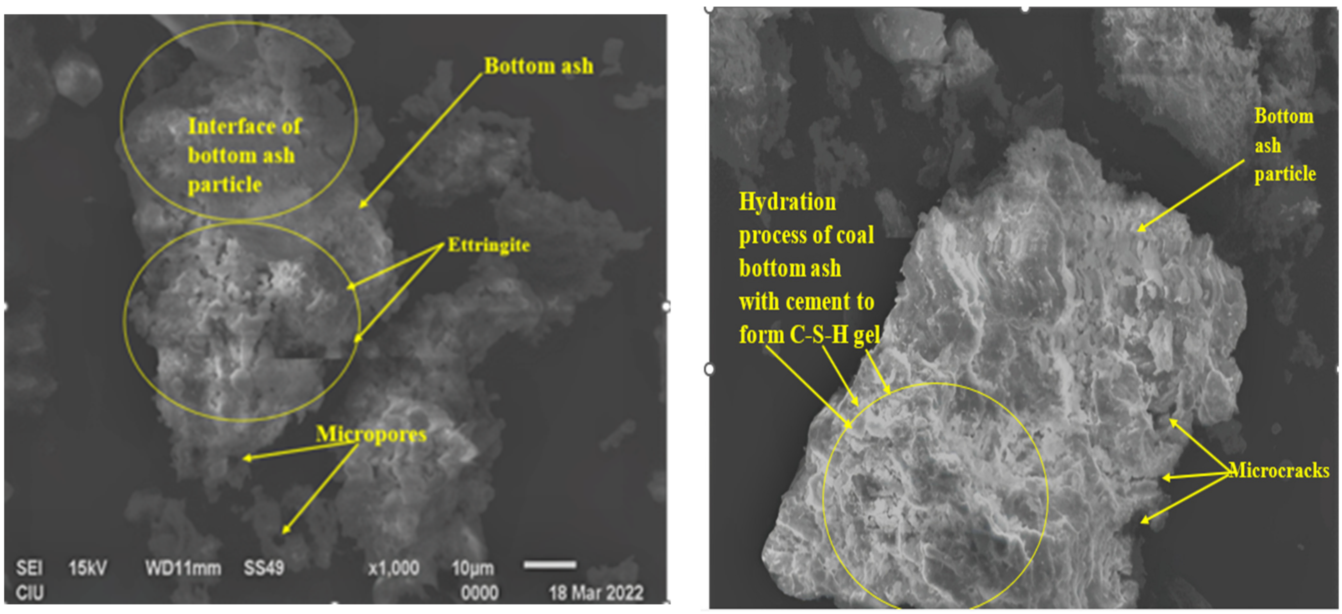
3.9. SEM Analysis

To analyze the microstructural characteristics of the modified mortar, scanning electron microscopy (SEM) was used. SEM pictures were taken to study the effect of WGP and CBA on the microstructure of mortar in the cube. Figures 29 and 30 show the SEM pictures, which present the microstructure of both WGP and CBA. It is found that the two materials have a low porosity compared in the control cement mortar, which helps in the compressive strength of the mortar. However, the picture illustrates that the aforementioned waste materials act as a good filler material. The glass powder fills the micropores and mechanically interacts with the other phases to contribute to compressive strength. The hydrated byproducts of a solid and mature gel comprising needle-shaped ettringite crystals are evenly dispersed and well-contained with glass particles. On the other hand, the SEM of CBA shows that the composition of coal bottom ash is mostly determined by the coal's content and the furnace's operating conditions. However, depending on the coal composition and furnace conditions, alumina silicates such as clays melt and break down to generate glass or mullite.



(**a**) (**b**)

Figure 29. SEM photomicrograph of waste glass powder. (**a**) The irregular angular shapes of waste glass powder. (**b**) The display of the interface of glass particles, the micro cracks, and the pore holes in waste glass powder.



(**a**) (**b**)

Figure 30. SEM photomicrograph of coal bottom ash. (**a**) The interface of bottom ash, ettringite distribution, and micropore. (**b**) The ingress of C-S-H gel reaction of bottom ash with cement paste.

4. Conclusions

Following extensive experimentation, assessment, and discussion of the data obtained for different characteristics of the precursors as a partial supplementary cementitious material mortar containing WGP and CBA have been determined to be the best at a 20% replacement level with 1.5% as a supplementary component with a set W/B of 0.35. The study was based on the behavior of WGP and CBA on the flowability, mechanical properties, and durability of the modified mortar, and the detailed findings can be drawn.

