Synthesis of Concrete Waste Powder in Fly Ash Based Geopolymer Mortar: Assessing Strength, Durability Properties and Environmental Impact

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Abstract: The sustainable reuse of concrete waste in the form of aggregates and finely milled Concrete Water Powder (CWP) in Geopolymer Mortar (GPM) is an emerging area of research. This study examines the influence of CWP and Silica Fume (SF) on the strength, durability, and sustainability of Fly Ash (FA)-based GPM. This way, the potential for coupled valorisation fly ash and demolition wastes was assessed, thus promoting circularity in construction sector. GPM was substituted with CWP at 0%, 10%, 20%, 30%, and 40%, while SF substitution was maintained at 10% in all mixes except the control. Workability decreased with increasing CWP content, whereas compressive strength peaked at 20% CWP substitution. This mix also demonstrated superior durability, attributed to a densified microstructure and enhanced calcium hydroxide formation, as evidenced by SEM analysis. Environmental and economic assessments indicated that the 20% CWP–10% SF mix achieved the highest Sustainability Index (SI) and Economic Index (EI), supporting its viability. These findings highlight the potential of CWP as a precursor in sustainable GPM production.

Keywords: Geopolymer mortar, Concrete waste powder, Circular economy, Waste valorisation, Low-Carbon binder.

1. INTRODUCTION

The rising developmental and construction activities to accommodate growing world population, has put an enormous burden on the cement and concrete industry worldwide. Ordinary Portland Cement (OPC) is the only universally accepted binding material for concrete and mortar to this day. This makes OPC the second most often used substance on earth after water. However, the manufacturing of OPC involves burning of a huge amount of fuel for calcination of limestone and other minerals, thus contributing to enormous CO_2 emissions. Given the energy intensive and carbon emissive processes involved in the manufacture of OPC, tremendous rise in carbon dioxide (CO_2) emissions have been observed, in the last decade. This is a great hurdle in controlling global warming and attaining sustainability [1, 2]. Further, it has also led to heavy consumption of natural minerals like limestone and alumina rich clays [3]. Consequently, the cement industry faces growing pressure to transition toward low-carbon and resource-efficient alternatives in line with the principles of a circular economy, which advocates minimizing waste generation and maximizing the reuse of industrial by-products. The introduction of geopolymers by Joseph Davidovits in 1980s, as a sustainable alternative to the OPC was a significant advancement in this direction [4, 5]. Geopolymer is a binding material that can perfectly substitute the OPC while retaining the physical and durability properties of concrete and mortar [6, 7]. Further, introducing geopolymers as binding material instead of OPC, in concrete and mortar, can help curtail CO_2 emissions by 80-90%. Moreover, it can help to control the excessive exploitation of natural limestone and clay resources required in OPC production, by using alternative aluminosilicate rich industrial by-products/wastes instead [8]. This dual benefit of waste valorisation and emission reduction makes geopolymer technology a pivotal approach in realizing a circular and sustainable construction sector. Some common industrial by-products that can be used in GPC and GPM include Fly ash (FA), Ground Granulated Blast Furnace Slag (GGBS), Silica Fume (SF), metakaolin, rice husk ash etc [9, 10]. These aluminosilicate powders are known as precursors. The precursor undergoes a chain of reactions under influence of an alkaline activator to form a condensed polymer matrix referred to as geopolymer. A blend of Sodium Silicate (Na_2SiO_3) and Sodium hydroxide (NaOH) is commonly used as the activator solution [11]. However, potassium silicate-potassium hydroxide blend or sodium carbonate etc can also be used as activators in GPC or GPM.

Apart from the high carbon footprint associated with OPC, the disposal of construction and demolition activities generally known as Construction and Demolition Waste (CDW) in landfills, and the overexploitation of natural aggregates stand as other significant challenges associated with construction industry [12]. A study by Central Pollution Control Board of India (CPCB) revealed that India produces close to 14.5 million tons of CDW per year, which is an enormous amount of waste [13]. Many researchers around the world are exploring new ways to utilize this waste in a productive way that will relieve the pressure

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on limited landfill space [9]. Therefore, the recycling of CDW as an ingredient in concrete and mortar, is seen as essential practice in construction industry [12, 14, 15]. Initially, the most recognized way of recycling CDW was by converting them into Recycled Coarse Aggregates (RCA) and using as a replacement for Natural Coarse Aggregate (NCA) in concrete and mortar. The use of concrete with RCA was limited to only base courses and non-structural elements [16]. However, the use of RCA has some determinantal effects on the quality of concrete *i.e.* water absorption and porosity get increased leading to a decrease in resistance to environmental factors and durability [17]. The research has shown that the use of RCA in concrete is possible with up to a 25% decrease in strength [18-21]. The replacement proportion of RCA to NCA is generally limited to up to 30% for satisfactory results [22]. Further, the idea of using Recycled Fine Aggregate (RFA) as a replacement for Natural Fine Aggregate (NFA) also came up in continuation to the recycling of CDW. RFA has a substantial amount of residual mortar and cement paste attached to it that contains some un-hydrated cement particles [23]. The unhydrated cement particles contribute to the formation of extra nucleation sites for the development of hydration products [24]. Some researchers have also documented that if RFA is further ground to a fine powder (known as Concrete Waste Powder (CWP)), it can be advantageously synthesized in GPM and GPC [25]. The CWP is rich in calcium content due to presence of unhydrated cement from CDW. When CWP is used as partial replacement with precursor, it enhances the strength and durability properties of GPC and GPM. This owes to the simultaneous formation of the calcium silicate hydrate (CSH) and calcium aluminium silicate hydrate (CASH) gels in addition to the geopolymer gel [26, 27]. Thomas *et al*. (2009) [23] reported that substituting CWP at a 20% replacement level accelerates cement hydration and improves cement paste's compressive strength. Even 5% CWP can cause the early strength gain of slag-cement paste [28]. Thus, the CWP become promising supplementary cementitious materials due to the presence of un-hydrated cement content. Ren *et al*. [29] reported a 13% increase in compressive strength when CWP was used at 20% replacement of the slag and resistance to environmental impacts also improved. Khater, 2013 [30] shows the inclusion of SF up to 7% has improved the compressive strength of geopolymer. Memon *et al*., 2013 [31] results depict that the inclusion of SF reduces the workability and side-by-side increases the compressive strength by 6.9%, tensile strength by 12.8% and flexural strength by 11.5% for 10% of replacement to the main binder.

The literature reviewed above reveals that CWP and SF can act as synergistic supplementary materials in geopolymer systems—CWP providing reactive calcium to promote additional C–S–H/C–A–S–H formation, and SF supplying fine silica to enhance geopolymerization and matrix densification. However, very limited research has examined their combined influence in fly ash-based geopolymer mortars (GPM).

The literature discussed above reveals that CWP can be used as a source of calcium in the geopolymer process to enhance the overall properties of GPM. Silica is another constituent which significantly influences the geopolymerisation process hence, SF can act as an excellent source of fine silica when used as another partial replacement FA in the GPM. Moreover, SF is a very fine silicious material which leads to densification of the microstructure and enhanced strength and durability properties. Since very limited literature is available on the simultaneous substitution of CWP and SF in FA-based GPM, in this study, combinations of FA along with CWP and SF have been used to assess the strength and durability properties of the GPM. Six FA-GPM mixes were prepared to consist of one control mix and other mixes with 0%, 10%, 20%, 30% and 40% replacement of FA with CWP along with consistent 10% replacement of FA with SF. The mixes were evaluated for workability, setting time, compressive strength, and durability characteristics such as water absorption, porosity, and acid resistance. Furthermore, sustainability and economic indices were assessed to holistically evaluate the environmental and financial viability of these mixtures. The environmental performance of GPM was evaluated using Global Warming Potential (GWP), Embodied Energy (EE), and the Sustainability Index (SI). The GWP and EE values of individual raw materials, sourced from credible literature and databases (Table **4**), were summed to determine the total GWP and EE of each mix. The SI was then computed for overall environmental assessment using *Equation (1)* [32-34]. Similarly, the economic assessment of GPM mixes was conducted based on material cost and the Economic Index (EI). The unit cost of each raw material (Table **4**) was used to calculate the total cost per cubic meter of mix, while the EI was determined using *Equation (2)* [34, 35]. Both SI and EI follow the *“smaller-is-better”* criterion, implying that lower values indicate more sustainable and cost-effective mixes. The 28-day compressive strength (CS) of ambient-cured samples was used for computing SI and EI.

