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Strength and Durability Properties of Geopolymer Mortar Made with Concrete Waste Powder †

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Abstract: With each passing season, the need for sustainability is growing exponentially. This target of sustainability can only be achieved by innovation in new materials and technologies. Geopolymer binders are innovative materials that can replace cement and play a vital role in attaining sustainability in infrastructure. This paper discusses the effective utilization of Concrete Waste Powder (CWP) as a binder to assess the strength and durability properties of geopolymer mortar. Herein a CWP was partially replaced with Ground Granulated Blast Furnace Slag (GGBS) at different replacement levels of 0%, 10%, and 20%. The alkaline solution for geopolymer mortar was made from sodium hydroxide and sodium silicate solutions. For all geopolymer mortar mixes, 0.45 alkali/binder ratio, 12 molarity (M) of sodium hydroxide, 2 of sodium silicate/sodium hydroxide ratio, and 0.35 of water/solid were kept constant. The strength property in terms of compressive strength and durability was accessed in terms of water absorption and porosity of all geopolymer mortar mixes at both ambient and heat curing conditions at 7 and 28 days. The presence of silica, alumina, and calcium in CWP makes it a potential binder for geopolymer mortar. The results suggest that increasing the substitution of GGBS with CWP improves the strength and durability of geopolymer mortar mixes by providing appropriate calcium content along with a geopolymer reaction. The compressive strength increases and water absorption and porosity decrease significantly with a 20% content of GGBS. The utilization of CWP in the production of geopolymer mortar sourced from concrete waste can help to achieve a sustainable environment.

Keywords: geopolymer mortar; Concrete waste powder; GGBS; compressive strength; water absorption

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1. Introduction

To fulfil the ever-increasing infrastructure need, there is tremendous growth in construction activities nowadays. The commonly used material for construction projects is cement-based concrete, and emission from the cement production process accounts for 7% of worldwide CO_2 emissions, which contributes a large part to global warming [1]. Thus, there is a great need to develop a replacement to cement concrete to achieve sustainability. Geopolymer concrete can be a potential replacement for cement-based concrete as it has the same mechanical and durability properties with the advantage of environmental benefit, i.e., reducing CO_2 emission [2]. Geopolymers are an inorganic, non-flammable, heat-resistant three-dimensional network of that may swiftly alter and adopt a shape at low temperatures [3]. Joseph Davidovits developed the term geopolymer for these materials in 1978 [4]. A geopolymer is mainly composed of two main constituents, namely the base material (alumina-silicate rich) and the alkaline liquids (alkali hydroxide and alkali silicate). The chemistry of the base material, alkaline activators, and curing conditions all influence the rate of chemical reaction and strength development of geopolymer [5].

With the increase in urbanisation, every infrastructure is repaired and renovated, thus creating a large amount of concrete waste whose disposal is again a great challenge