1. Flowability observation shows the workability of the samples enhanced as the glass powder content replacing cement expand. WGP of 20% has the highest flowability because of its lightweight surface area which leads to an increase in flow. The improvement in mortar flow with the influence of waste glass powder may be the effect of glass material, which is cleaner in nature. The maximum improvement was reached at the supplementation of 20% of glass powder.
2. The flowability outcome indicates that the effect of coal bottom ash as an alternative for cement improves the flow value of specimens.
3. The compressive strength test demonstrates that the development of the compressive strength continues with age. At a fixed water cement ratio of 0.35, substituting 20% of the cement with WGP enhances the compressive strength of the mortar.
4. Flexural strength exhibits a different pattern than compressive strength because the flexural strength of CM diminishes more than that of WGP, and it is also observed that 10% WGP and 10% CBA increases flexural strength compared to the control mix.
5. At three different temperatures (200, 400, and 600 °C), mortar modified with GP and CBA shows significant resistance to fire. At 200 °C, a development in residual compressive strength was observed approximately 400 and 600 °C, and the hydrating activity of the raw binders' particles became less intense. Due to their heat insulation capabilities, which minimize heat conduction between cement and aggregate at 600 °C, WGP and CBA blends produced an unexpected outcome in terms of residual strength.
6. The research reveals that WGP and CBA are more resistant to sulfuric acid assault than the control mixture, which lost considerable mass and strength and suffered considerable surface degradation. Because of their characteristics, CBA particles increase overall performance by preventing acid from penetrating deep into the system. After exposure to the acidic medium, a mixture of WGP and CBA in the mortar exhibited a noteworthy performance.
7. Due to their significant surface area and pozzolanic activity rate, 15% CBA and 5% WGP were found to have the highest autogenous shrinkage across all ages. This was followed by 20% CBA. The research found that 20% WGP lessened drying shrinkage by reducing hydration rate, heat loss, and water loss across all ages.
8. Additionally, SEM analysis confirmed that incorporating WGP and CBA into cement mortar enhanced porosity. In contrast, the combination of WGP and CBA was shown to be quite beneficial in improving the ITZ and obtaining a denser and more compacted microstructure.

In conclusion, based on the analysis and findings, it is determined that the inclusion of WGP and CBA plays an advantageous importance in terms of structural and long-term strength characteristics of cement mortar. It should be mentioned that a combination of 10% WGP and 10% CBA can also improve the overall performance of cement-based mortar.

5. Future Recommendations

The relevant GP and CBA properties in cement composites could not all be examined because of the constraints and limitations of time and facilities. Therefore, the following recommendations are put forward.

1. Investigating the influence of glass powder or coal bottom ash as a cement substitute on structural steel in an attempt to decide the long-term sustainability of glass powder and coal bottom ash use in offshore construction.
2. Investigating the impact of combining glass powder with other supplementary cementitious materials as a partial cement substitute on the properties and behaviors of various concrete mixtures.

3. From an environmental standpoint, coal bottom ash utilization in cement-based composites should be increased. Recently, it was noted that natural aggregate supplies are progressively diminishing and that commercially cost-effective quarries are getting harder to find in some countries. As a result, the use of recycled or by-product aggregates as an alternative to natural aggregates is recommended, especially since the development of new quarries may have adverse impacts on the ecosystem. It is advantageous to utilize coal bottom ash in place of conventional aggregates because of its sustainable application and the preservation of natural resources.
4. Additional research should be conducted along the lines of enhanced utilization of coal bottom ash in addition to implementing the integration of coal bottom ash into building structures that might benefit from the unique properties of coal bottom ash.