This study thus contributes to the advancement of circular and low-carbon geopolymer materials through the valorisation of two major industrial waste streams—fly ash and construction/demolition wastes—thereby aligning material innovation with global sustainability goals.

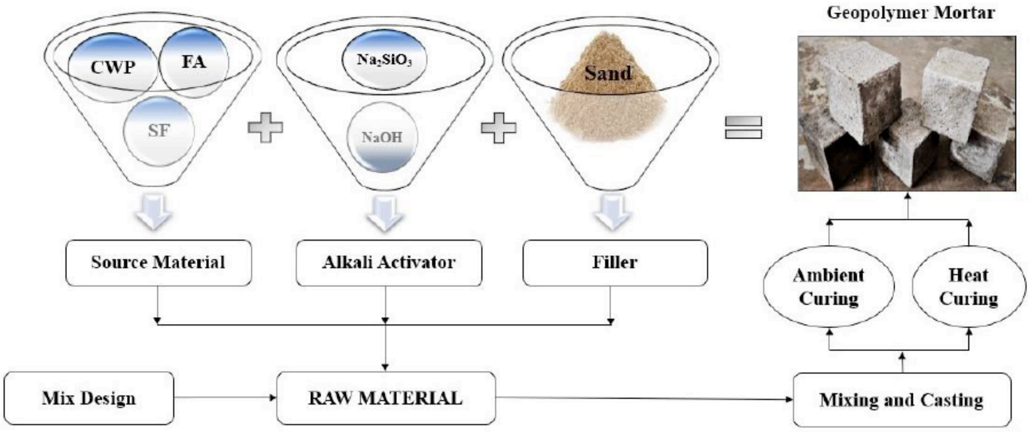
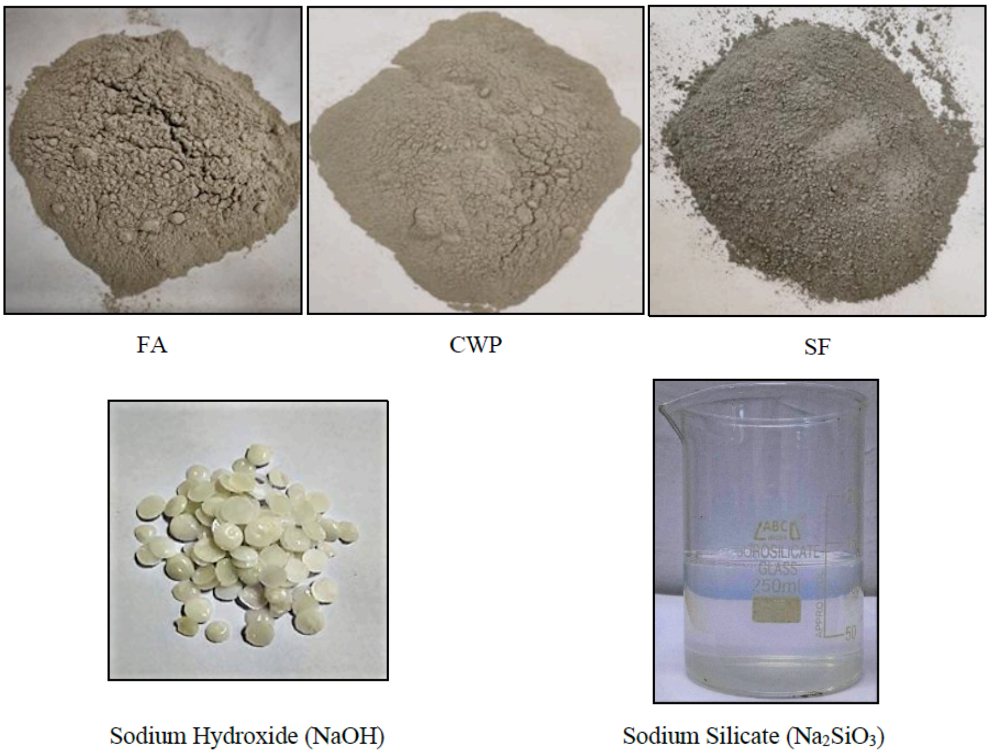


Figure 1: Flow chart for production of geopolymer mortar (GPM).

2. MATERIALS

2.1. Precursors

The material composition of GPM was decided after thoroughly studying the literature and chemical compositions of precursors. The precursor source material is supposed to be rich in alumina and silicate content. A pictorial representation of precursor, alkali activator and filler material used for GPM, is presented in Figure **1**. The precursor undergoes activation under the influence of alkali activator and acts as a binding material. In this study, the precursors used are FA (Class F), CWP and SF. The FA was procured from the Rajpura Thermal Power Plant, situated in district Patiala, Punjab, India. The specifications of FA conformed to the Indian code IS 3812-2003 [36] as a pozzolanic material. The CWP was created using Fine Recycled Aggregates (FRA) particles collected at the concrete technology laboratory of the author's institute. The moisture content in FRA particles was removed completely by oven drying to constant weight for at least 24 hours at 105° C. Then the oven-dried FRA particles were powdered using a ball mill machine to a maximum size of 75 microns [25]. The SF confirming to ASTM, C1240- 2020 [37] was procured from M/s Elkem Materials Inc., India. The photographs of FA, CWP and SF powders are presented in Figure **1**. Further, the particle size distribution of FA, CWP and SF was determined using a laser particle sizer. The particle size distribution of the FA, CWP and SF are presented in Figure **2**. The physical and chemical properties of FA, CWP and SF are presented in Table **1**.


FA CWP SF

Sodium Hydroxide (NaOH) Sodium Silicate (Na_2SiO_3)

Figure 2: Precusors (FA, CWP and SF), Sodium Hydroxide pellets (SH) and Sodium Silicate solution (SS).

The Natural Fine Aggregate (NFA) used in preparing GPM mixes, were obtained from the river quarry situated at river Raavi, in district Pathankot, Punjab (India). The NFA conforms to Zone III class of coarse sand as specified by the Indian code IS:383-2016 [38]. The specific gravity of the NFA was 2.53 and water absorption of the fine aggregate was observed to be 1.5%.

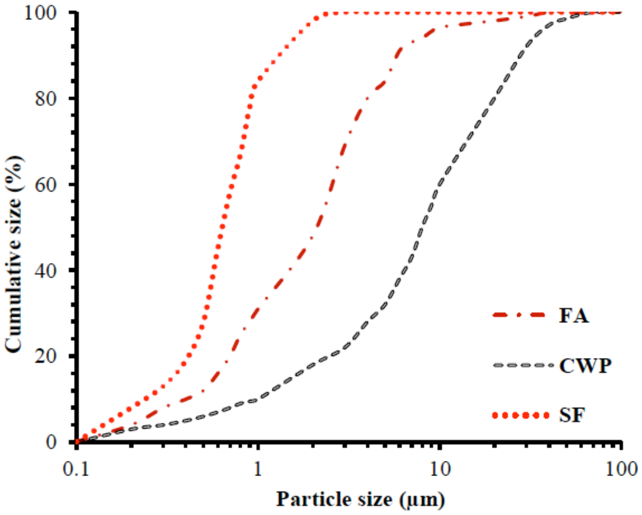


Figure 3: Particle size distribution of FA, CWP and SF.

