Original Article
ISSN (Online): 2582-7472

ShodhKosh: Journal of Visual and Performing Arts
June 2024 5(6), 2484–2499

POTENTIAL OF USING CRUMB RUBBER AND COPPER SLAG AGGREGATES IN GEOPOLYMER CONCRETE: STRENGTH AND DURABILITY STUDIES

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DOI
10.29121/shodhkosh.v5.i6.2024.3085

Funding: This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

ABSTRACT

This study focused on the production of ambient cured sustainable geopolymer concrete (GPC), utilising industrial by-products, including fly ash and alccofine, as well as partially incorporating recycled aggregates, a 50:50 mix of crumb rubber aggregates and copper slag aggregates, given a combined name of crumb-slag aggregates (CSA) as fine aggregates replacement (up to 30% by weight). The raw binders were activated using a mixture of sodium silicate (SS) and sodium hydroxide (SH). Results indicated that the compressive strength improved with CSA substitution up to 20%, and the highest compressive strength achieved was 58.57 MPa at 365 days. The highest chloride penetration resistance (576 C), the lowest water absorption (4.93%) and the sorptivity (0.0040 mm/sec1/2) were also noticed for the same mix at 365 days, indicating improved durability. It was concluded that recycled CSA mix could be used as a substitution for fine aggregates to produce concrete with improved strength and durability.

Keywords: Geopolymer Concrete, Alccofine, Crumb Rubber Aggregates, Copper Slag Aggregates, Chloride Ion Resistance, Sorptivity, ANOVA

Highlights

- Utilisation of crumb rubber and copper slag aggregates as a partial substitution of sand.
- Combined effects of OPC-43 and alccofine in geopolymer concrete.
- Geopolymer concrete with improved mechanical and durability performance.
- Correlations between strength and durability properties were established.

1. INTRODUCTION

Creation of massive number of by-products in manufacturing industry is a rising concern in modern society. Disposal of such industrial wastes is often environmentally challenging. One viable solution to reduce such environmental burden is to reuse the waste materials. The pozzolanic properties exhibited by some of these byproducts, such as fly ash, copper slag, and rice husk ash (RHA), which are rich in silica and alumina, enable them to be used as potential substitutes for conventional concrete ingredients. These wastes have been successfully used to create sustainable geopolymer concrete (GPC), through activation of solution containing sodium hydroxide (SH) and sodium silicate (SS). In other words, GPC can be used as a sustainable alternative construction material, which not only alleviates waste disposal concerns, but also reduces the use of traditional binder such as cement.

One of the key challenges with practical application of GPC is its heat curing requirement. This has spurred researchers to focus on the development of ambient-cured slag based GPC with equivalent mechanical performance as heat-cured GPC (Parveen et al. 2019; Saloni et al. 2020b). One feasible solution was the addition of calcium content rich additives, such as OPC and slag, which released heat and therefore eliminated the requirement of heat curing (Gill & Parveen, 2022). Several researchers (Jindal et al. 2017; Nath and Sarker 2014) found that GPC's properties were improved considerably when calcium rich additives were incorporated, even under ambient curing condition (Yaswanth et al. 2022).

In addition, fly ash-based GPC incorporating alccofine (Alccofine is also termed as ultrafine slag, which is a refined form of GGBS, so alccofine can have eCO2 value similar or slightly more than that of GGBS) was developed by Parveen et al. (2018a). Alccofine incorporation was found to enhance the properties of GPC. Similar findings were reported by Saloni et al. (2020a), in which two types of curing conditions were adopted (ambient curing at 27°C and heat curing at 90°C) to produce GPC incorporating alccofine. Ariffin et al. (2013) investigated the effect of sulphuric acid exposure on GPC and found that the GPC outperformed conventional concrete in terms of acid resistance. The mechanical and permeability properties of metakaolin-based sustainable GPC incorporating alccofine were investigated by Parveen et al. (2019). They reported that the inclusion of alccofine up to 15% improved the mechanical properties. In short, previous studies indicated that the properties of GPC were comparable to conventional concrete if slag was incorporated in the mixes (Dhirendra Singhal and Garg 2017; Jindal et al. 2020; Parveen et al. 2017).