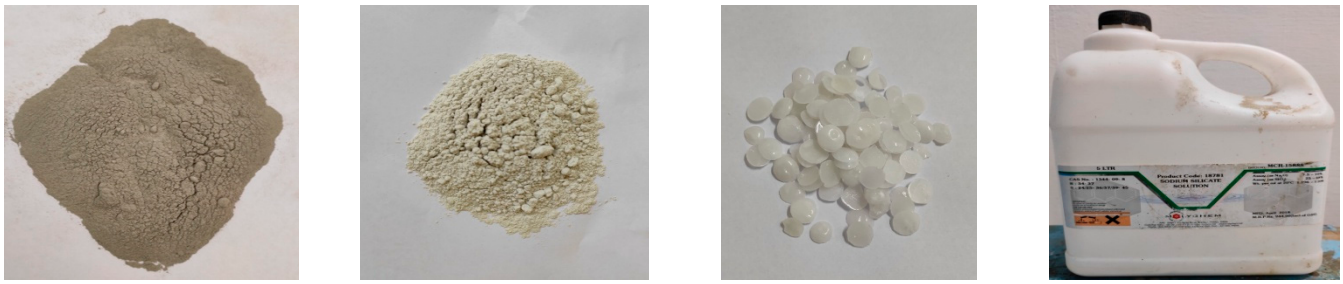
for sustainability. The Central Pollution Control Board of India conducted a study that noted that India produces close to 14.5 million tons of concrete waste per year, which is an enormous amount of waste [6]. Thus, the reuse of concrete waste in new engineering construction; for example, geopolymer concrete/mortar is considered an integral part of reversing this trend [7]. In recent years, extensive research has been conducted to produce geopolymers from different raw materials which are rich in silica and alumina. However, very-little work has been performed on the utilization of concrete waste in the production of geopolymer concrete/mortar. The concrete waste used in geopolymer production is limited to use as aggregate only. Furthermore, a few studies have indicated that if recycled concrete waste fine particles are further ground into powder form called Concrete Waste Powder (CWP) they can be advantageously used with geopolymer binder to increase the calcium content in geopolymer concrete/mortar [8]. Previous studies have investigated that fact that the presence of calcium compounds in the raw material can improve the mechanical properties of geopolymer products due to the interaction between the geopolymer gel, the calcium silicate hydrate (CSH), and calcium aluminium hydrate (CAH) gels [9]. Even 5% CWP can cause an early strength gain in slag–cement paste [10]. Thus, CWP becomes a promising supplementary cementitious material due to the presence of un-hydrated cement content. Ren et al. [11] reported a 13% increase in compressive strength when CWP is used with 20% slag replacement, and resistance to environmental impacts also improved.

From the above literature, it was found that CWP was used as a partial replacement for primary binder to provide calcium content in order to evaluate the strength and durability properties. In the current study, CWP was used as a primary binder in the geopolymer mortar to enhance the geopolymer reaction. However, it was observed that CWP contains 10–15% calcium content in the form of unhydrated cement, which may limit it to a lower strength. To enhance the mechanical strength of geopolymer mortar, the GGBS was used as a partial replacement for CWP to access the strength and durability properties of geopolymer mortar. The substitution of GGBS may enhance the mechanical properties of geopolymer mortar due to the appropriate content of calcium compounds [12]. The main objective of this study is to evaluate the strength and durability properties of geopolymer mortar using CWP as a primary binder with partial replacement of GGBS. Further, the utilization of CWP in geopolymer mortar in the form of waste helps to attain sustainability.

2. Experimental Program

2.1. Material

In this study, geopolymer mortar was prepared from CWP, which was obtained by powdering concrete waste concrete aggregates of sizes less than 4.75 mm. The concrete waste obtained from the institute laboratory was dried in an oven for at least 24 h to remove moisture if present and powdered to a desired maximum size of 75 µ using a ball mill [8]. The GGBS used as a replacement of CWP was obtained from Aastra Chemicals Chennai as shown in Figure 1 and used according to the code IS 16714-2018 [13]. The particle size distribution of CWP and GGBS are as shown in Figure 2, which was obtained from a laser particle sizer.



(**a**) (**b**) (**c**) (**d**)

Figure 1. (**a**) CWP, (**b**) GGBS, (**c**) sodium hydroxide pallets, (**d**) sodium silicate solution.