2.2. Alkali Activators

The alkaline activators used in the GPM mixes *i.e.* SH and SS have been shown in Figure **2**. Both SS and SH were obtained from Garg Chemical Industries situated in district Jalandhar, Punjab (India). The SH flakes of 98% purity, were dissolved in distilled water to make a 12 M solution (36% solids and 64% water), 24 hours prior to the mixing and casting of GPM. This was done so that the SH solution cools down to room temperature and the exothermic action of SH flakes dissolution in water is completed before the mixing. The SS solution was composed of a SiO_2 to Na_2O ratio of 3.02. The solution contained 35% solids and remaining 65% water by weight.

To prepare the activator solution for GPM, SS and SH solutions were mixed in a ratio of 2:1 by weight, 30-60 minutes prior to mixing with other raw materials. The appropriate ratios for the mix design were considered with reference to the relevant the literature [25]. The physical and chemical characteristics of the SS and SH are presented in Table **2**.

Table 2: Physical and Chemical Properties of SS and SH Solutions

Properties	SS	SH
Molecular formula	Na_2SiO_3	NaOH
Colour	White translucent	Transparent
pH	12-14	13-14
Density (g/cm^3)	1.53	1.13
Na_2O (%)	9.0	--
SiO_2 (%)	27.2	--
H_2O (%)	65	64

2.3. Mix Proportion and Casting of GPM

In this study, a total number of six mixes were prepared and corresponding notations of those mix proportions are listed in Table **3**. In all the mixes, F100C0 is considered a control mix with no CWP and SF. The content of CWP was increased by 10% in subsequent mixes, replacing the equal amount of FA by weight. The proportion of SF was kept at 10% in all these subsequent mixes. The motive of doing so was to observe if 10% SF substitution can compensate for any possible deterioration of strength and durability properties of GPM with increasing content of CWP. Other parameters like binder content which denotes the weight of binder per unit volume were kept at 500 Kg/m^3, water- water-solid ratio which denotes the weight of water to weight of total solid kept at 0.35, the weight of alkali activator solution to weight of binder content *i.e.* alkali/binder ratio kept at 0.45, SS/SH ratio is 2 and 12 M molarity of NaOH solution considered as

Table 1: Physical and Chemical Properties of Source Material

Properties	FA	CWP	SF
Specific Gravity	2.1	2.5	2.2
Fineness (kg/cm^3)	4125	3100	15000-30000
SiO_2	56.5 %	58.0 %	85.0 %
Al_2O_3	17.7 %	11.0 %	1.46 %
Fe_2O_3	11.0 %	2.0 %	1.12 %
CaO	3.2 %	15.0 %	0.80 %
MgO	2.3 %	-	0.70 %
Loss of Ignition	1.2 %	-	<6.0 %

Table 3: Mix Compositions of GPM Mixes (kg/m^3)

Mix ID	Precursor Composition	FA	CWP	SF	NFA	SS	SH
F100C0	100% FA + 0% CWP + 0% SF	500	0	0	1500	150	75
F90C0S	90% FA + 0% CWP + 10% SF	450	0	52.8	1500	150	75
F80C10S	80% FA + 10% CWP + 10% SF	400	59.52	52.8	1500	150	75
F70C20S	70% FA + 20% CWP + 10% SF	350	119.04	52.8	1500	150	75
F60C30S	60% FA + 30% CWP + 10% SF	300	178.57	52.8	1500	150	75
F50C40S	50% FA + 40% CWP + 10% SF	250	238.09	52.8	1500	150	75

constant. Natural fine aggregates are taken as three times the binder content which is also kept constant for all mixes. The primary purpose of this research was to analyse the effects of adding CWP at successive rates along with constant SF content on the physical strength and durability of GPM. GPM casting requires special care and must be scheduled at least one day in advance. The raw materials, which include FA, CWP, SF, and sand, are first weighed and thoroughly dry mixed in a pan for around two to three minutes before casting. The already-prepared alkali solution was added to the mixture in the following step, and it was then stirred for 5-8 minutes to form a uniform mixture. The resultant mixture is then placed into the moulds, tamped and vibrated to compact it. The filled-up moulds are covered with a plastic sheet that will prevent water content from evaporation. Ambient curing was carried out at room temperature, and heated curing involves keeping the moulds in an electric oven at a continuous 60 °C temperature for 24 hours.

3. EXPERIMENTAL PROGRAMME

3.1. Workability

The workability of GPM was evaluated in terms of flow table values. The flow table test was conducted on a freshly prepared GPM mix. The test equipment is made up of a steel plate and a steel cone measuring 100 mm base in diameter, 70 mm top in diameter, and 50 mm tall confirming to IS: 5512-1983 [39]. The initial and final diameters of the mortar sample were recorded for the flow calculation in accordance with IS 4031-Part 7 [40].

3.2. Setting Time

The initial and final setting time of GPM was measured using the Vicat apparatus by preparing a paste of source materials confirming IS 4031- Part 5 and the specification of the Vicat apparatus in accordance with IS 5513, 1996 Indian codes.

3.3. Compressive Strength

The compressive strength tests were performed on both ambient and heat-cured GPM cubes on completion of 7, 28, and 56 days of curing, according to IS-4031-Part-6[41]. The test was conducted on a 70.6 mm size cube at a loading rate of 350 kg/cm^2 per minute as per ASTM C109/C109M-02, 2020 [42]. For each mix, a total number of three specimens of both ambient and heat cured for each period of curing were tested under a compressive testing machine.

3.4. Water Absorption and Porosity

The durability properties of GPM were determined in terms of water absorption and porosity. Water absorption and porosity tests were conducted on both ambient and heat-cured GPM on completion of 28 and 56 days of curing as per ASTM C642-13, 2015 [43]. The specimen considered for the test was a 70.6 mm cube and a minimum of 3 samples of each mix were tested.

3.5. Acid Attack

The acid attack test was performed to determine the resistance of GPM exposed to sulphate solution according to ASTM C267 [44]. Geopolymer mortar specimens were exposed to 5% concentrated sulphuric acid for 28 and 56 days. The test was conducted for both ambient and heat-cured specimens of size 70.6mm cube at 28 and 56 days of curing. The weight change was measured on completion of 28 and 56 days of exposure to acid.

3.6. Environmental and Economic Assessment

The environmental assessment of GPM can be done on the basis of its GWP, EE and SI. The GWP and EE values of the raw materials were obtained from authentic literature and databases as mentioned in Table **4**. The GWP of each mix was calculated as the sum of GWP due to every raw material. Likewise, the EE of each mix was also calculated as the sum of EE of every raw material. Further, the SI of every mix was calculated for environmental assessment, as per equation 1 [34].

On the similar lines, the economic assessment of GPM mixes was done on the basis of cost and EI. The total cost of every raw material incurred per kg has been mentioned in Table **4**. The total cost of a mix per m^3 was calculated as the sum of cost of all raw materials. The EI of every mix was calculated as per equation 2 [34]. Both SI and EI follow smaller the better criteria *i.e*. lower value means better mix and vice versa. Ambient cured 28 day CS were used for computing SI and EI.

$$\mathrm{SI} = \frac{\mathrm{GWP} + (0.050 \times \mathrm{EE})}{28\ \mathrm{day\ CS}} \tag{1}$$

$$\mathrm{EI} = \frac{\mathrm{Total\ cost\ of\ 1\ m^3\ GPM}}{28\ \mathrm{day\ CS}} \tag{2}$$

4. RESULTS AND DISCUSSION

The physical strength and durability characteristics of GPM samples that were cured at ambient conditions and an increased temperature of 60º C, or heated curing, have been examined in the present investigation about the influence of CWP and SF. The properties like setting time and workability of GPM in the fresh state were determined using suitable methods. Then GPM was tested for compressive strength and durability parameters that include water absorption, porosity and acid attack at a hardened state. The results of all the experiments conducted on various GPM mixes, environmental and economic assessment are discussed in the following subsections.