End of life tyres due to their low recyclable uses are a new source of environment nuisance. However, rubber aggregates with different sizes could be extracted from crushed tyres, and have found a recycling alternative in geopolymer concrete. Rubber aggregates are known to enhance ductility, tenacity, toughness, impact resistance and vibration damping in concrete (Kaloush et al., 2005). But, crumb rubber aggregates have shown to hamper the strength properties of GPC (Roychand et al., 2020). Meanwhile, copper slag is one of the main wastes generated from the copper manufacturing industry. Approximately 2.2 tonnes of slag are produced per tonne of copper production (Gorai et al. 2003) and requires huge land space for dumping. In contrast, the rapid consumption of the natural resources (such as sand) motivates the use of fine copper slag aggregates as a substitution of fine aggregates in GPC. Previous research demonstrated that the mechanical and the durability performance of GPC improved when copper slag was included in GPCClick or tap here to enter text. (Gill, Jangra, & Ashish, 2023). The properties of such GPC were studied by Mahendram and Arunachalam (2016). Fine aggregates were replaced by copper slag up to 100%, with an increment of 10% for each mix. 14 M NaOH solution was used and the mixes were cured at 60°C and at ambient temperature. The results showed an enhancement in the compressive strength when copper aggregate was incorporated in GPC, as copper slag contributed to improved bonding among various ingredients. The flexural characteristics of GPC produced using copper slag were investigated by Sreenivasulu et al. (2020). Fine aggregates were replaced by copper slag at levels of 0, 20, 40 and 60% by weight, and for all substitution levels, better performance was observed. Another study revealed that copper slag aggregates does not affect the strength of the geopolymer concrete however concentration of NaOH had directly relation with the compressive strength.

According to the literature, only a few studies related to the strength and the durability parameters of GPC with copper slag and crumb rubber are available. The combined effects of incorporating OPC-43 and alccofine with crumb rubber-copper slag aggregates (CSA) in GPC are also unknown. Considering OPC-alccofine and CSA have similar silica concentrations, there is a possibility of mutual interaction, resulting in improvement of bonding among different constituents, which has not been investigated so far. Therefore, a thorough investigation on the abovementioned factors is deemed valuable, which spurred the research presented in this paper.

The objective of this research was to develop a GPC using recycled CSA, as well as to determine its strength and durability. To determine the characteristics of GPC in the fresh stage, various properties of GPC incorporating CSA, including workability, temperature, air content and density were experimentally examined. Their mechanical performance was also investigated by conducting compression tests on standard sized specimens. Various durability parameters, including water absorption, chloride ion resistance and sorptivity, were then examined. Linear regression was used to investigate the relationships between different parameters. Statistical analysis method, namely, analysis of variance (ANOVA) was also implemented on the results to study their statistical significance.

2. TESTING METHOD
2.1. MATERIALS AND SAMPLES PREPARATION

Fly ash (with low calcium 1.97%) conforming to Indian standard IS 3813 (I) (2013) was procured from a coal power plant near New Delhi, India, and used as the main binder along with OPC-43 and alccofine. In the current study, OPC-43 and alccofine were used as binder additive to fly ash to produce GPC. Crumb rubber aggregates were extracted from discarded truck tires using the ambient grinding method and purchased from a commercial tire processing facility in Bahadurgarh, India. Copper slag aggregates were obtained from a copper manufacturing industry near Delhi, India. The alkaline solution was prepared using SH pellets (with 97 - 98% purity) and SS. The chemical composition of fly ash, OPC-43, alccofine and CSA is summarised in Table 1. Crumb granite and river sand obtained from the Yamuna River, India, were used as aggregates. The physical properties of various GPC constituents are summarised in Table 2. The specific gravities for fly ash, alccofine, OPC-43, crumb rubber and copper slag were noted as 1.92, 2.71, 3.08, 0.95 and 3.52, respectively.