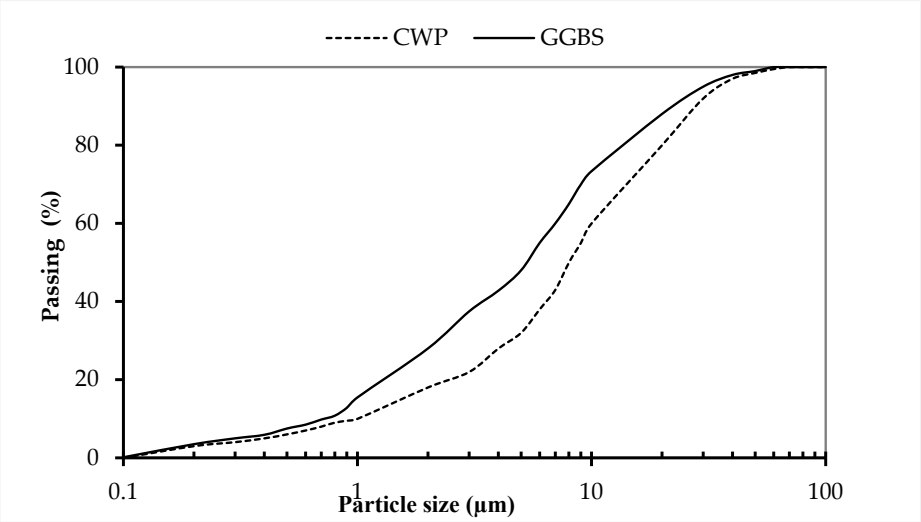


Figure 2. Particle size distribution curve CWP.

Natural Fine Aggregates used to make geopolymer mortar were obtained from a nearby source and in accordance with IS: 383 2016 guideline confirming zone III [14]. The specific gravity of NFAs was 2.53 and its water absorption is 1.5%. The physical and chemical properties of FA and CWP are presented in Table 1.

Table 1. Properties of CWP and GGBS.

Properties	CWP	GGBS
Fineness, cm^2/gm	3500	3900
Specific gravity	2.5	2.85
SiO_2	58%	33.1%
Al_2O_3	11%	18.2%
Fe_2O_3	2%	0.31%
CaO	15%	35.3%
MgO	-	7.6%
Loss of ignition	-	0.26

2.2. Alkaline Solution

For making a geopolymer concrete, commonly used alkaline activators consist of alkali hydroxide and alkali silicate. In this work, sodium hydroxide (SH) was used as alkali hydroxide and sodium silicate (SS) was used as alkali silicate, as shown in Figure 1a,b. The 98% pure sodium hydroxide solution of 12 M molarity was prepared by dissolving flakes in water about 24 h before casting. This was performed to bring the temperature of the sodium hydroxide solution to normal room temperature. Sodium silicate solution (SiO_2/Na_2O = 3.02) was utilised. The sodium hydroxide and sodium silicate solution in a proportion of 2:1 by weight were mixed for about 30–60 min before their addition to the raw mixture. The properties of the alkali activators are shown in Table 2.

Table 2. Properties of alkaline activators.

Properties	SH	SS
Molecular formula	NaOH	Na_2SiO_3
Colour	White	White
pH	13–14	13–14
Na_2O content (%)	-	9
SiO_2 content (%)	-	27.2
H_2O content (%)	-	63.8

2.3. Mix Proportion and Mixing of Geopolymer Mortar

In this study, the casting of three mixes was performed, i.e., C100, C90G10, and C80G20. Here, the mix C100 is the control mix which contains 100% CWP as the binder. In other mortar mixes, CWP was partially replaced by GGBS at 10% and 20%, denoted as C90G10 and C80G20, respectively, as shown in Table 3. The term alkali/binder ratio, i.e., the weight of alkali hydroxide and alkali silicate to the weight of binder, was kept constant for all mixes. Here an alkali/binder ratio of 0.45, SH of 12 M molarity, SS/SH ratio of 2, and water/solid ratio, i.e., the total amount of SS, SH, and extra water added to the solid content of SS, SH, and binder taken as 0.35 were used. The mixing and casting of geopolymer mortar involves a series of steps; firstly, the thorough dry mixture is prepared by a pan mixer and the measured quantity of binder with the saturated surface dry NFA is mixed in the pan for 3–5 min, followed by the addition of the alkaline solution and further mixing for 8–10 min. After that, the moulds were filled and sealed with poly wrap to avoid moisture loss. Ambient curing was performed at room temperature and for heat curing, another method, specimens were kept in an oven at 60 degrees Celsius for 24 h.

