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Utilization of Blast Furnace Slag as an Enhancer in Masonry Mortars Made with Thermally Treated Waste Concrete Powder

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Abstract: Every year, a massive amount of natural materials are subjected to high temperatures during cement production, resulting in 5% to 8% of total global carbon dioxide (CO_2) emissions. The employment of supplementary cementitious materials (SCMs) for developing construction materials could reduce the use of natural materials and CO_2 emissions during cement manufacturing. One option to accomplish this is to examine the possibility of producing masonry mortars using thermally treated waste concrete powder (WCP) and ground granulated blast furnace slag (GGBFS). The main objective of the present study is based on this. The study was conducted in two phases. In Phase I, WCP was thermally treated at various temperatures of 0 °C, 300 °C, 500 °C, and 700 °C and then used to prepare mortars at a binder-to-fine aggregate ratio of 1:3. From the strength results obtained in Phase I, a mortar mixture made with 500 °C WCP was selected for Phase II investigation. Mortars were produced by replacing the 500 °C WCP with GGBFS at 0%, 25%, 40%, 60%, 70%, and 85%. It was found that the performance of the mortars was enhanced when GGBFS was used up to 60%. The mortar mixture containing 60% thermally treated WCP and 40% GGBFS produced the optimal physical and mechanical properties. Also, material characterization was carried out on the binders using X-ray fluorescence, scanning electron microscopy, and thermogravimetric analysis. The results indicate that the thermally treated WCPs and GGBFS contain oxides similar to cement, making them suitable for mortar production. In conclusion, the study has shown the feasibility of producing masonry mortars using thermally treated WCP and GGBFS.

Keywords: waste concrete powder; masonry mortar; blast furnace slag; heat treatment; compressive strength; density; morphology; water absorption

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1. Introduction

Large quantities of natural materials such as limestone, clay, and shale are required to produce cement. These raw materials are blended and fired at high temperatures during cement manufacturing, resulting in 5% to 8% of the total global carbon dioxide (CO_2) emissions [1,2]. The substitution of ordinary Portland cement (OPC) with by-products or waste materials could lead to reductions in both natural materials and CO_2 generation worldwide. The replacement of cement with waste concrete powder (WCP) and ground granulated blast furnace slag (GGBFS) is an option that can be employed to accomplish this goal. Consequently, a number of researchers have conducted studies using thermally treated WCP or GGBFS as a partial substitution for OPC.

In a study conducted by Sui et al. [3], WCP was obtained by crushing waste concrete using a jaw crusher. The WCP was thermally treated by subjecting it to different temperatures of 0 °C, 200 °C, 400 °C, 600 °C, 700 °C, and 800 °C using a laboratory furnace. Mortars were prepared by substituting 30% OPC with the various treated WCPs. It was reported that the treated temperatures employed significantly affected the performance of the produced mortars. For instance, 28-day compressive strength values of 42.6 MPa, 47.7 MPa, and 37.0 MPa were obtained for mortars made with WCPs treated at 400 °C, 700 °C, and 800 °C, respectively. Also, mortar mixtures containing 0 °C, 200 °C, and 400 °C WCPs recorded 28-day flexural strengths of 8.79 MPa, 6.18 MPa, and 7.07 MPa, respectively.

Florea et al. [4] produced WCP by crushing laboratory waste concrete. The 150 µm WCP obtained was treated at 0 °C, 500 °C, and 800 °C. Recycled mortars were made by replacing OPC with treated WCP at 0%, 10%, and 30% levels using a water–binder (w/b) ratio of 0.50. It was mentioned that the compressive strength of the mortars was reduced as the replacement content of the treated WCP increased, regardless of the treatment temperature used. The 28-day compressive strength of the control mortar declined from 50.0 MPa to 46.0 MPa and 40.0 MPa when 10% and 20% of OPC were substituted with 800 °C WCP, respectively.

Bogas et al. [5] evaluated the effect of thermally treated WCP on the strength properties of cement mortars. It was reported that the 28-day compressive strength of the control mortar decreased from 41.9 MPa to 2.6 MPa and 4.1 MPa when 75% of the OPC was substituted with 0 °C WCP and 650 °C WCP, respectively. Again, the 28-day elastic modulus of the control mortar was reduced from 35.5 GPa to 7.0 GPa upon the complete replacement of OPC with 650 °C WCP.

In the process of thermal treatment, chemical reactions such as the decomposition of C-S-H and $Ca(OH)_2$ occurred in the WCP, which resulted in the generation of active materials that could react with water [3]. The activity of the WCP after high-temperature treatment significantly increased [6]. Sui et al. [3] reported that the mass loss of the WCP increased as the treatment temperature increased. The authors added that the free calcium oxide (CaO) content in the WCP increased with the increase in the treatment temperature. The free CaO could quickly react with water, and more contents would affect the cement properties [3].

Sambowo et al. [7] examined the influence of GGBFS on the mechanical properties of mortars. Mortars were prepared by adding 0%, 10%, 20%, 30%, 40%, and 50% GGBFS of the cement to the control mortar. The 7-day compressive strength of the control mortar was increased from 10.9 MPa to 17.3 MPa when 20% GGBFS was added to the mixture, representing an increment of 58.7%. The effects of GGBFS on the strength and durability properties of geopolymer mortars were assessed by Oleiwi et al. [8]. It was reported that the mortar mixture containing 100% GGBFS obtained the highest compressive strength of 78.3 MPa at 7 days.

In a study conducted by Ngo et al. [9], mortars were made by substituting OPC with GGBFS at 0%, 15%, 30%, 45%, and 60% by mass. It was reported that the 28-day compressive strength of the control mortar increased from 97.0 MPa to 108.0 MPa upon a 15% replacement of OPC with GGBFS. Similarly, Sandhu et al. [10] produced mortars by replacing OPC with GGBFS at 0%, 5%, 10%, 15%, and 20% contents. It was mentioned that the 28-day compressive strength of the control mortar increased from 26.3 MPa to 32.7 MPa and 29.8 MPa when 5% and 10% of the cement were substituted with GGBFS, respectively.

The reactivity of GGBFS is considered a significant parameter to evaluate the effectiveness of GGBFS in cement matrix composites. In order to predict the hydraulic activity of GGBFS, various basicity ratios have been proposed, as summarized in Table 1. However, studies have shown that these ratios do not necessarily give an accurate prediction of a slag's performance [11,12]. For instance, Mantel [12] investigated the hydraulic activity of five different slags, and the conclusion was that there was no clear correlation between the basicity ratios and the properties of slag blends.