4.1. Workability

A flow table test was conducted on the freshly mixed GPM for accessing workability on each mix and their values are well described in Figure **4**. The results of 10% SF replacement to FA in the mix (F90C0S) revealed a marginal decrease in flow values, *i.e*. 3.03%, when compared to the control mix (F100C0), since SF has an extremely fine particle, resulting in a greater surface area and, as a result, more water requirement, leads to lower workability of fresh GPM. When 10% CWP and 10% SF were added to the mix (F80C10S), the flow values were reduced by 12.87% compared to the control mix (F100C0) and 10.15% compared to the mix (F90C0S). For other mixes *i.e*. (F70C20S), (F60C30S) and (F50C40S) flow values continued to decrease by 16.66%, 22.72% and 25.75% respectively as compared to the control mix (F100C0). With the increase in CWP by 10% content in each successive mix, the decrease in flow value rises to 16.66%, 22.72% and 25.75%. This can be explained by two reasons (i) The greater calcium content introduced by the CWP which accelerates the setting of the mix, and (ii) the Rough and angular surface texture of the CWP particles causing hindrance to the flow. Broadly, an increase in CWP content causes a near-linear decline in the flow values representing the workability of mortar in a fresh state.

However, on the positive side, workability of these mixes can be improved by using adequate superplasticizers and retarders as admixtures when CWP is included. Polycarboxylate ether and Sulphonated melamine formaldehyde based superplasticizers adhere well on the rough textured surface of calcium rich minerals [53,54]. Consequently, the mutual repulsions between adhered layer of superplasticizer on CWP particles shall maintain suspension and enhance flowability. Likewise, the reaction of CWP can be slowed by using glucose, citric acid or tartaric acid based admixtures to a reasonable extent, thereby enhancing the flow retention over a prolonged time period. However, use of superplasticizers and retarders shall be optimised to avoid adverse repercussions on other mix properties and may be considered in scope of future developments in this study.

Table 4: GWP, EE and Cost of the Raw Materials used in GPM Mixes

Raw material	GWP (kg CO_2 eq./kg)	EE (MJ/kg)	Cost (INR/kg)
FA	0.027 [45,46]	0.1 [46,47]	0.9
CWP	0.032 [34]	0.62 [34]	1
SF	0.024 [48,49]	0.05 [50]	25
NFA	0.015 [46,48,49]	0.08 [47,51,52]	1
SS solution	0.445 [46]	5.37 [46,52]	20
SH solids	0.625 [46]	10.8 [46]	45
Water	0.0003 [49,52]	0.01 [34,47]	1

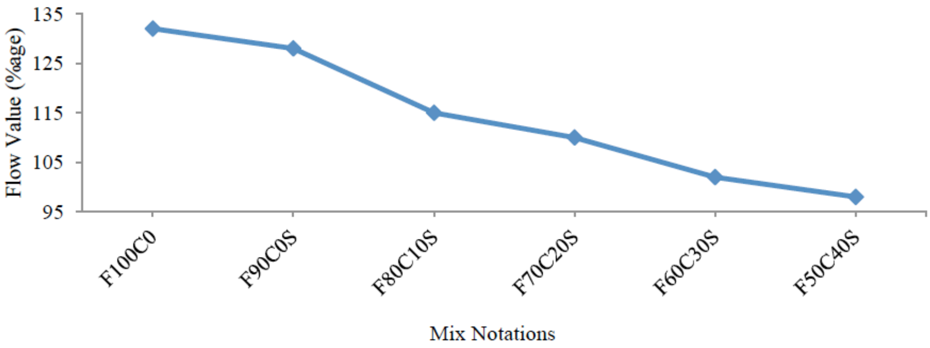


Figure 4: Effect of CWP and SF on flow value of geopolymer mortar mixes.

4.2. Setting Time

Initial and final setting time test was conducted on the geopolymer paste according to the IS 4031- Part V, 1988 [55] and its values are well shown in Figure **5**. The results demonstrate that the initial and final setting for the control mix *i.e*. (F100C0) is the highest of the rest of the mixes. The literature confirms that the setting time of FA-based geopolymer is high and can be reduced by incorporating other suitable materials [56], [57]. The results of 10% SF (F90C0S) inclusion show a maximum decrease in initial and final setting time which is 44.44% and 69.56% respectively concerning control mix (F100C0). Further with the inclusion of 10% CWP *i.e*. (F80C10S) initial and final setting time gets decreased by 20% and 9.5% concerning mix (F90C0S) and 55.56% and 72.4% concerning control mix (F100C0). When the CWP content is increased by 10% in the mix (F70C20S), the initial setting and final setting times are reduced by 61.11% and 76.44%, respectively, in comparison to the control mix (F100C0). This decreasing trend continues further with an increase in CWP content with marginal differences in setting times. For other mixes *i.e*. (F60C30S) and (F50C40S) decrease in initial setting time is 66% and 73.33% and in the final setting, time is 78.26% and 79.71% respectively as compared to control mix. From the results, it can be seen that SF and CWP play a good role in decreasing the setting time of geopolymer paste. This is explainable by the introduction of calcium content in the mix by the addition of CWP and SF which acts as an accelerator to the setting of the unhydrated cement in the CWP. This setting of unhydrated cement adds to the solidification occurring due to geopolymerisation.

4.3. Compressive Strength (Effect of SF and CWP on Compressive Strength)

A compressive strength test was conducted on geopolymer mortar made from FA, CWP and SF according to *IS-4031-PART-6-1988* [41] and their results are depicted in Figure **6**. It was found that the compressive strength for the control mix (F100C0) which included 100% FA for ambient and heat curing at 7 days was 4 MPa and 10 MPa which subsequently increased to 10 MPa and 13 MPa at 28 days and 56 days respectively for ambient curing and 14 MPa and 16.5 MPa at 28 days and 56 days respectively for heat curing. The compressive strength of the mix (F90C0S) kept at ambient curing, marginally decreased by 12.23%, 5.0% and 3.0% concerning the control mix, at the ages of 7, 28 and 56 days respectively. However, at heat curing, its compressive strength decreased by 9.0%, 4.28% and 2.40% concerning the control mix, at the age of 7, 28 and 56 days respectively. This decrease in compressive strength is mainly due to

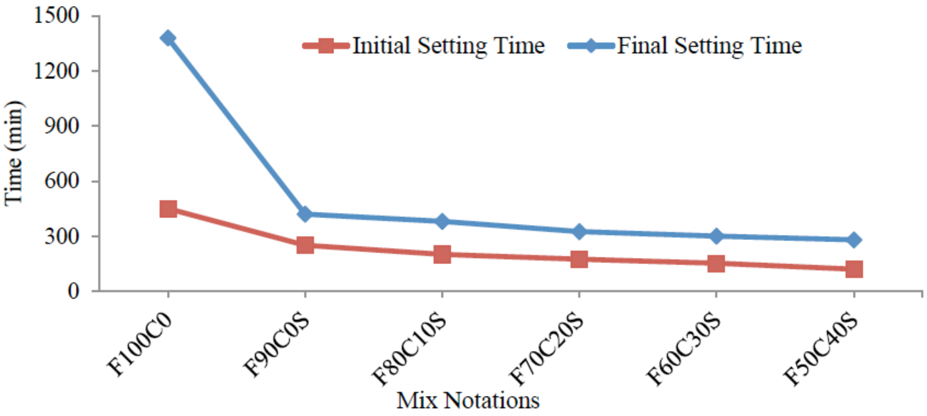


Figure 5: Effect of CWP and SF on setting time of geopolymer mortar mixes.