Table 3. Mix proportions (all values are in kg/m^3).

Mix Notations	Mix Description	CWP	GGBS	NFA	SS	SH
C100	100% CWP	500	-	1500	150	75
C90G10	90% CWP + 10% GGBS	450	57	1500	150	75
C80G20	80% CWP + 20% GGBS	400	114	1500	150	75

3. Test Methods

3.1. Compressive Strength

The compressive strength of geopolymer mortar was observed for both ambient and heat curing conditions at 7 and 28 days from the date of casting according to IS 4031-Part 6 [15]. As per IS 4031-Part 6, the cube size adopted for the compressive strength test of mortar was 70.6 mm. For each mix, 3 specimens of both heat-cured and ambient-cured samples were tested.

3.2. Water Absorption and Porosity

The durability properties of the geopolymer mortar were observed to be greater than conventional OPC mortar [16]. Here, the durability of geopolymer mortar was determined in terms of water absorption and porosity having an inversely proportional relationship. The test was conducted on 70.6 mm cubes at 28 days from the date of casting for both ambient- and heat-cured samples in accordance with ASTM C642–13 [17]. A minimum of three specimens of each mix were tested and the average value was recorded.

4. Results and Discussion

4.1. Compressive Strength

4.1.1. Effect of GGBS Replacement on Compressive Strength

The mechanical property of mortar is mainly determined by its compressive strength. The average compressive strength in MPa of the 3 ambient- and heat-cured specimens tested at 7 and 28 days are shown in Figure 3. The result shows that in comparison to C100 with the inclusion of GGBS up to 10% (C90G10), the compressive strength increases by 75% and 96.42% at 7 and 28 days, respectively, at ambient curing. This pattern of increase in compressive strength continues when a 20% (C80G20) replacement of GGBS is performed, and is 375% and 250% more at 7 and 28 days, respectively. The same pattern is followed for heat-curing conditions, as the compressive strength at 10% replacement is 275% and 201.22% more than the control mix C100. With another 10% replacement, i.e., when the mix C80G20 percentage increases, the strength is 385% and 283.53% at 7 and 28 days, respectively. The increase in compressive strength is due to the presence of a calcium

compound in GGBS, which accelerates the geopolymer reaction and provides an additional nucleation site in the form of CASH/NASH gel [18].

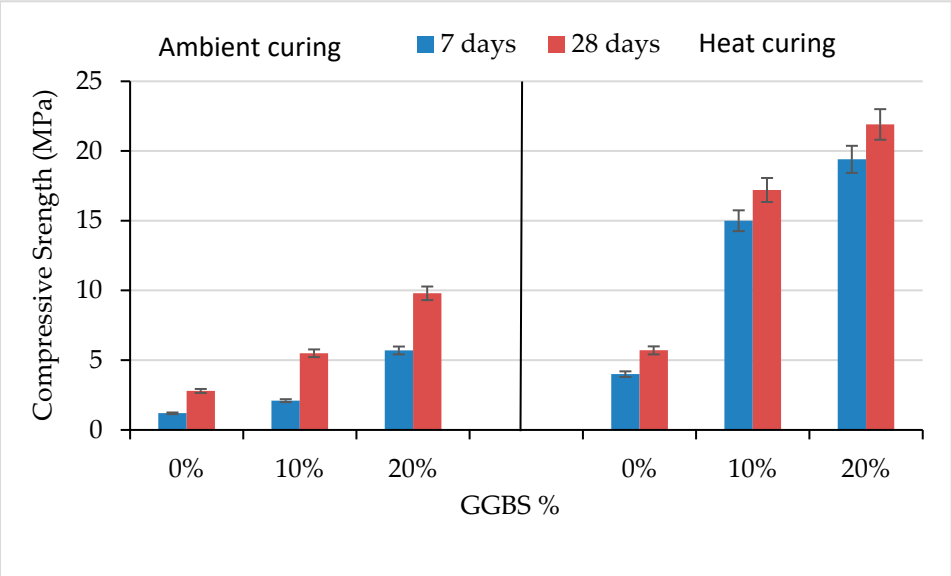


Figure 3. Effect of GGBS replacement on compressive strength of geopolymer mortar.