Table 1. Basicity ratios for assessment of hydraulicity of GGBFS.

Formula	Requirement for Good Performance
$BR_1 = CaO/SiO_2$	Greater than 1 [13]
$BR_2 = (CaO + MgO)/(SiO_2)$	Greater than 1 [14]
$BR_3 = (CaO + MgO)/(SiO_2 + Al_2O_3)$	Greater than or equal to 1 [13]
$BR_4 = (CaO + MgO + Al_2O_3)/(SiO_2)$	Between 1.5 and 1.9 is good, above 1.9 very good [13]

The preceding shows that studies on cement mortars containing WCPs or GGBFS are available in the literature. However, studies relating to the production of masonry mortars made with only WCP and GGBFS are yet to be found in the literature. Hence, the objective of the current study is to examine the feasibility of making masonry mortars using WCP and GGBFS.

Purpose and Process of the Study

The purpose of the current study was to assess the effects of GGBFS on the fresh and hardened properties of masonry mortars made with thermally treated WCP. Figure 1 outlines the research process. The materials required for the mortar production were collected and prepared. Testing and characterization of the materials were performed to ascertain their suitability. Mortar mixtures were designed. The mixing, casting, and curing of the mortar specimens were carried out. The fresh and hardened properties of the mortars were determined using the appropriate standards. Finally, the obtained results were discussed, and conclusions were drawn.

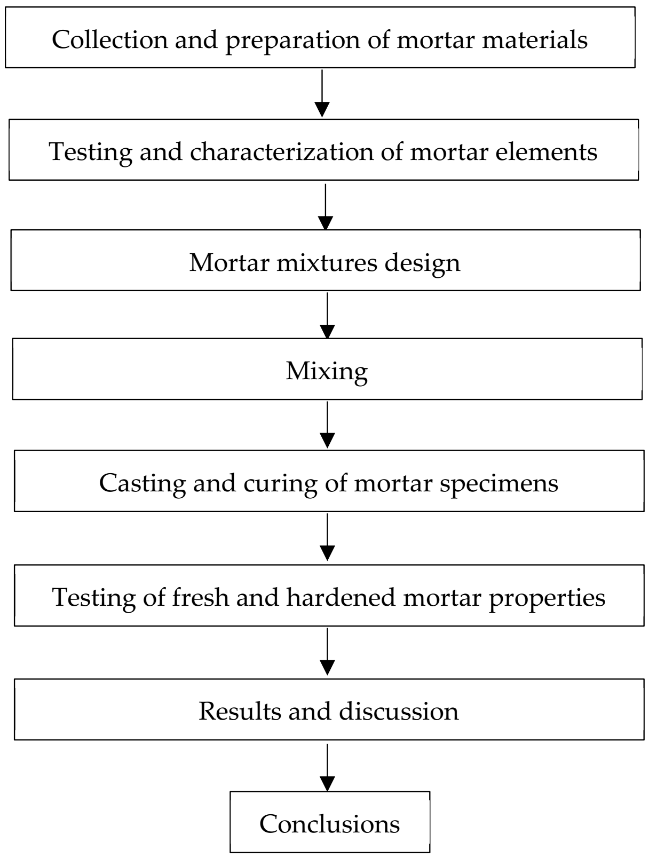


Figure 1. Flowchart of the research process.

2. Experimental Procedure

2.1. Materials

Thermally treated WCP, GGBFS, river sand, and water were employed for the preparation of the mortars. The GGBFS was obtained from Afrisam Limited, South Africa. The river sand was obtained from Sand Shifters Limited, South Africa. The sand was in conformity with the grading of [15]. The waste concrete was obtained from a disposal site in Johannesburg, South Africa. Table 2 shows the physical properties of the sand and the binders. Potable water was used for the preparation and curing of the mortars. Also, Table 3 shows the granulometric composition of the sand.

Table 2. Physical properties of the sand and the binders.

Property	Type of Material		
	Sand	**Thermally Treated WCP**	**GGBFS**
Bulk density (kg/m^3)	1689.40	-	-
Fineness modulus	2.76	-	-
Moisture content (%)	2.31	-	-
Silt and clay content (%)	3.00	-	-
Specific gravity	2.75	2.63	2.91
Blaine fineness (cm^2/g)	-	2817.10	4000.00

Table 3. Granulometric composition of sand.

Scheme	Sieve Diameter (mm)							Fineness Modulus
	2.36	**1.18**	**0.60**	**0.30**	**0.15**	**0.075**	**<0.075**	
Partial	1.00	4.00	20.00	40.00	20.00	11.60	3.40	2.78
Full	1.00	5.00	25.00	65.00	85.00	96.60		

Preparation of the Thermally Treated Waste Concrete Powder

The WCP was prepared in the same manner as described by Ohemeng et al. [16]. The processed WCP was subjected to temperatures of 300 °C, 500 °C, and 700 °C for 4 h using a laboratory furnace. The furnace was heated at a rate of 5 °C/min, starting from room temperature. The obtained thermally treated WCPs, referred to as dehydrated WCPs (DWCPs), were used for the present study.

2.2. Methods

2.2.1. Chemical Composition, Morphology, Thermogravimetry, and Particle Size Distribution Analyses

X-ray fluorescence (XRF) analysis was performed using a Malvern Panalytical spectrophotometer. An Oxford X-max EDS detector and Tescan VEGA3 scanning electron microscopy (SEM) were used for the microscopic investigation. The thermal gravimetric analysis was carried out using a NETZSCH thermobalance. A laser diffraction particle size analyser Malvern-Mastersizer 2000-Hydro G was used to conduct particle size distribution (PSD) analysis.

2.2.2. Casting and Curing of the Mortars

The experimental study was conducted in two (2) phases. Phase I was performed to evaluate the effect of thermally treated WCPs on the compressive strength of masonry mortars. Using a binder-to-sand ratio of 1:3, mortar mixtures were prepared with the WCPs treated at 0 °C, 300 °C, 500 °C, and 700 °C, and were labelled as DWCP-0, DWCP-300, DWCP-500, and DWCP-700, respectively. The 0 °C WCP refers to the processed 75 µm WCP obtained after sieving that was not treated at any temperature (i.e., the original WCP). Table 4 shows the mortar mixture proportions in Phase I. Based on the 28-day compressive strength values obtained, the mortar mixture made with 500 °C WCP was selected for study in Phase II. In Phase II, mortars were prepared by replacing the 500 °C WCP with GGBFS at different contents of 0%, 25%, 40%, 60%, 70%, and 85%. The casting and curing of the mortars were performed in the same way as described by Ohemeng et al. [16]. The mixture proportions of the mortars in Phase II are presented in Table 5.