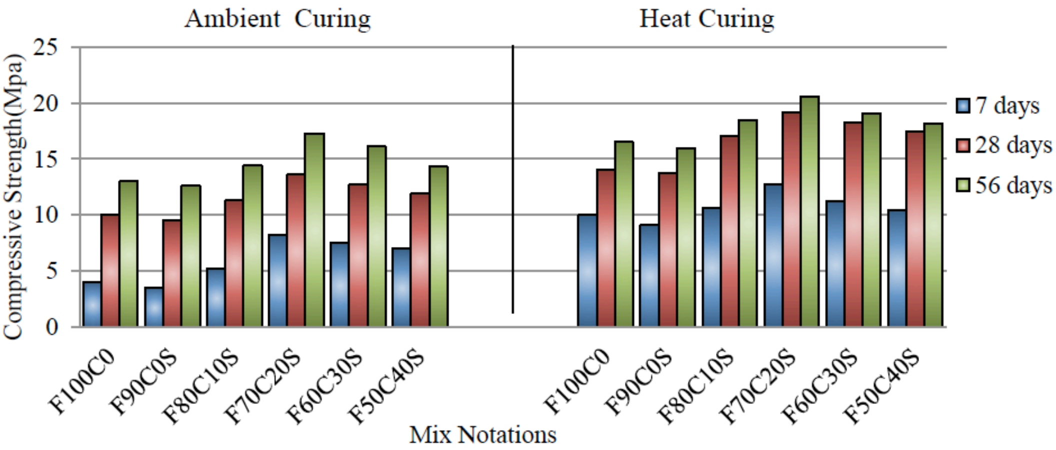


Figure 6: Effect of CWP and SF on compressive strength of geopolymer mortar mixes.

increased silica concentration from SF which results in a rod-like two-dimensional cross-linked poly-sialate that has weaker strength and hardening capabilities when compared to a three-dimensional network. This structure is related to an increased Si/Al ratio [58]. On further inclusion of CWP at 10% (F80C10S) compressive strength for ambient cured GPM increases by 30.0%, 13.0% and 10.7% at 7, 28 and 56 days respectively as compared to the control mix (F100C0). However, in the case of heat curing, the compressive strength increases by 6.50%, 22.14% and 12.12% at 7, 28 and 56 days respectively. This increase is the result of additional calcium content from CWP which involves in reaction with silica to give a sialate bridge (Si-O-Al-O-) formation and high active SiO2 from SF form a siloxo bridge (-Si-O-Si-O-) in geopolymerisation process. Mortar's ingredients are securely held in place by this chain-like structure, which results in a more compact and denser matrix [35, 50]. The trend of increasing compressive strength is followed up to mix (F70C20S) to 8.20Mpa, 13.60Mpa and 17.30Mpa and 12.70Mpa, 19.20Mpa and 20.60Mpa at 7, 28 and 56 days for ambient and heat curing respectively which is the maximum of all mixes in this study. The mix (F70C20S) with 70 % FA, 20 % CWP, and 10% SF achieves the optimal compressive strength of geopolymer mortar with FA, CWP, and SF. Up to 20% of CWP replacement the calcium in it was utilized completely but on further increasing the CWP proportion keeping the SF content at 10% constant compressive strength decreases both in ambient and heat curing due to excess calcium that remained unreacted. On 30% CWP replacement with 10% SF compressive strength decreased by 8.5%, 6.6% and 6.9% of ambient curing and 11%, 4.6% and 4.6% of heat curing at 7, 28 and 56 days as compared to mix (F70C20S). The decrement in trend is followed up by a 40% replacement of CWP.

4.4. Compressive Strength (Effect of Curing Condition)

The compressive strength test that was carried out on a 70.6 mm cube of GPM subjected to both ambient curing *i.e*. at room temperature and heated curing *i.e*. at 60° C temperature at a curing interval of 7, 28 and 56 days shown in Figure **7**. It was noted from Figure **4** that heat curing gives higher compressive strength than

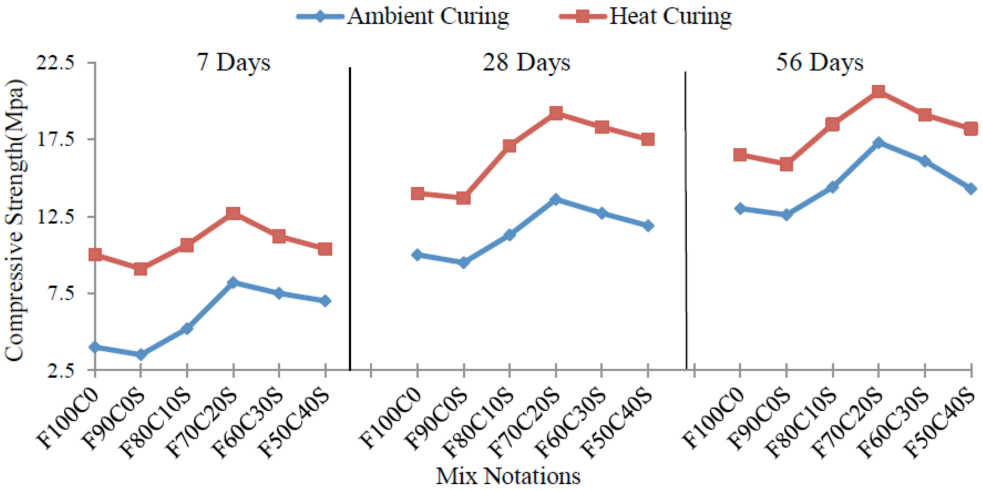


Figure 7: Effect of curing condition on compressive strength of geopolymer mortar mixes.

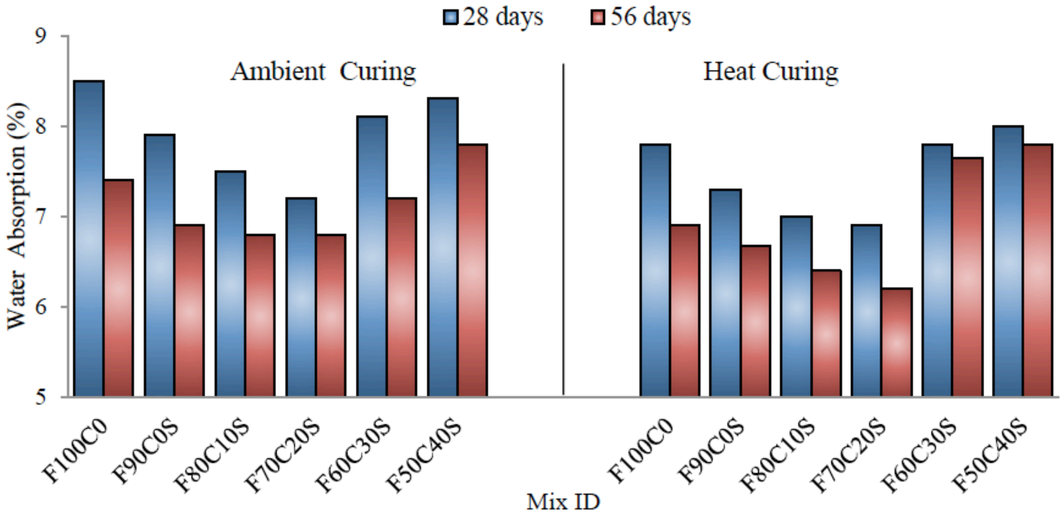


Figure 8: Effect of CWP and SF on water absorption of GPM.

ambient curing at all ages of curing *i.e*. 7, 28 and 56 days. In addition to this, it has been shown that the curing temperature has a considerable impact on the compressive strength of GPM because in heat curing a proper activation of aluminosilicate compound takes place giving a complete reaction which is not possible in case of ambient curing due to low temperature and weak activation [61]. From Figure **4** the increasing and decreasing trend of compressive strength is almost the same in both ambient and heat curing irrespective of the variation magnitude of compressive strength. In heat curing, the rate of gain of compressive strength at early age is high as compared to late age [62].