Author Contributions: S.B.O.: conceptual framework, assessment, methodological approach, materials, writing—preliminary draft, and modification of writing. M.A.M.: conceptual framework, assessment, methodological approach, materials, writing—preliminary draft, and modification of writing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data will be made available upon request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Yakut, A. Preliminary Seismic Performance Assessment Procedure for Existing Rc Buildings. *Eng. Struct.* **2004**, *26*, 1447–1461. [CrossRef]
2. Kumar, S.; Aleem, G.M.A.; Dinesh, S. Application of geopolymer concrete. *Int. Res. J. Eng. Technol.* **2015**, *2*, 96–99.
3. Imam, A.; Kumar, V.; Srivastava, V. Review study towards the Effect of Silica Fume on the fresh and hardened properties of concrete. *Adv. Concr. Constr.* **2018**, *6*, 145.
4. Aliabdo, A.A.; Abd Elmoaty, M.; Auda, E.M. Reuse of waste marble dust in the production of cement and concrete. *Constr. Build. Mater.* **2014**, *50*, 28–41. [CrossRef]
5. Aruntaş, H.Y.; Gürü, M.; Dayı, M.; Tekin, İ. Utilization of waste marble dust as an additive in cement production. *Mater. Des.* **2010**, *31*, 4039–4042. [CrossRef]
6. Danish, A.; Mosaberpanah, M.A.; Salim, M.U.; Fediuk, R.; Rashid, M.F.; Waqas, R.M. Reusing marble and granite dust as cement replacement in cementitious composites: A review on sustainability benefits and critical challenges. *J. Build. Eng.* **2021**, *44*, 102600. [CrossRef]
7. de Sensale, G.R. Strength development of concrete with rice-husk ash. *Cem. Concr. Compos.* **2006**, *28*, 158–160. [CrossRef]
8. Salim, M.U.; Mosaberpanah, M.A. Mechanical and durability properties of high-performance mortar containing binary mixes of cenosphere and waste glass powder under different curing regimes. *J. Mater. Res. Technol.* **2021**, *13*, 602–617. [CrossRef]
9. Elaqra, H.A.; Abou Haloub, M.A.; Rustom, R.N. Effect of new mixing method of glass powder as cement replacement on the mechanical behavior of concrete. *Constr. Build. Mater.* **2019**, *203*, 75–82. [CrossRef]
10. Khan, M.N.A.; Liaqat, N.; Ahmed, I.; Basit, A.; Umar, M.; Khan, M.A. Effect of brick dust on strength and workability of concrete. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *414*, 012005. [CrossRef]
11. Tiwari, V.; Shukla, A.; Bose, A. Acoustic properties of cenosphere reinforced cement and asphalt concrete. *Appl. Acoust.* **2004**, *65*, 263–275. [CrossRef]
12. IEA. *Tracking Industrial Energy Efficiency and CO2 Emissions*; OECD: Paris, France; IEA: Paris, France, 2007; pp. 1–321.
13. Rashed, A.M. Recycled Waste Glass as Fine Aggregate Replacement in Cementitious Materials Based on Portland cement. *Constr. Build. Mater.* **2014**, *72*, 340–357. [CrossRef]
14. Sobolev, K.; Türker, P.; Soboleva, S.; Iscioglu, G. Utilization of waste glass in ECO-cement: Strength properties and microstructural observations. *Waste Manag.* **2007**, *27*, 971–976. [CrossRef] [PubMed]
15. Qaidi, S.; Najm, H.M.; Abed, S.M.; Özkılıç, Y.O.; Al Dughaishi, H.; Alosta, M.; Sabri, M.M.; Alkhatib, F.; Milad, A. Concrete containing waste glass as an environmentally friendly aggregate: A review on fresh and mechanical characteristics. *Materials* **2022**, *15*, 6222. [CrossRef]
16. Afshinnia, K.; Rangaraju, P.R. Impact of Combined Use of Ground Glass Powder and Crushed Glass Aggregate on Selected Properties of Portland Cement Concrete. *Constr. Build. Mater.* **2016**, *117*, 263–272. [CrossRef]