4.1.2. Effect of Curing on Compressive Strength

From Figure 3 it can be easily observed that, on average, heat curing a specimen delivers more compressive strength in comparison to ambient curing. This is because with an increase in temperature, the degree of geopolymerization also increases, thus giving a higher amount of reaction product [19]. Here, the heat curing delivers 233.33% and 103.92% more compressive strength in comparison to ambient curing at 7 and 28 days for control mix C100. It can be observed that heat curing causes more rapid strength gain in comparison to ambient curing. From the results, we can notice that in ambient curing the gains in compressive strength from 7 days to 28 days for mixes C100, C90G10, and C80G20 are 133.33%, 161.9%, and 71.9%, respectively, whereas in heat curing the gains in compressive strength from 7 days to 28 days for C100, C90G10, and C80G20 are 42.7%, 14.6%, and 12.8%, respectively. In short, the strength gain rate at an early age is higher in heat curing compared to ambient curing [20]. For the other mixes, C90G10 and C80G20, at 7 days heat curing results in 614.28% and 212.72 more strength, whereas at 28 days this % increase is somewhat less, i.e., 240.35% and 123.46%, respectively.

4.2. Water Absorption and Porosity

4.2.1. Effect on Water Absorption

The water absorption of geopolymer mortar was assessed at 28 days of curing and the results are represented in Figure 4. From the results, it can be seen that by increasing the GGBS content the water absorption decreases in both ambient curing and heat curing; however, heat curing results in comparatively less water absorption. For ambient curing, the C90G10 and C80G20 mixes, respectively, result in 19.6% and 30.3% less water absorption in comparison to control mix C100. Similarly, for heat curing the C90G10 and C80G20 mixes, respectively, result in 23.6% and 29.8% less water absorption in comparison to C100.

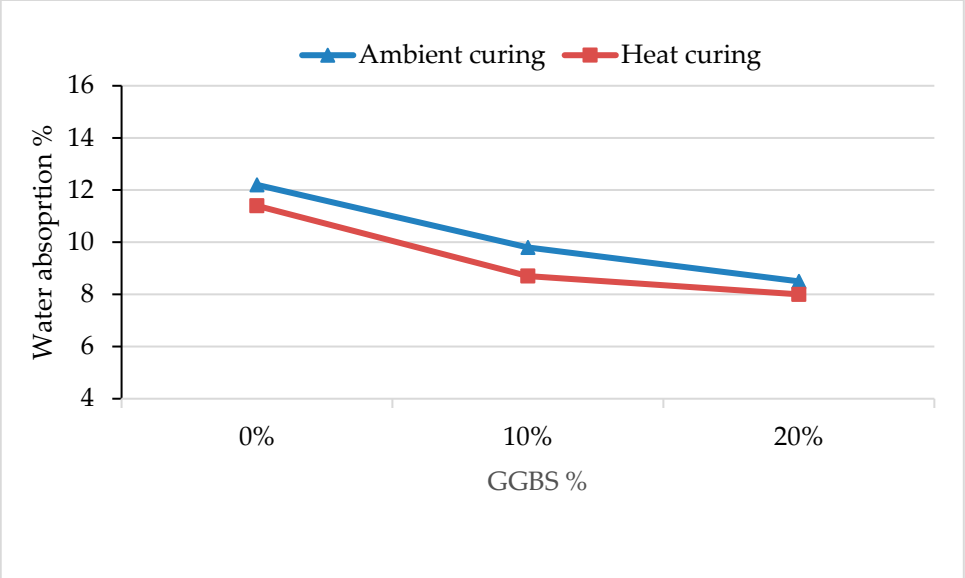


Figure 4. Water absorption results of geopolymer mortar mixes.