4.5. Water Absorption

According to the specifications (ASTM C642-13, 2015), a water absorption test was carried out after 28 and 56 days of curing under both ambient and heat curing conditions. Results of all mixes tested at 28 and 56 days are shown in Figure **8**. As the geopolymer reaction advances with increasing curing age, water absorption diminishes and a dense mortar is produced. Figure **8** shows that both ambient curing and heat curing reduce the amount of water absorbed by 7.05 per cent and 6.4 per cent at 28 days, respectively, and by 6.7 per cent and 3.3 per cent at 56 days with the 10% SF replacement (F90C0S). In comparison to the control mix (F100C0), the addition of CWP along with a fixed amount of 10% SF reduces water absorption by 11.70% and 10.25% at 28 days and 8.10% and 7.24% at 56 days for ambient and heat curing. This decrease continues up to 20% CWP replacement *i.e*. (F70C20S) has the lowest water absorption of 7.2% and 6.9% at 28 days and 6.8% and 6.2% at 56 days of ambient and heat curing in comparison to all other mixes. On comparing curing conditions, the heat-cured mix (F70C20S) has the lowest water absorption of all mixes. With further increasing the CWP content by more than 20% water absorption starts increasing. Both ambient and heat curing have the same pattern of decreasing

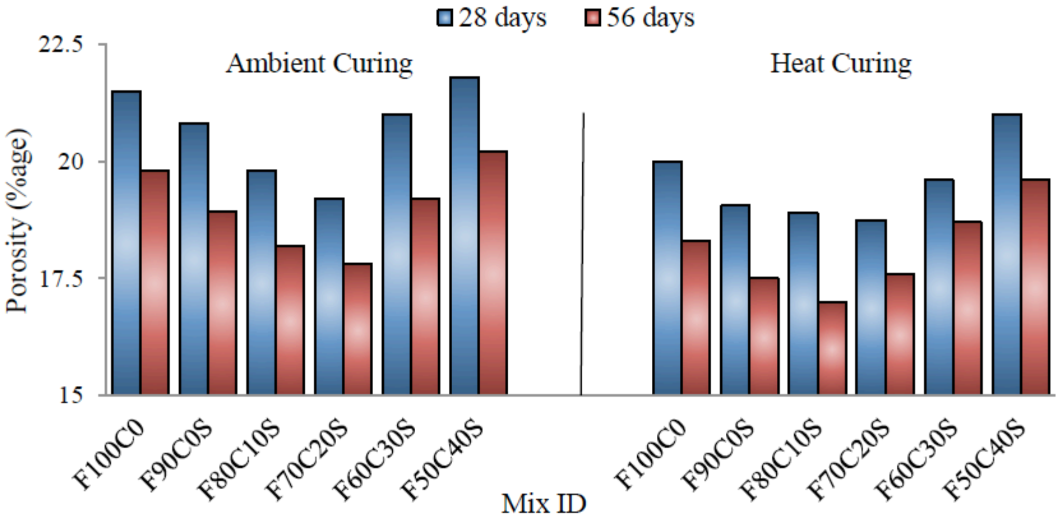


Figure 9: Effect of CWP and SF on porosity of geopolymer mortar mixes.

and increasing but heat curing gives lower values for each mix.

In GPM, the heat curing is extremely advantageous as for heat-cured mortar specimens the water absorption comes out to be less than the ambient curing mortar which is because at high temperatures the complete reaction takes place in geopolymer mortar which is not possible at lower temperature.

4.6. Porosity

According to the standards (ASTM C642-13, 2015), a permeability test was carried out after 28 and 56 days of curing under both ambient and heat curing. The results of the mixes are shown in Figure **9**. From Figure **9** it can be seen that the porosity of the control mix (F100C0) decreases by 3.16% and 4.70% at 28 days and 4.39% and 4.37% at 56 days for ambient curing and heat curing respectively on the inclusion of 10% SF (F90C0S). This is due to the filler effect of SF as it has a smaller size as compared to FA and effectively reduces the porosity giving a dense structure [63]. On 10 % CWP replacement with FA, the porosity further decreases by 7.9% and 5.5% at 28 days and 6.5% and 7.0% at 56 days of ambient and heat curing respectively. This decrease continues to mix (F70C20S) giving porosity values of 19.20 and 18.75 at 28 days and 17.80 and 17.60 at 56 days of ambient curing and heat curing respectively. With increasing the CWP content by more than 20% the porosity values increase. It was observed that the heat curing of GPM leads to comparatively less porosity than ambient curing for the same proportions of GPM.

4.7. Acid Attack

An acid attack Test was performed on both ambient and heat-cured GPM according to code (ASTM C1012-04). A 28-day cured GPM specimen was exposed to 5% sulphuric acid. The weight of the specimen was measured before and after immersing in 5% sulphuric acid solution for 28 and 56 days and the loss in weight was measured (difference in initial and final weight). The results obtained are shown in Figure **10**. Geopolymer mortar is more resistant to acid as compared to cement-based mortar. A chemical interaction between sulphuric acid and calcium hydroxide is mainly responsible for the weight loss in acid attacks but as GPM is composed of less calcium gives low weight loss contrarily cement-based mortar composed of high calcium content gives a high weight loss [64,65]. The results shown in Figure **10** reveal that ambient cured GPM loses significantly more weight than heat curing. However, the weight loss were marginal and acceptable. After 28 and 56 days of exposure to 5% sulphuric acid, the weight loss of the control mix was 2.9% and 3.1% for ambient curing and 2.3% and 2.7% for heat curing. With the inclusion of 10% SF (F90C0S) weight loss was reduced by 24% and 22.5% of ambient curing and 26% and 22.2% of heat curing at 28 and 56 days of exposure respectively. Further inclusion of CWP at 10% proportion (F80C10S) loss in weight reduces by 22.7% and 16.67% of ambient curing and 23.5% and 23.8% of heat curing at 28 and 56 days of exposure. Weight loss reduces with increases in CWP content to 20% and further increasing the CWP content weight loss increases because of an increase in unreacted calcium content which reacts with the sulphuric acid causing expansion and tension strain in specimens causing loss in weight. Minimum weight loss corresponds to the mix (F70C20S).

4.8. Scanning Electron Microscopy (SEM) Characterisation

The SEM images of the mixes F100C0, F70C20S and F50C40S were studied to get a comparative insight into the micromorphology of the mixes for a better understanding of the effects of CWP substitution

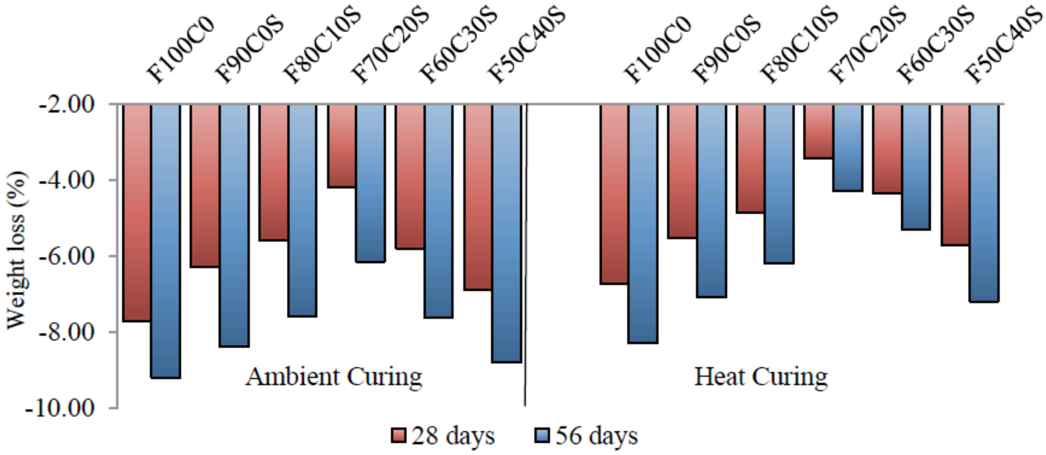


Figure 10: Weight loss of geopolymer mortar mixes on exposure to acid.

in geopolymers. The SEM of mixes F100C0, F70C20S and F50C40S have been shown in Figure **11**. It can be observed that the microstructure of the F70C20S shows more compactness and less voids as compared to the F50C40S and F100C0 mixes. This can be accredited to the adequate quantities of FA, SF and C-S-H gel from the unhydrated cement paste in ascending order, thus filling most of the pores in the microstructure. This is consistent with the results of the compressive strength as well as durability properties of the mixes since F70C20S has shown the optimum performance. Apart from this, abundant calcium hydration products like hexagonal Ca $(OH)_2$ crystals are seen in the mixes containing CWP, which are the hydration products of the unhydrated cement of the CWP. The SEM images and the experimental results are mutually consistent.