17. Shi, C.; Zheng, K. A review on the use of waste glasses in the production of cement and concrete. *Resour. Conserv. Recycl.* **2007**, *52*, 234–247. [CrossRef]
18. Jiang, X.; Xiao, R.; Bai, Y.; Huang, B.; Ma, Y. Influence of waste glass powder as a supplementary cementitious material (SCM) on physical and mechanical properties of cement paste under high temperatures. *J. Clean. Prod.* **2022**, *340*, 130778. [CrossRef]
19. Bilondi, M.P.; Toufigh, M.M.; Toufigh, V. Experimental investigation of using a recycled glass powder-based geopolymer to improve the mechanical behavior of clay soils. *Constr. Build. Mater.* **2018**, *170*, 302–313. [CrossRef]
20. Tan, K.H.; Du, H. Use of waste glass as sand in mortar: Part I—Fresh, mechanical and durability properties. *Cem. Concr. Compos.* **2013**, *35*, 109–117. [CrossRef]
21. Xiao, R.; Polaczyk, P.; Zhang, M.; Jiang, X.; Zhang, Y.; Huang, B.; Hu, W. Evaluation of Glass Powder-Based Geopolymer Stabilized Road Bases Containing Recycled Waste Glass Aggregate. *Transp. Res. Rec. J. Transp. Res. Board* **2020**, *2674*, 22–32. [CrossRef]
22. Wang, Y.; Ke, G. The research on the fineness modulus and fractal dimension of waste glass powder with different grinding time. *Appl. Mech. Mater.* **2014**, *638–640*, 1465–1471.
23. Taha, B.; Nounu, G. Utilizing waste recycled glass as sand/cement replacement in concrete. *J. Mater. Civ. Eng.* **2009**, *21*, 709–721. [CrossRef]
24. Letelier, V.; Henríquez-Jara, B.I.; Manosalva, M.; Moriconi, G. Combined use of waste concrete and glass as a replacement for mortar raw materials. *Waste Manag.* **2019**, *94*, 107–119. [CrossRef] [PubMed]
25. *C-09*; Committee Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. ASTM International: West Conshohocken, PA, USA, 2013.
26. Omran, A.; Tagnit-Hamou, A. Performance of glass-powder concrete in field applications. *Constr. Build. Mater.* **2016**, *109*, 84–95. [CrossRef]
27. Zeybek, Ö.; Özkılıç, Y.O.; Karalar, M.; Çelik, A.İ.; Qaidi, S.; Ahmad, J.; Burduhos-Nergis, D.P. Influence of replacing cement with waste glass on mechanical properties of concrete. *Materials* **2022**, *15*, 7513. [CrossRef]
28. Özkılıç, Y.O.; Çelik, A.İ.; Ufuk, T.U.; Karalar, M.; Deifalla, A.; Alomayri, T.; Althoey, F. The use of Crushed Recycled Glass for Alkali Activated Fly Ash Based Geopolymer Concrete and Prediction of Its Capacity. *J. Mater. Res. Technol.* **2023**, *11*, 8267–8281. [CrossRef]
29. Çelik, A.İ.; Ufuk, T.U.; Bahrami, A.; Karalar, M.; Mydin, M.A.; Alomayri, T.; Özkılıç, Y.O. Use of Waste Glass Powder toward more Sustainable Geopolymer Concrete. *J. Mater. Res. Technol.* **2023**, *12*, 8533–8546. [CrossRef]
30. Cheriaf, M.J.; Rocha, C.; Pera, J. Pozzolanic properties of pulverized coal combustion bottom ash. *Cem. Concr. Res.* **1999**, *29*, 1387–1391. [CrossRef]