Table 1: Chemical composition of fly ash, OPC-43, alccofine and copper slag aggregates.

Content (%)	CaO	SiO_2	Al_2O_3	FeO	SO_3	MgO	K_2O	Na_2O
Fly ash	1.97	51.81	29.50	14.71	0.50	0.85	0.47	0.19
OPC-43	63.21	19.38	7.71	5.29	3.19	0.47	0.78	0.36
Alccofine	32.94	35.64	21.38	1.71	0.14	6.87	0.92	0.40
Copper slag aggregates	3.45	32.54	4.12	54.73	1.45	1.62	1.27	0.82

Table 2: Physical properties of various GPC constituents.

Material	Appearance	Specific gravity	Fineness modulus	Specific surface area (m^2/kg)	Water absorption (%)	Unit weight (kg/m^3)
River sand	Grey	2.58	2.24	9.36	2.84	1240
Coarse aggregates	–	2.67	6.12	0.24	1.28	1690
Fly ash	Light greyish	1.92	-	415	-	1175
OPC-43	Light grey	3.08	-	306	-	1413
Alccofine	Blackish	2.71	-	1200	-	1020
Crumb rubber aggregates	Black, Rough texture	0.95	2.78	-	0.21	516
Copper slag aggregates	Black, Glassy texture	3.52	3.15	178	0.42	1980

The physical images of alccofine, fly ash, crumb rubber and copper slag aggregates are shown in Fig. 1. To determine the grading of sand and copper slag, sieve analysis was performed in accordance with American society for testing and materials ASTM C136 (2014) and the particle size distribution curve obtained is shown in Fig. 2. The curves obtained were within the specified limits for Zone II for aggregates, as mentioned in IS 383 (2016). Naphthalene based chemical admixture/water reducing admixture was used.

Figure 1 Physical images of fly ash, alccofine, crumb rubber and copper slag aggregates.

8M SH solution was prepared and cooled for 2 to 3 hours. Then, for about 5 - 7 minutes, SH and SS were mixed together to prepare an activator solution, and it was kept at room temperature for 24 hours before final mixing. Dry mixing of all the ingredients was done in a pan mixture, and then the activator solution was slowly added. The mix design proposed by Parveen and Singhal (2017) was adopted to prepare the reference mix of GPC. CSA with substitution levels of 0, 10, 20 and 30% were used as substitution for sand, and the GPC mixes were designated as 0CSA-GPC, 10CSA-GPC, 20CSA-GPC and 30CSA-GPC, respectively. Alkaline activator liquid (AAL) to binder ratio was kept as 0.4, while SS to SH ratio was fixed as 2.5. Table 3 summarises the detailed composition of different mixes in kilograms per cubic meter. The specimens were cast and then cured at room temperature.

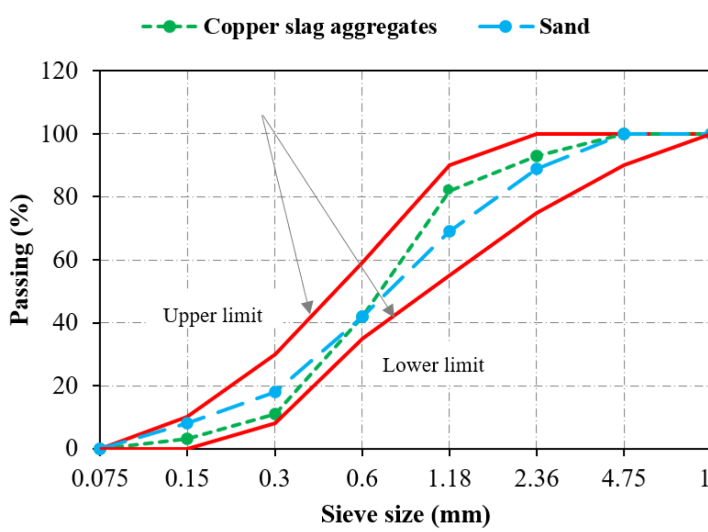


Figure 2 Particle size distribution curve of aggregates.