4.9. Environmental Assessment

The GWP and EE of the mixes have been presented in Figure **12** (**a**) and the calculated SI have been presented in Figure **12** (**b**). It can be observed that 10% replacement of FA with SF leads to a marginal decrease in the GWP of mix F90C0S relative to control mix F100C0. However, the increasing replacement level of FA with CWP in mixes F80C10S, F70C20S, F60C30S and F50C40S led to a consistent GWP increase of 0.39%, 0.86%, 1.32% and 1.79%, respectively, relative to the control mix F100C0. This increasing trend is attributed to the higher GWP associated with CWP as compared to FA as mentioned in Table **4**. The CWP needs to be crushed and finely ground to the particle size comparable to FA before being used as a precursor in GPM. Therefore, significant amount energy is exerted in its conversion, thus leading to higher associated GWP and EE [34].

The EE of mixes follows similar trends as that of GWP. A marginal decrease was observed in EE of mix F90C0S as compared to mix F100C0. However, the increasing replacement level of FA with CWP in mixes F80C10S, F70C20S, F60C30S and F50C40S led to a consistent EE increase of 2.33%, 4.85%, 7.37% and 9.89%, respectively, relative to the control mix F100C0. Again, the rising trend owes to the higher EE associated with CWP, relative to the FA as mentioned in Table **4**. The conversion of CWP to fine powder adds to EE of the powder [34].

Despite the surge in GWP and EE due to increase in replacement level of FA with CWP, a CS improvement of 13%, 36%, 27% and 19% was observed in mixes F80C10S, F70C20S, F60C30S and F50C40S, respectively, relative to the control mix F100C0 even at ambient curing conditions. Therefore,

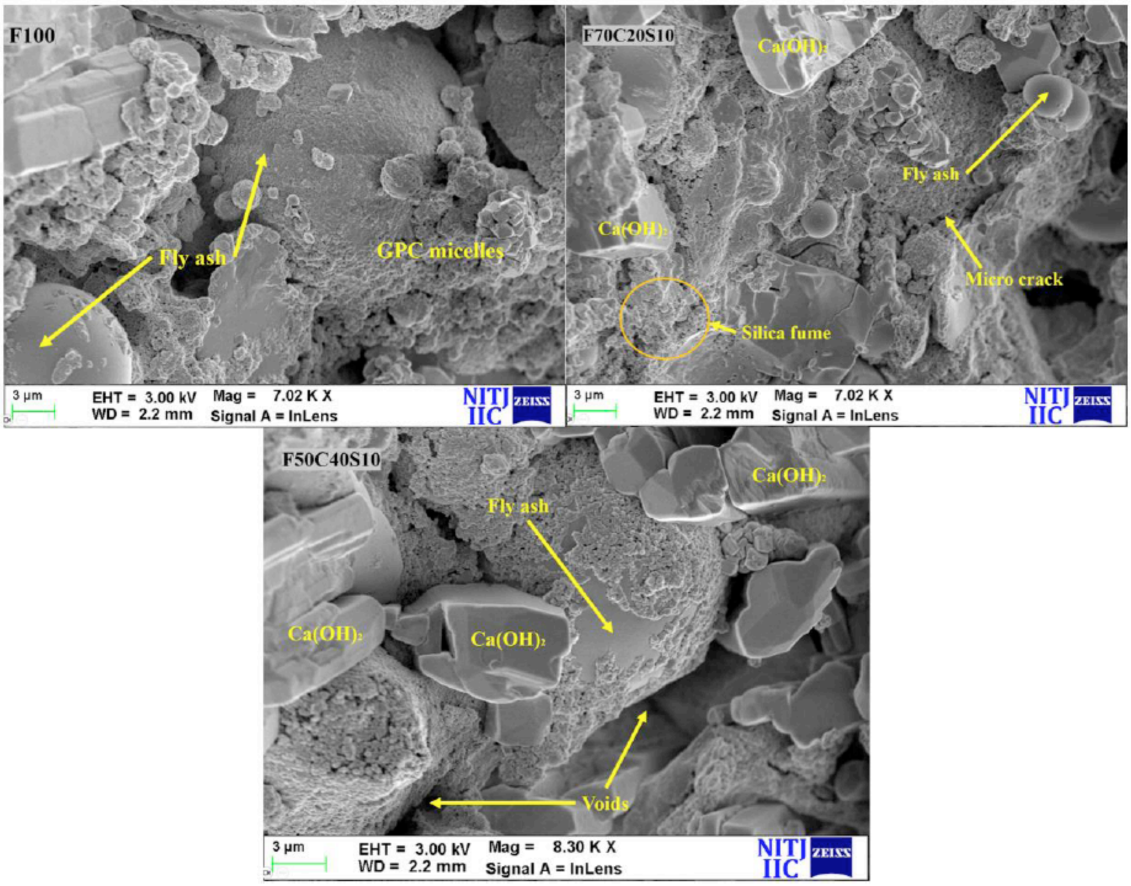


Figure 11: SEM images of the mixes F100C0, F70C20S and F50C40S respectively.

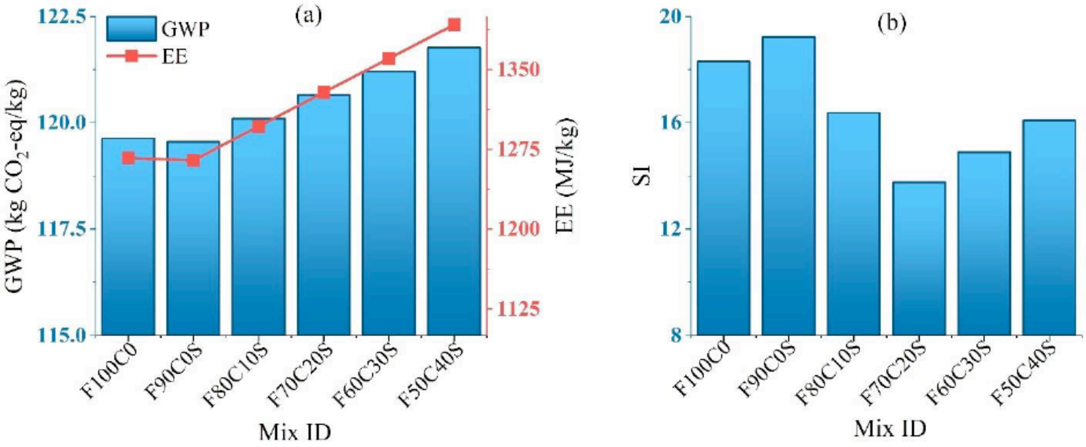


Figure 12: (**a**) GWP and embodied energy of GPM mixes, and (**b**) SI of all mixes.

the comprehensive environmental feasibility of FA replacement with CWP was assessed in terms of SI, calculated as per equation 1, such that the role of GWP, EE and CS is considered altogether. The mix F90C0S exhibited a significant increase in SI as compared to control mix F100C0, attributed to the decreased CS. However, the replacement of FA with CWP up to 20% shows a falling trend of the SI denoting improved performance. The mixes F80C10S and F70C20S exhibited 10.56% and 24.82% reduction in SI, respectively, as compared to F100C0. This is ascribed to the improved CS of these mixes relative to the F100C0. However, the SI surges upon further replacement of FA with CWP in mixes F60C30S and F50C40S. This indicates that the effect of rising GWP and EE on SI surpasses the effect of improved CS as the replacement level is increased beyond 20%. Nonetheless, the SI remains 18.57% and 12.10% lower than the F100C0 mix even in F60C30S and F50C40S mixes, respectively. Therefore, the replacement of FA with CWP stands environmentally feasible in terms of SI up to replacement level of 40% with the optimum performance at 20% replacement level.