31. Zainal Abidin, N.E.; Wan Ibrahim, M.H.; Jamaluddin, N.; Kamaruddin, K.; Hamzah, A.F. The effect of bottom ash on fresh characteristic, compressive strength and water absorption of self-compacting concrete. In *Applied Mechanics and Materials*; Trans Tech Publications Ltd.: Wollerau, Switzerland, 2014; Volume 660, pp. 145–151.
32. Abubakar, A.U.; Baharudin, K.S. Properties of Concrete using Tanjung Bin Power Plant Coal Bottom Ash and Fly ash. *Int. J. Sustain. Constr. Eng. Technol.* **2012**, *3*, 56–69.
33. Marto, A.; Tan, C.S. Properties of coal bottom ash from power plants in Malaysia and its suitability as geotechnical engineering material. *J. Teknol.* **2016**, *78*, 1–10. [CrossRef]
34. Tiwari, M.; Sahu, S.K.; Bhangare, R.C.; Ajamal, P.Y.; Pandit, G.G. Elemental Characterization of Coal, Fly Ash and bottom ash using an energy dispersive Xray fluorescence technique. *Appl. Radiat. Isot.* **2014**, *90*, 53–57. [CrossRef]
35. Singh, M.; Siddique, R. Properties of concrete containing high volume of coal bottom ash as fine aggregate. *J. Clean. Prod.* **2014**, *91*, 269–278. [CrossRef]
36. Ngoc Minh, V.T.; Pham, V.H.; Tung, V.H.; Tung, C.T.; Phuong, N.T.H. Firing-Associated Recycling of Coal-Fired Power Plant Fly Ash. *J. Anal. Methods Chem.* **2023**, *2023*, 8597376. [CrossRef] [PubMed]
37. Hamada, H.; Alattar, A.; Tayeh, B.; Yahaya, F.; Adesina, A. Sustainable application of coal bottom ash as fine aggregates in concrete: A comprehensive review. *Case Stud. Constr. Mater.* **2022**, *16*, e01109. [CrossRef]
38. Karalar, M.; Bilir, T.; Çavuşlu, M.; Özkiliç, Y.O.; Sabri, M.M. Use of recycled coal bottom ash in reinforced concrete beams as replacement for aggregate. *Front. Mater.* **2022**, *9*, 1064604. [CrossRef]
39. Casanova, S.; Silva, R.V.; de Brito, J.; Pereira, M.F.C. Mortars with alkali-activated municipal solid waste incinerator bottom ash and fine recycled aggregates. *J. Clean. Prod.* **2021**, *289*, 125707. [CrossRef]
40. Aramraks, T. Experimental study of concrete mix with bottom ash as fine aggregate in Thailand. In *Symposium on Infrastructure Development and the Environment*; 2006; pp. 1–5.
41. Aggarwal, P.; Aggarwal, Y.; Gupta, S.M. Effect of Bottom Ash as Replacement of Fine. *Asian J. Civ. Eng. (Build. Hous.)* **2007**, *8*, 49–62. [CrossRef]
42. Raju, R.; Paul, M.M.; Aboobacker, K.A. Strength Performance of concrete using bottom ash as fine aggregate. *Int. J. Res. Eng. Technol.* **2014**, *2*, 111–112.
43. Ramzihannan, N.; Shahidan, I.R.S.; Maarof, M.Z.; Ali, N. Physical and Chemical Properties of Coal Bottom Ash (CBA) from Tanjung Bin Power Plant. *IOP Conf. Ser. Mater. Sci. Eng.* **2016**, *160*, 12056.
44. *ASTM C150/C150M-21*; Standard Specification for Portland Cement. ASTM International: West Conshohocken, PA, USA, 2021. [CrossRef]