Table 4. Proportions of the mortar mixtures in Phase I.

Notation	Constituents of Mortar (g)		
	DWCP	Sand	Water
DWCP-0	146.50	439.50	87.90
DWCP-300	146.50	439.50	95.23
DWCP-500	146.50	439.50	102.55
DWCP-700	146.50	439.50	109.88

DWCP—dehydrated waste concrete powder.

Table 5. Proportions of the mortar mixtures in Phase II.

Notation	Constituents of Mortar (g)			
	500 °C WCP	GGBFS	Sand	Water
DWCP100-G0 (control mortar)	146.50	0.00	439.50	102.55
DWCP75-G25	109.88	36.62	439.50	102.55
DWCP60-G40	87.90	58.60	439.50	102.55
DWCP40-G60	58.60	87.90	439.50	102.55
DWCP30-G70	43.95	102.55	439.50	102.55
DWCP15-G85	21.98	124.52	439.50	102.55

WCP—waste concrete powder; GGBFS—ground granulated blast furnace slag.

2.2.3. Mortar Properties Tests

Five (5) samples were used to obtain the average value of each mortar mixture test. The flow and the setting times of the mortar mixtures were determined as per [17] and [18], respectively. A statistical tool in Python was employed to determine the mean values. Table 6 shows the hardened mortar properties and the standards that were used for their testing.

Table 6. Testing of hardened mortar properties.

Type of Property	Reference Standard/Formula	Sample Size (mm)	Testing Day(s)
Dry bulk density	[19]	50 × 50 × 50	28
Apparent porosity	[19]	50 × 50 × 50	28
Water absorption	[20]	50 × 50 × 50	28
Density	[21]	50 × 50 × 50	3, 7, 28, 90
Compressive strength	[22]	50 × 50 × 50	3, 7, 28, 90
Flexural strength	[23]	40 × 40 × 160	3, 7, 28, 90
Splitting tensile strength	$f_t = 2P/\pi dl$	100 (d) × 200 (l)	3, 7, 28, 90

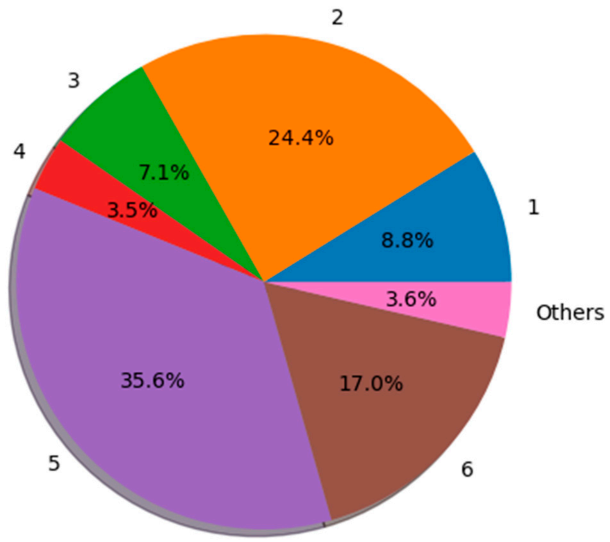
f_t is the flexural strength, P is the applied load, d is the diameter of the specimen, and l is the length of the specimen.

3. Results and Discussion

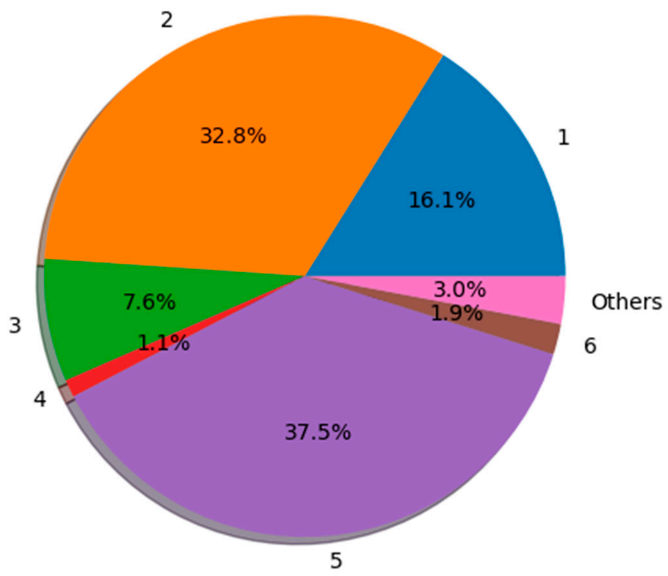
3.1. Material Characterization

3.1.1. Binders and Their Types of Oxides

An XRF analysis was carried out to ascertain the chemical composition of the binders. Figure 2a,b show the binders and their types of oxides. The main oxides found in WCP are silicon dioxide (SiO_2), CaO, loss on ignition (LOI), and aluminium oxide (Al_2O_3), constituting 85.8% weight of the total oxide. For the GGBFS, it is obvious that Al_2O_3, CaO, magnesium oxide (MgO), and SiO_2 account for 94.0% of the total oxide. The BR_1, BR_2, and BR_4 of the GGBFS were 1.14, 1.38, and 1.87, respectively. This indicates that the slag met the requirements according to the aforementioned standards. However, 0.92 was obtained for BR_3, which is below the expected requirement.



(**a**)



(**b**)

Figure 2. (**a**) Types of oxides in WCP (1—Al_2O_3, 2—CaO, 3—Fe_2O_3, 4—MgO, 5—SiO_2, 6—LOI, Others—K_2O, MnO, Na_2O, P_2O_5, SO_3, and TiO_2). (**b**) Types of oxides in GGBFS (1—Al_2O_3, 2—SiO_2, 3—MgO, 4—MnO, 5—CaO, 6—SO_3, Others—BaO, Fe_2O_3, K_2O, Na_2O, and TiO_2).