4.10. Economic Assessment

The cost (INR/m^3) and EI of the mixes have been presented in Figure **13**. The mix F90C0S exhibits a steep increase in price as compared to control mix F100C0. This is ascribed to the high cost associated with SF as mentioned in Table **4**. However, the cost of CWP is only slightly higher than FA. Therefore, the cost surge stagnates as the FA replacement with CWP is increased from 10% to 40% in mixes F80C10S, F70C20S, F60C30S and F50C40S, respectively.

Despite the increase in cost, the mixes F80C10S, F70C20S, F60C30S and F50C40S exhibited an improved CS as compared to control mix F100C0 even at ambient curing conditions. Therefore, the EI of all mixes was calculated as per equation 2, to assess the collective impact of cost and CS on the economic performance of mix. The mix F90C0S exhibits a 27.03% higher EI than F0C100. This is accredited to the steep rise in cost due to SF and decrease in CS of the mix F90C0S relative to F0C100. However, the replacement of FA with CWP up to 20% causes a declining EI trend in mixes F80C10S and F70C20S. This is attributed to the CS improvement in these mixes as the CWP level is increase. Conversely, further increase in FA to CWP replacement from 20% to 40% root a rising trend in the EI of mixes F60C30S and F50C40S. This indicates that the effect of higher cost is more prominent than improved CS if the replacement level is increased beyond 20%. Nonetheless, the mixes F70C20S and F60C30S exhibit 10.91% and 4.41% lower EI than F0C100, denoting better economic feasibility. The mix F20C70S stands as the optimum mix in terms of EI, attributed to the maximum improvement in CS.

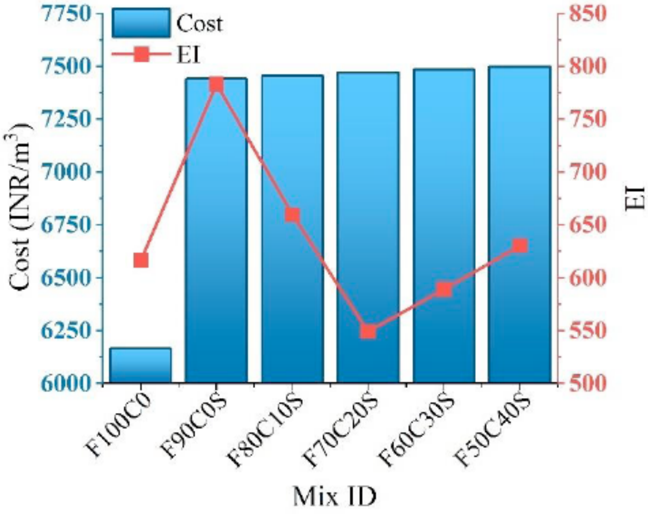


Figure 13: The cost (INR/m^3) and economic index of all GPM mixes.

4.11. CDW diversion potential of CWP in GPM

Substitution of CWP up to 40% was investigated in GPM. Although the optimum substitution level was identified at 20% considering overall performance, the mix F50C40S (with 40% CWP) exhibited compressive strength and other hardened properties comparable to the control mix. Based on the CWP content range of 119–238.1 kg/m³ of GPM (Table **3**), this approach demonstrates strong potential to divert CDW from landfills by utilizing it as a viable binder supplement.

Assuming the specific gravity and density of CDW as 2.4 and 2400 kg/m³, respectively (as per IS 875 – Part 1), and that 1 kg of CDW yields approximately 30–40% CWP, it can be inferred that 1 m³ of GPM has the potential to divert CWP equivalent to about 0.283 m³ of landfill waste. This represents a significant reduction in CDW disposal and highlights the strong potential of CWP as a sustainable secondary precursor or binder in GPM production.

5. CONCLUSIONS

The following were some conclusions that may be drawn based on the tests that were performed and the findings: -

- The addition of CWP and SF to FA-based GPM led to a significant reduction in setting time in comparison to the control mix. The early gain in strength is imputed to the fact that calcium from CWP and silica from SF facilitate the reaction.
- The flow value of the FA-based GPM drops when the primary binder FA is replaced by SF and CWP. The flow values continue to decrease with an increase in the fraction of CWP while maintaining the same level of SF.
- The compressive strength of geopolymer mortar was slightly reduced when 10 per cent SF was included, however, the compressive strength increased when CWP was added up to 20 per cent of the replacement level. This phenomenon occurred during heat curing as well as ambient curing. The mix having 70% FA, 20% CWP and 10% SF gives the maximum compressive strength due to the optimum proportion of silica and calcium content in the mortar.
- It was seen that the inclusion of SF can compensate for the sacrifice in compressive strength of the GPM well up to 20% and 30% replacement of FA with CWP. This happens because of the microstructure densification caused by fine-sized SF particles.
- The size of FA was greater than the size of SF and was smaller than the size of CWP. When FA was replaced by SF and CWP, it created a dense structure with a well-graded proportion and complete filling phenomenon, resulting in a reduction of voids and water absorption. The minimum values of water absorption and porosity were obtained when FA was replaced by 20% CWP and 10% SF.
- Geopolymer mortar (GPM) showed good resistance against acid attack (H_2SO_4) although heat curing geopolymer has represented little more resistance towards the acid attack as compared to ambient curing. For including 10% SF, weight loss during acid attacks has been favourably reduced, and the addition of 20% CWP has further improved acid resistance.
- Heat curing of GPM was better than ambient curing mortar as it delivered more compressive strength for the same proportion and was even more durable when assessed in terms of water absorption and porosity. Heat curing gives somewhat less water absorption and slightly less porosity which makes it more durable in the atmosphere.
- The SI of all mixes containing CWP, was lower than the SI of control mix F100C0, denoting environmental feasibility. The optimum performance was exhibited by mix F70C20S with 24.82% lower SI than F100C0.
- The EI of mixes F70C20S and F60C30S were 10.91% and 4.41% lower than control mix F100C0. This denotes economic feasibility in 20% to 30% replacement of FA with CWP.

The findings of this study not only advance the technical understanding of CWP-incorporated GPM but also contribute to the broader objectives of green construction frameworks. The demonstrated reductions in embodied energy and GWP directly align with material sustainability credits under Leadership in Energy and Environmental Design (LEED) and Building Research Establishment Environmental Assessment Method (BREEAM) rating systems, while also supporting India’s national mission on resource efficiency and sustainable infrastructure development.

The inclusion of Global Warming Potential (GWP) and Embodied Energy (EE) indicators in this study reflects an early-stage life-cycle thinking approach. However, these metrics capture only part of the environmental performance. Future work should therefore focus on performing a cradle-to-grave Life

Cycle Assessment (LCA) that accounts for all key life cycle stages: raw material extraction, transportation, production, service life, and end-of-life disposal or recycling. Such an analysis would provide a more robust comparison between geopolymer and OPC mortars, supporting evidence-based adoption of geopolymer materials in sustainable construction.

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AUTHORSHIP CONTRIBUTION STATEMENT

Pankaj Saini: Writing the original draft and analysis.

Paramveer Singh: Conceptualisation, content analysis, review and editing.

Tejinderpal Singh: Writing the original draft, sustainability and economic analysis.

Kanish Kapoor: Conceptualisation, content analysis, review and editing.

SP Singh: Content analysis, review and editing.

CONFLICT OF INTEREST

The author has no such competing financial interests that shall influence the work reported in this manuscript.

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