45. *ASTM C33/C33M-18*; Standard Specification for Concrete Aggregates. ASTM International: West Conshohocken, PA, USA, 2018. [CrossRef]
46. *ASTMC136/C136M-19*; Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates. ASTM International: West Conshohocken, PA, USA, 2019.
47. *ASTM C128-15*; Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate. ASTM International: West Conshohocken, PA, USA, 2015. [CrossRef]
48. *ASTMC270-19a*; Standard Specification for Mortar for Unit Masonry. ASTM International: West Conshohocken, PA, USA, 2019. [CrossRef]
49. *ASTM C305-20*; Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortar of Plastic Consistency. ASTM International: West Conshohocken, PA, USA, 2020. [CrossRef]
50. *ASTM C511-21*; Standard Specification for Mixing Roms, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cement and Concrete. ASTM International: West Conshohocken, PA, USA, 2021. [CrossRef]
51. *ASTM C1437-20*; Standard Test Method for Flow of Hydraulic Cement Mortar. ASTM International: West Conshohocken, PA, USA, 2020. [CrossRef]
52. *ASTMC109-21*; Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50 mm] Cube Specimens). ASTM International: West Conshohocken, PA, USA, 2021. [CrossRef]
53. *ASTM C348-21*; Standard Test Method for Flexural Strength of Hydraulic-Cement Mortars. ASTM International: West Conshohocken, PA, USA, 2021.
54. *ASTM C642-13*; Standard Test Method for Density, Absorption, and Voids in Hardened Concrete. ASTM International: West Conshohocken, PA, USA, 2021. [CrossRef]
55. *ASTM C267-20*; Standard Test Methods for Chemical Resistance of Mortars, Grouts, and Monolithic Surfacing's and Polymer Concretes. ASTM International: West Conshohocken, PA, USA, 2020. [CrossRef]
56. *ASTM E119-20*; Standard Test Methods for Fire Tests of Building Construction and Materials. ASTM International: West Conshohocken, PA, USA, 2020. [CrossRef]
57. Bar, B.; Hoseinian, S.B.; Beygi, M.A. shrinkage of concrete stored in natural environments. *Cem. Concr. Compos* **2003**, *25*, 19–29. [CrossRef]
58. *ASTM C596-18*; Standard Test Method for Drying Shrinkage of Mortar Containing Hydraulic Cement. ASTM International: West Conshohocken, PA, USA, 2018.
59. Ramachandran, V.S. *Concrete Admixture Handbook: PROPERTIES, Science and Technology*; William Andrew: Norwich, NY, USA, 1996.
60. Daniel, D.G. Factors influencing concrete workability. In *Significance of Tests and Properties of Concrete and Concrete-Making Materials*; ASTM International: West Conshohocken, PA, USA, 2006.
61. Jiang, X.; Xiao, R.; Ma, Y.; Zhang, M.; Bai, Y.; Huang, B. Influence of waste glass powder on the physico-mechanical properties and microstructures of fly ash-based geopolymer paste after exposure to high temperatures. *Constr. Build. Mater.* **2020**, *262*, 120579. [CrossRef]
62. Torkittikul, P.; Nochaiya, T.; Wongkeo, W.; Chaipanich, A. Utilization of coal bottom ash to improve thermal insulation of construction material. *J. Mater. Cycles Waste Manag.* **2017**, *19*, 305–317. [CrossRef]
63. Patel, D.; Shrivastava, R.; Tiwari, R.P.; Yadav, R.K. Properties of cement mortar in substitution with waste fine glass powder and environmental impact study. *J. Build. Eng.* **2020**, *27*, 100940. [CrossRef]
64. Zhao, J.; Li, S. Study on processability, compressive strength, drying shrinkage and evolution mechanisms of microstructures of alkali-activated slag-glass powder cementitious material. *Constr. Build. Mater.* **2022**, *344*, 128196. [CrossRef]
65. Wang, Y.; Li, Y.; Su, Y.; He, X.; Strnadel, B. Preparation of waste glass powder by different grinding methods and its utilization in cement-based materials. *Adv. Powder Technol.* **2022**, *33*, 103690. [CrossRef]
66. Chindasiriphan, P.; Meenyut, B.; Orasutthikul, S.; Jongvivatsakul, P.; Tangchirapat, W. Influences of high-volume coal bottom ash as cement and fine aggregate replacements on strength and heat evolution of eco-friendly high-strength concrete. *J. Build. Eng.* **2023**, *65*, 105791. [CrossRef]
67. Nakararoj, N.; Tran, T.N.; Sukontasukkul, P.; Attachaiyawuth, A.; Tangchirapat, W.; Ban, C.C.; Rattanachu, P.; Jaturapitakkul, C. Effects of High-Volume bottom ash on Strength, Shrinkage, and creep of High-Strength recycled concrete aggregate. *Constr. Build. Mater.* **2022**, *356*, 129233. [CrossRef]
68. Ganesan, H.; Sachdeva, A.; Petrounias, P.; Lampropoulou, P.; Sharma, P.K.; Kumar, A. Impact of Fine Slag Aggregates on the Final Durability of Coal Bottom Ash to Produce Sustainable Concrete. *Sustainability* **2023**, *15*, 6076. [CrossRef]
69. *ASTM C618-19*; Standard Specification for Coal Fly and Raw or Calcined Natural Pozzolan for use in Concrete. ASTM International: West Conshohocken, PA, USA, 2019.
70. Singh, A.; Zhou, Y.; Gupta, V.; Sharma, R. Sustainable use of different size fractions of municipal solid waste incinerator bottom ash and recycled fine aggregates in cement mortar. *Case Stud. Constr. Mater.* **2022**, *17*, e01434. [CrossRef]
71. Aygörmez, Y. Sulfate and chloride resistance of bottom ASH doped slag-based geopolymer composites. *Sigma* **2023**, *41*, 288–301. [CrossRef]

72. Mansour, M.A.; Ismail, M.H.B.; Imran Latif, Q.B.A.; Alshalif, A.F.; Milad, A.; Bargi, W.A.A. A systematic review of the concrete durability incorporating recycled glass. *Sustainability* **2023**, *15*, 3568. [CrossRef]
73. Bai, Y.; Darcy, F.; Basheer, P.A. Strength and drying shrinkage properties of concrete containing furnace bottom ash as fine aggregate. *Constr. Build. Mater.* **2005**, *19*, 691–697. [CrossRef]