3.1.2. Thermogravimetry Analysis

The DWCPs were examined through TG tests, as shown in Figure 3. The DWCP-0 first mass loss was observed in the TG curve between 50 °C and 200 °C. This could be due to the release of free water found in the material [24]. Also, between 450 °C and 550 °C, a small peak was observed, which could be attributed to the decomposition of organic materials [24]. The final mass loss was observed between 650 °C and 750 °C, which could be ascribed to the release of CO_2 from the decomposition of $CaCO_3$ [24]. DWCP-300 experienced a similar trend of mass loss as described for DWCP-0. The sample obtained its first mass loss between 50 °C and 200 °C and the second mass loss occurred between 450 °C and 550 °C. The final mass loss was noticed between 650 °C and 750 °C. The DWCP-500 sample was stable with no apparent mass loss up to a temperature of 720 °C.

This significant mass loss could be due to the emission of CO_2 from the decomposition of $CaCO_3$. The figure shows that the mass loss of the WCP increased as the treatment temperature increased. These weight losses were a direct result of the evolution of CO_2 gas. The residue is the remaining CaO that failed to decompose [25]. This indicates that the CaO content in the DWCPs increased as the treatment temperature rose to 500 °C. The results are in agreement with the study conducted by Sui et al. [3]. The TG curve for DWCP-700 shows that the structural stability of the DWCP started to be disrupted when the treatment temperature surpassed 500 °C.

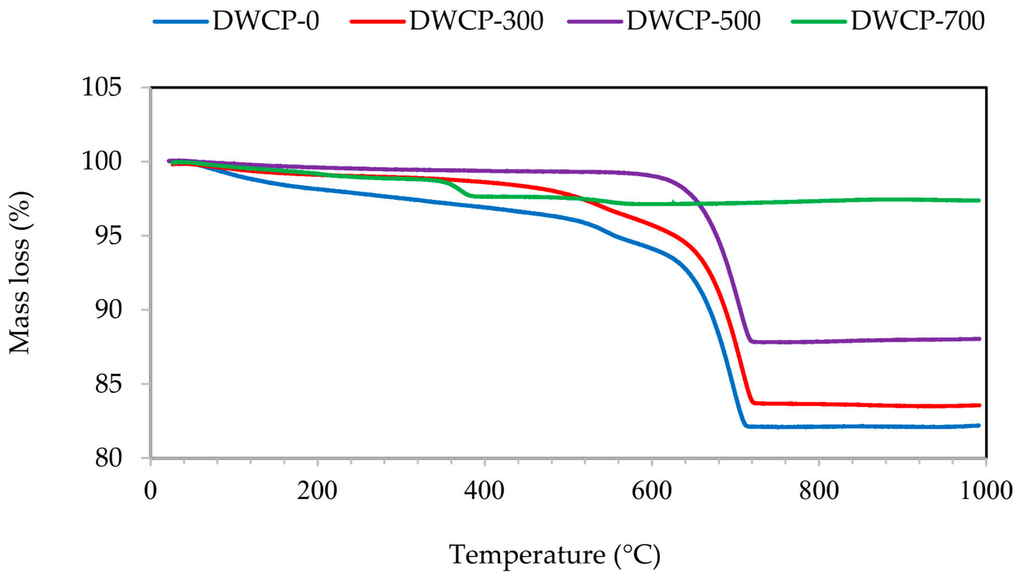


Figure 3. TG results of the various DWCPs.

3.1.3. Particle Size Distribution of the Mortar Components

Figure 4 presents the PSD of the mortar components. Most of the DWCP-500 particles were between 18.5 μm and 420.0 μm in size, with an average diameter of 61.5 μm for d_{60}. The GGBFS particle sizes fell between 0.4 μm and 400 μm, with mean diameters of d_{40} = 21.5 μm. For the sand, the majority of the particle sizes were between 20 μm and 650 μm.

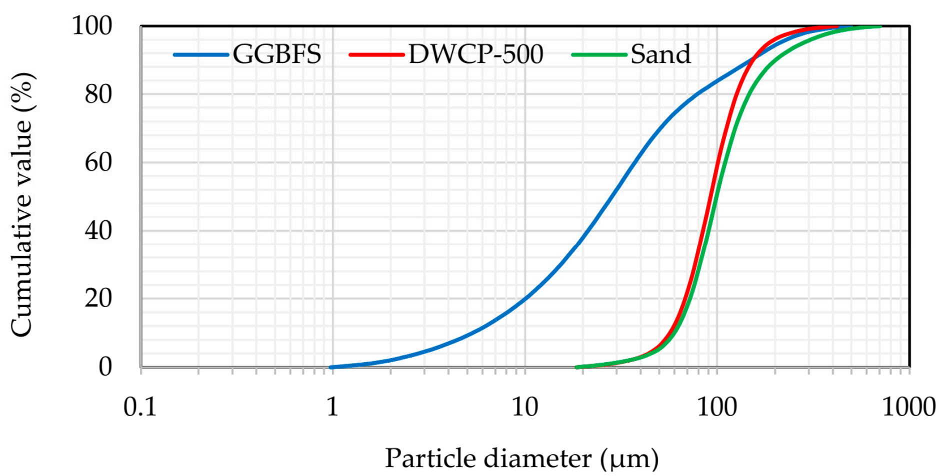


Figure 4. Particle size distribution of the mortar components.

3.1.4. Morphology of the Mortars

Figure 5 presents the microstructure of the mortar specimens prepared in Phase I using SEM. The results show that the pores in the microstructure of the mortars decreased as the treatment temperature increased. The increase in CaO content as the treatment temperature rose could be the cause of the improvement in the microstructure of the mortars (Section 3.1.2). However, the microstructure pores of the mortars started to increase when the treatment temperature exceeded 500 °C. This could be attributed to the disruption of the DWCP's structural stability when the treated temperature surpassed 500 °C (Section 3.1.2).