Table 3 Details of GPC mix proportions.

Mix	0CSA-GPC	10CSA-GPC	20CSA-GPC	30CSA-GPC
Fly ash (kg/m^3)	320	320	320	320
OPC-Alccofine* (kg/m^3)	80	80	80	80

Sand (kg/m³)	580	522	418	292
CSA** (%)	0	10	20	30
Coarse Aggregates (kg/m³)	1240	1240	1240	1240
AAL/binder ratio	0.4	0.4	0.4	0.4
AAL (kg/m³)	160	160	160	160
NaOH (kg/m³)	45.71	45.71	45.71	45.71
Na_2SiO_3 (kg/m³)	114.29	114.29	114.29	114.29
Na_2SiO_3/NaOH	2.5	2.5	2.5	2.5
Admixture (%)	1.5	1.5	1.5	1.5

*Note- OPC-Alccofine is a 50:50 mix of OPC-43 and alccofine by weight.
**Note- CSA is 50:50 mix of crumb rubber and copper slag aggregates by weight.

2.2. TESTING OF SPECIMENS

The slump cone test is widely used to evaluate workability, a property that specifies the efforts needed to manipulate a certain amount of freshly mixed concrete with minimal homogeneity loss. The compaction factor and the Vee-bee consistometer tests were performed in addition to the slump cone test to examine the behaviour of fresh GPC. These tests were done in accordance with IS 1199 (2018). Percentage air content in concrete is important with respect to strength, freezing and thawing performance. The testing was done in accordance with EN 12350-7 (2009).

The samples were tested for density in the saturated surface dry condition and using ASTM C642-13 (2013). The most significant property of hardened concrete is its compressive strength. Compressive strength tests on concrete cylinders (measuring 150 × 300 mm) were carried out using a compression testing machine at 7, 28, 90 and 365 days of age, in accordance with the requirements of ASTM C39 (2020). Water absorption tests were performed according to ASTM C642-13 (2013) to assess the permeability of GPC specimens. The resistance against chloride attack was examined using the rapid chloride permeability test (RCPT), and guidelines of ASTM C1202 (2012) were adopted. The total charge passed correlates to the resistance of the concrete specimen to chloride ions. ASTM C1585-13 (2013) was followed to measure the sorptivity. In this test, all surfaces of GPC specimens except one surface were sealed using a sealant, and the surface which was not sealed was exposed to water at room temperature, water ingress primarily happened due to capillary suction. Apart from 7 and 28 days, testing of various properties was also done at 90 and 365 days to study the long-term durability performance, it has also been observed in previous studies that testing at higher age gave more accurate results ("Concrete durability testing - Kryton International Inc." 2014). The fractured pieces from the inner core of GPC specimen were taken out after conducting compressive strength tests. To perform statistical analysis on GPC specimens, statistical package for the social sciences (SPSS) Version 20 was used.

3. RESULTS AND DISCUSSIONS

3.1. FRESH STAGE PROPERTIES

The slump cone, compaction factor and Vee-bee consistometer tests were carried out to determine the workability, and the results are arranged in Table 4. Slump of GPC mixes was in the range of 115 - 155 mm. The highest slump was observed for the Mix 20CSA-GPC (155 mm). Any further increase in CSA% increased chances of bleeding and segregation, and thus slightly poor workability. This was due to lower water absorption of crumb rubber and copper slag (0.21% and 0.42%, respectively) as compared to sand, leading to excessive water release in the mixes. Also, an uptrend in compaction of material is seen as CSA content is increased. At 0% CSA, the value of compaction factor is observed to be 0.89. As CSA content increases further from 0% to 10%, 20% and 30%, a constant rise in the values of compaction factor is noted i.e., 0.96, 0.97 and 0.98 respectively. As compactness increases, the material is less porous and its bonding strength increases allowing it to be more workable.