4.2.2. Effect on Porosity

Figure 5 shows the porosity results at 28 days for the different geopolymer mortar mixes when they are exposed to ambient and heat curing. Porosity values decrease with the addition of GGBS for both ambient and heat curing, but heat curing delivers slightly less porosity. Porosity is inversely proportional to durability. This implies that the inclusion of GGBS increases the durability property of geopolymer mortar. From Figure 5 it can be noted that for ambient curing the mixes C90G10 and C80G20, respectively, deliver 10.3% and 10.5% less porosity than concerning control mix C100. Similarly, heat curing the mixes C90G10 and C80G20, respectively, results in 12.1% and 12.8% less porosity concerning control mix C100. If compared with conventional mortar made with cement, porosity values go up to 20% porosity with the addition of 60% CWP [21]. Considering the high water absorption of CWP in comparison to the cement, the porosity value increases for geopolymer mortar.

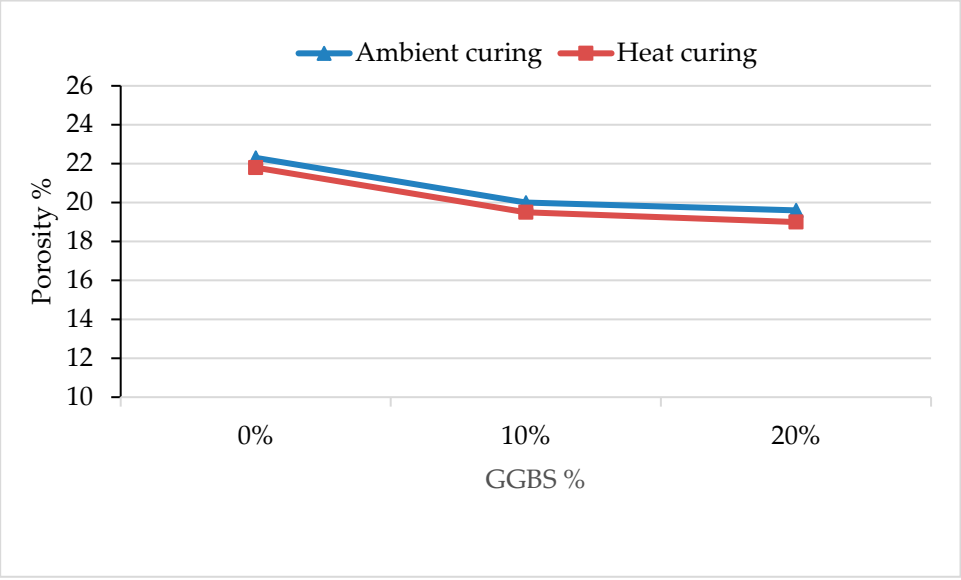


Figure 5. Porosity results of geopolymer mortar mixes.

5. Conclusions

- The CWP alone is capable of providing a satisfactory compressive strength in geopolymer mortar; however, along with GGBS its compressive strength is increased in ambient conditions and becomes enhanced in heat-curing conditions. By including GGBS, compressive strength can be gained at an early stage of curing.
- The size of the GGBS particle is comparatively smaller than the CWP grain and works advantageously in filling the void when substituted with CWP, resulting in a decrease in porosity and water absorption. In this study, both porosity and water absorption decreased by up to 20% of the replacement level.
- Heat-cured geopolymer mortar is better than ambient-cured mortar as it results in more compressive strength for the same proportion and is even more durable when checked in terms of water absorption and porosity. Heat curing delivers somewhat less water absorption and slightly less porosity, which makes it more durable to the atmosphere.

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