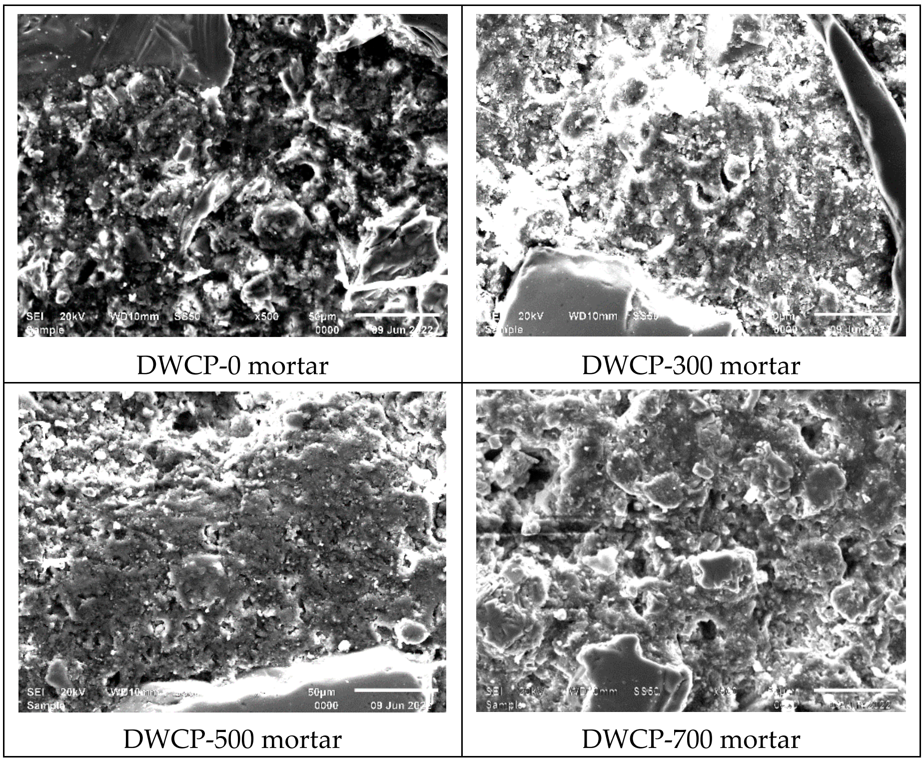


Figure 5. Morphology of the mortar samples obtained via SEM.

3.2. Compressive Strength of the Mortars in Phase I

The compressive strengths of the mortars prepared with various DWCPs are presented in Figure 6. Evidently, the compressive strength of the mortars increased as the temperature increased up to 500 °C, regardless of the curing age. The 28-day compressive strength of the mortar mixture DWCP-0 increased from 1.64 MPa to 4.24 MPa for the mortar made with DWCP-500. The increase in CaO content as the treatment temperature increased could be the reason for the compressive strength enhancement (Section 3.1.2). However, when the treatment temperature exceeded 500 °C, the mortars' compressive strength started to decrease. The 28-day compressive strength of mortar mixture DWCP-500 declined from 4.24 MPa to 1.31 MPa for the mortar samples prepared with DWCP-700. The disruption of the DWCP's structural stability as the treatment temperature surpassed 500 °C could be responsible for the decrease in the compressive strength. The figure also demonstrates that, irrespective of the treatment temperature, the compressive strength of the mortars increased as the curing age advanced. For instance, when the curing age increased from 28 days to 90 days, the compressive strength of the DWCP-300 mortar mixture increased from 2.02 MPa to 2.96 MPa. This could be due to the prolonged curing that accelerated the hydration process, which improved the bonding capacity of the mortar paste [26,27].

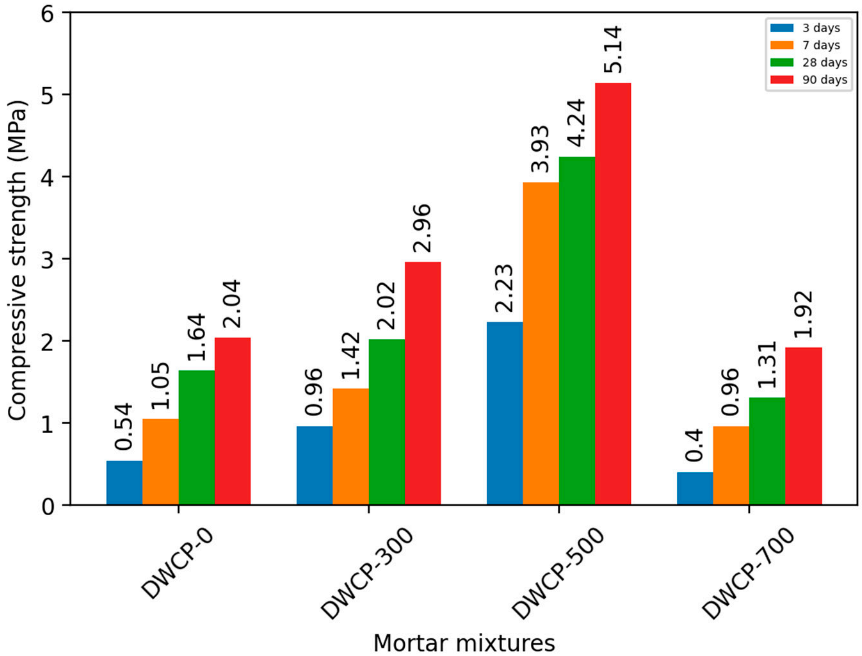


Figure 6. Compressive strength of the mortars made with different DWCPs.

3.3. Mortar Properties in Phase II

3.3.1. Flow

The flow values of the mortars are shown in Figure 7. As the GGBFS replacement level increased, so did the mortar flow. The flow of the control mortar increased from 107 mm to 135 mm when 85% of the DWCP was replaced with GGBFS. This could be due to the smooth and dense surface of the GGBFS particles, which reduces its absorption rate during initial mixing [28].

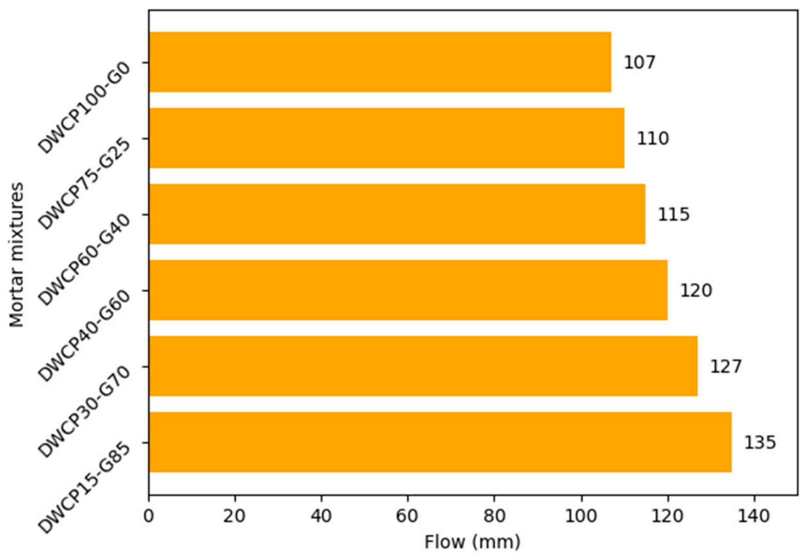


Figure 7. Flow of the mortars.