Table 4: Properties of fresh GPC.

Mix	0CSA-GPC	10CSA-GPC	20CSA-GPC	30CSA-GPC
Slump (mm)	115	150	155	150

Compaction factor	0.89	0.96	0.97	0.98
Vee-bee consistometer (s)	3.1	2.6	2.4	2.4
Air temperature (°C)	24	25	25	26
Concrete temperature (°C)	25	25	25	25
Air content (%)	2.8	2.6	2.5	2.7
Fresh GPC density (kg/m^3)	2375	2388	2402	2412

According to the Vee- bee consistometer test, it was observed that time fluctuated from 3.1- 2.4s with increase in CSA content up to 20% in the GPC mixes. However, when the CSA substitution exceeded 20%, there was no considerable fluctuation noticed. The smooth and glassy surface of the CSA was responsible for this enhancement. In addition, alccofine also improved the flowability of GPC mixes (Parveen et al. 2018b), leading to better workability.

Air contents in the GPC mixes varied from 2.5 - 2.8%, and the lowest air content was observed for mix 20CSA-GPC (2.5%), which indicated fewer voids and a denser matrix structure. The inclusion of alccofine and CSA filled up the voids in GPC due to the formation of additional calcium products by OPC and alccofine and the amorphous nature of CSA, which helped in bond development among ingredients and reduced the air content.

The density of fresh GPC was 2,375 kg/m3 for the control Mix (0CSA-GPC). When CSA% increased, the density increased, and the highest value was 2,412 kg/m3 (for the Mix 30CSA-GPC). However, the increase was marginal due to the higher specific gravity of CSA (3.52) than that of sand (2.58). The smooth and glassy surface of CSA reduced the water requirements and increased the possibility of the development of a homogeneous mix with fewer voids (as indicated by lower air content of GPC mixes with CSA). This was the primary cause for the increase in density and a more compact structure.

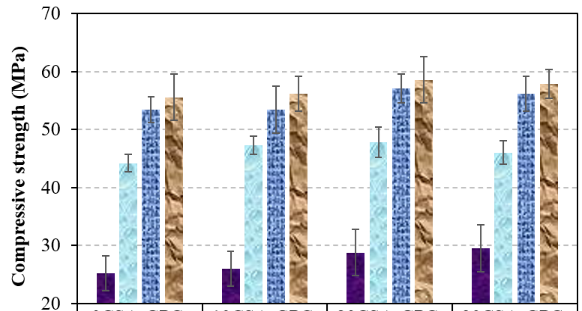
In addition, the CSA particles supported the polymerisation process by forming additional polymerisation products in the presence of the alkaline solution. Due to the reaction of CSA with other ingredients, additional polymerisation gel was formed, which enhanced the microstructure of the GPC matrix, which was also observed in previous study (Sreenivasulu et al. 2020). However, an increase in air content is seen with higher CSA content in 30CSA-GPC as a negative result on bonding of the material. This high concentration of CSA leads to a decrease in bonding strength and leads to formation of extra voids and cracks due to capillary action within the material which tend to weaken the overall matrix structure.

The workability of concrete mixes containing CSA was studied by Gupta and Siddique (2020), the results showed an enhancement in workability with the increment of CSA% in concrete. Characteristics of GPC mixes produced using CSA were investigated by Sreenivasulu et al. (2020), and the study reported the development of a compact structure with lower voids and air content when CSA was incorporated into GPC. The effect of CSA on the density of GPC mixes was studied by Mathew and Usha (2014), the results showed an increase in density when CSA was added into GPC. The outcomes of the current research agreed well with those reported in the above studies.