3.3.2. Setting Time

The influence of GGBFS on the mortar setting times is shown in Figure 8. The setting time increased as the amount of GGBFS in the mortar mixture increased. When 70% of the DWCP was replaced with GGBFS, the control mortar's initial and final setting times increased from 55 min and 180 min to 145 min and 278 min, respectively. GGBFS particle activation occurred when activators, such as alkalis, reacted with slag and disrupted its glassy structure. The alkalis in the DWCP caused the GGBFS particles to activate for the hydration process [29]. This chemical process slowed down the early hydration of GGBFS, extending the time required for the setting of the GGBFS mortars.

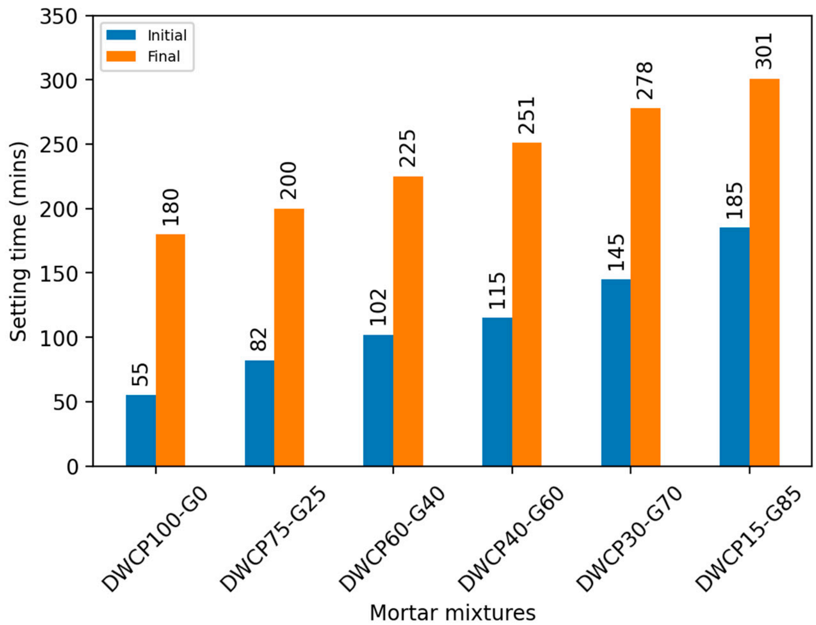


Figure 8. Setting time of the mortars.

3.3.3. Strength Properties

Table 7 presents the results of the mortars' strength properties. Compared with the control mortar, the mortars containing GGBFS had lower strength values at early ages (3 to 7 days). For instance, when 85% of the DWCP was replaced with GGBFS, the 3-day compressive strength and flexural strength of the control mortar decreased from 2.23 MPa and 0.38 MPa to 1.60 MPa and 0.28 MPa, respectively. Also, the tensile strengths of all GGBFS mortars lowered by 6.5% to 22.6% on curing day 7, compared with the control mortar. When a portion of the DWCP is replaced with GGBFS, the alkalis in the DWCP activates the slag particles for the hydration process [29]. The early hydration of GGBFS mortars is slowed by this chemical process, which delays the mortars' early strength development. However, the mechanical properties trending at later ages (28 to 90 days) differed from those at earlier ages. In later days, the strength properties of the GGBFS mortars were comparable to or slightly higher than those of the control mortar for replacement levels of GGBFS up to 60%. The compressive strength and flexural strength of the control mortar at 28 days increased from 4.24 MPa and 1.22 MPa to 6.06 MPa and 1.51 MPa, respectively, when 40% of the DWCP was replaced with GGBFS. Nonetheless, the mortars recorded lower strength values at later ages when the replacement level of GGBFS exceeded 60%. Mortar strength increases when GGBFS is used in a proper replacement ratio, but when slag is added in large quantities, hydration products and strength significantly decreases [30]. The table also shows the effect of curing age on the mortars' strength properties. Regardless of the amount of GGBFS used, the strength properties increased as the curing age advanced. From the compressive strength results obtained, the mortars satisfied the minimum strength requirements for masonry mortar types N and O, which are 5.2 MPa and 2.4 MPa, respectively [31,32].

Table 7. Strength properties of the mortars.

Notation	Compressive Strength (MPa)				Flexural Strength (MPa)				Splitting Tensile Strength (MPa)			
	Age (Days)				Age (Days)				Age (Days)			
	3	7	28	90	3	7	28	90	3	7	28	90
DWCP100-G0	2.23	3.93	4.24	5.14	0.38	0.62	1.22	1.60	0.13	0.31	0.43	0.64
DWCP75-G25	1.80	3.55	4.58	5.53	0.31	0.55	1.33	1.64	0.11	0.27	0.48	0.71
DWCP60-G40	2.15	3.82	6.06	7.28	0.35	0.60	1.51	2.16	0.12	0.29	0.62	0.94
DWCP40-G60	1.92	3.70	5.04	6.25	0.33	0.58	1.40	2.06	0.11	0.28	0.53	0.85
DWCP30-G70	1.75	3.20	4.14	5.02	0.30	0.54	1.29	1.48	0.10	0.26	0.42	0.61
DWCP15-G85	1.60	2.90	3.36	4.25	0.28	0.40	0.87	1.21	0.10	0.24	0.40	0.60

3.3.4. Density

Figure 9 shows the mortars' densities at different curing ages. As the GGBFS replacement level increased, the density of the mortars generally improved. The densities of the DWCP100-G0, DWCP75-G25, DWCP60-G40, and DWCP40-G60 mortar mixtures were 2144.30 kg/m^3, 2145.80 kg/m^3, 2147.40 kg/m^3, and 2143.92 kg/m^3, respectively, at curing day 28. The higher specific gravity of GGBFS compared with that of DWCP could be the cause of the increase in density of the GGBFS mortars (Table 2). However, DWCP30-G70 and DWCP15-G85 mortar mixtures had slightly lower density values than the control mortar. The density of the control mortar declined from 2147.86 kg/m^3 to 2142.50 kg/m^3 at curing day 90 for mortar mixture DWCP15-G85. Also, the figure exhibits that the density of the mortars increased as curing time advanced. When the curing age increased from 3 to 90 days, the density of the mortar mixture DWCP60-G40 increased from 2135.72 kg/m^3 to 2150.24 kg/m^3.

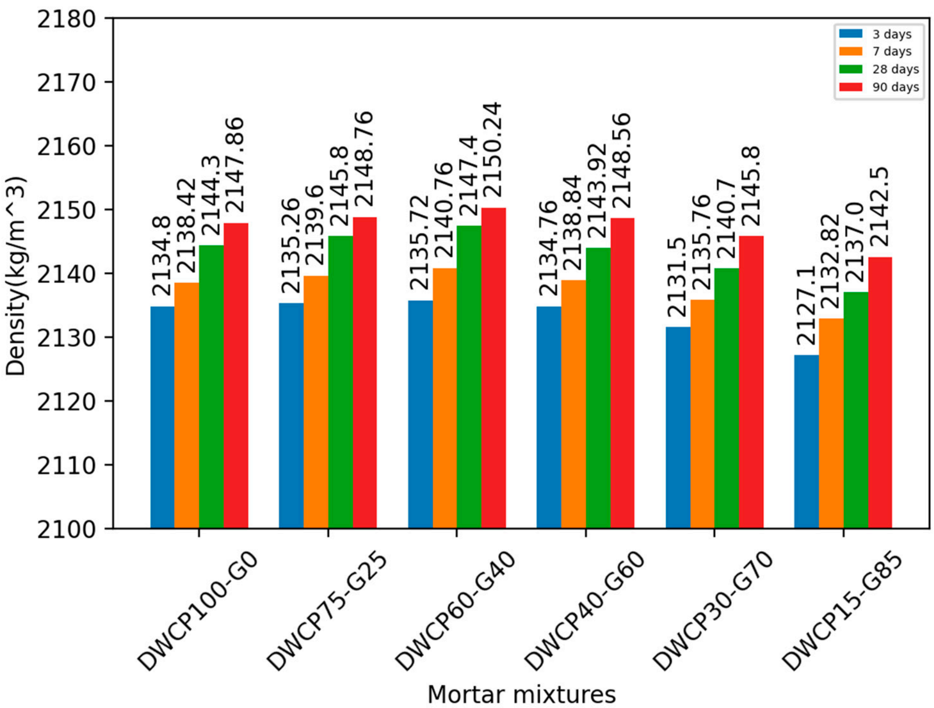


Figure 9. Density of the mortars.

3.3.5. Dry Bulk Density and Apparent Porosity

Figure 10 shows the dry bulk density and apparent porosity of the mortars. The employment of GGBFS had no adverse effects on the mortars' bulk density and apparent porosity performance when compared with the control mortar. A slight increase in the dry bulk density and a marginal reduction in the apparent porosity could be observed when GGBFS was used. For mortar mixtures made with 0%, 25%, 40%, and 60% GGBFS, the recorded dry bulk density values were 1853.90 kg/m^3, 1855.20 kg/m^3, 1860.51 kg/m^3, and 1856.39 kg/m^3, respectively. Also, the apparent porosity values of mortar mixtures DWCP100-G0, DWCP75-G25, DWCP60-G40, and DWCP40-G60 were 24.50%, 23.62%, 22.14%, and 23.00%, respectively. The improvement in the dry bulk density of the GGBFS mortars may be due to the GGBFS's higher density when compared with that of the DWCP (Table 2).

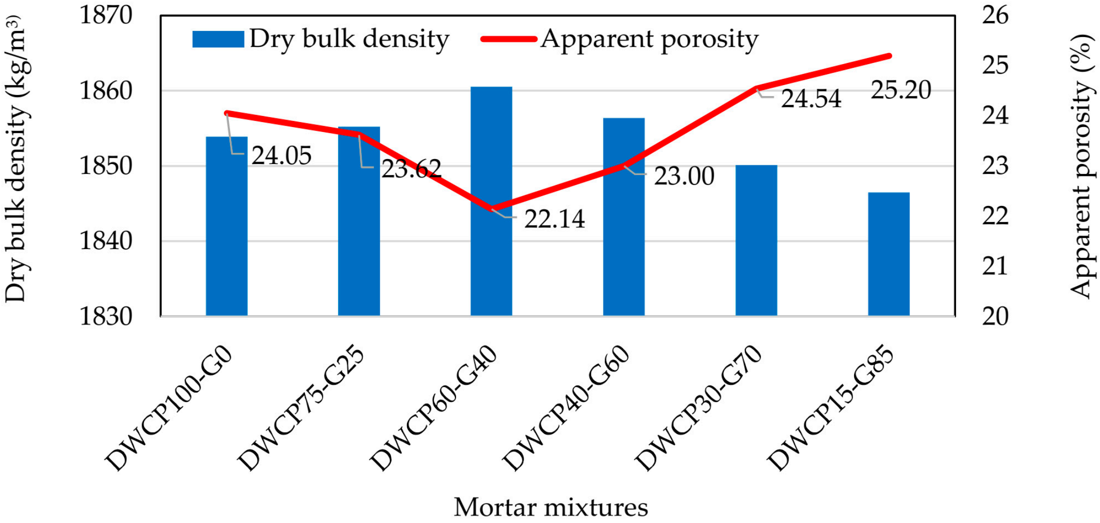


Figure 10. Dry bulk density and apparent porosity of the mortars.

3.3.6. Water Absorption

Figure 11 displays the effects of GGBFS content and immersion time on the mortars' water absorption. For all of the measured hours, replacing the DWCP with 25% to 60% GGBFS exhibited no detrimental impact on the performance of the mortars' water absorption compared with the control mortar. For an immersion period of 1 h, water absorption values of 20.50 g/100 cm^2, 19.83 g/100 cm^2, 17.48 g/100 cm^2, and 19.05 g/100 cm^2 were recorded for mortar mixtures DWCP100-G0, DWCP75-G25, DWCP60-G40, and DWCP40-G60, respectively. This shows that the water absorption of the control mortar decreased by 14.7% when 40% of the DWCP was replaced with GGBFS. However, the water absorption values in the mortar mixtures containing more than 60% GGBFS were higher than that of the control mortar. The water absorption of the control mortar increased from 50.60 g/100 cm^2 to 57.75 g/100 cm^2 for mortar mixture DWCP15-G85 during a 4 h immersion duration. The explanation of the trend for the results could be the same as the one already given for the behaviour of the mortars' strength properties in Section 3.3.3.

3.3.7. Relationship between the Compressive Strength and Density of the Mortars

Figure 12 shows the association between the compressive strength and density of the mortars. Evidently, there is a correlation between the two properties. Microsoft Excel 2016 was used to carry out the regression analysis and the mathematical models. The R^2 value of 0.8469 indicates that 84.69% of the change in density can be attributed to the compressive strength. The mathematical expression connecting the two properties is given in Equation (1).

$$D = -1.4334{c_s}^2 + 17.155c_s + 2095.7 \tag{1}$$

where D is the 28-day density and c_s is the 28-day compressive strength of the mortar.

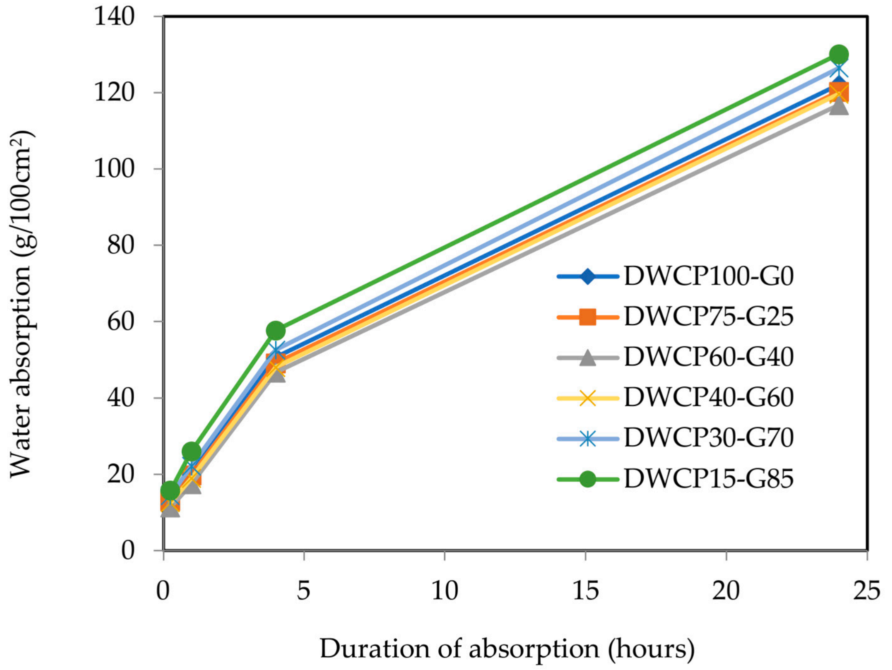


Figure 11. Water absorption of the mortars.

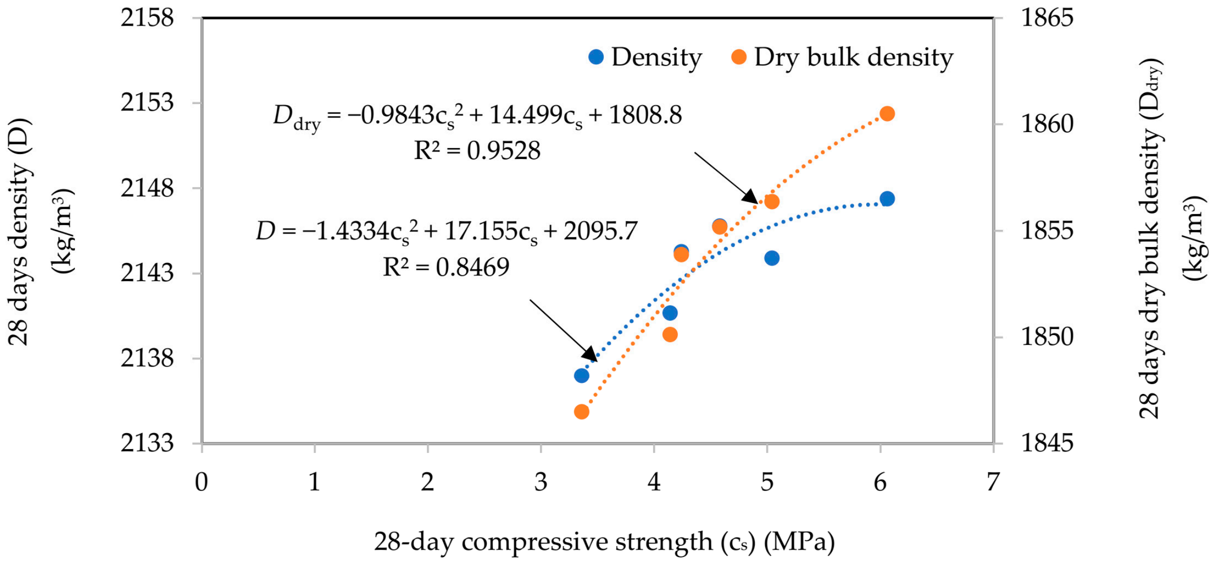


Figure 12. Relationship between compressive strength and densities of the mortars.

The figure also exhibits the relationship between the compressive strength and dry bulk density of the mortars. The dry bulk density increases as the compressive strength increases. It is obvious that 95.28% of the variations in the dry bulk density could be due to the compressive strength of the mortar. The equation linking the dry bulk density and compressive strength is given in Equation (2) as:

$$D_{\mathrm{dry}} = -0.9843{c_s}^2 + 14.499c_s + 1808.8 \quad (2)$$

where D_{dry} is the 28-day dry bulk density and c_s is the 28-day compressive strength of the mortar.

4. Conclusions

The present study examined the possibility of producing masonry mortars using DWCP and GGBFS. The GGBFS was used to partly replaced the DWCP in the mortars' production. The following key points can be drawn:

- The chemical analyses show that WCP and GGBFS contain oxides similar to cement and, hence, have the potential to be used as binders.
- The study has shown that treatment temperatures have an effect on the performance of masonry mortars.
- The performance of the masonry mortars was significantly improved when a GGBFS content of up to 60% was used as a replacement for 500 °C WCP.
- From the experimental results obtained, it is recommended that the optimal replacement of DWCP with GGBFS for masonry purposes should not exceed 60%.
- The mortar mixture made with 60% DWCP and 40% GGBFS produced the best physical and mechanical properties.
- The produced mortars met the minimum strength requirements for masonry mortar types N and O, which are 5.2 MPa and 2.4 MPa, respectively.
- The study has shown the feasibility of making masonry mortar using only DWCP and GGBFS.

5. Further Research

This study focuses on the production of masonry mortars using GGBFS and thermally treated WCP. Further studies should be conducted to determine the content of active elements such as CaO in WCPs before subjecting them to thermal treatment.

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