3.2. HARDENED STAGE PROPERTIES

3.2.1. COMPRESSIVE STRENGTH

The compressive strength of various GPC mixes at the curing ages of 7, 28, 90 and 365 days is presented in Fig. 3. An increase in the compressive strength was observed for the GPC mixes at all ages when CSA% increased from 0 to 20%, while with further increase to 30%, a slight reduction in the compressive strength was obtained at ages of 28, 90 and 365 days. At 7 days, a marginally higher compressive strength was observed for Mix 30CSA-GPC in comparison to Mix 20CSA-GPC. For the control mix (0CSA-GPC), the 28 day's compressive strength was noted as 44.18 MPa. The highest compressive strength was noticed for Mix 20CSA-GPC at all ages (28.79, 47.80, 57.10 and 58.57 MPa at 7, 28, 90 and 365 days, respectively), while the lowest strength was noticed for the control mix at all ages. The increase in compressive strength at various ages was identified as 13.97, 8.19, 6.90 and 5.37%, respectively, when CSA% increased from 0 to 20%. The highest strength gain was observed at the age of 7 days, and strength increased with age.



	0CSA-GPC	10CSA-GPC	20CSA-GPC	30CSA-GPC
7 days	25.26	25.98	28.79	29.52
28 days	44.18	47.27	47.80	46.04
90 days	53.41	53.44	57.10	56.12
365 days	55.58	56.22	58.57	[illegible]

Figure 3 Compressive strength of various GPC mixes

The increase in compressive strength could be attributed to an improved bonding between the GPC ingredients due to the combined reaction of fly ash and alccofine. Alccofine and OPC are rich in lime, and help in the formation of additional gels (calcium aluminate silicate hydrate (CASH) and calcium silicate hydrate (CSH) gels) in the mixes (Gill, Jangra, Roychand, et al., 2023). These additional gels along with sodium aluminate silicate hydrate (NASH) gel, which was the main product governing the strength of GPC, enhanced the bonding among GPC ingredients.

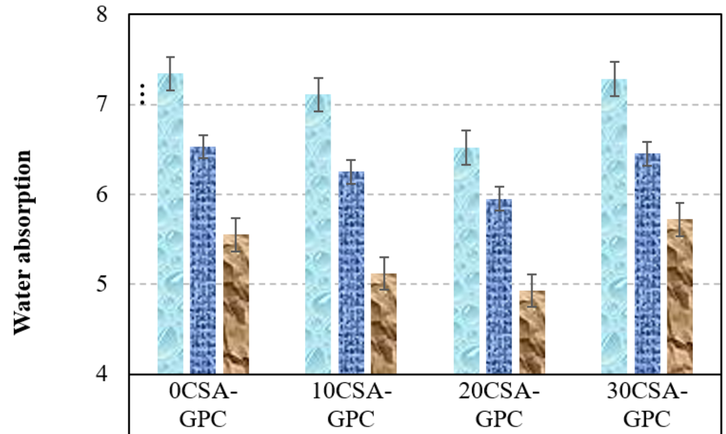
In addition, lower water demand of CSA increased the workability and thus, improved the strength. The CSA particles supported the polymerisation and formed a denser microstructure. Also, CSA particles helped to enhance the cohesion among various ingredients, thus forming an improved matrix, as suggested by Al-Jabri et al. (2011). Although sand has a rough surface, which improved the bond between concrete ingredients, the abrasion resistance of sand was weakened due to the weathering action with time, leading to the inferior properties of the composite materials. The angular CSA counteracted this and improved the cohesion of concrete. Besides, it was discovered that CSA relieved the stress as it possessed higher compressibility than sand (Wu et al. 2010), which was one of the reasons for improved strength (up to 20% CSA substitution).

At higher level of replacement, the probability of forming a poor matrix was higher due to lower water content of CSA (0.42%), which caused excess water release within the matrix, thus weakening the GPC matrix.

The compressive strength of GPC produced using ground granulated blast furnace slag (GGBS), and CSA was studied by Rathanasalam et al. (2020). It was reported that the 3-days compressive strength increased by 12.35% to 36.56 MPa with reference to GPC (32.54 MPa) when CSA was partially used as fine aggregates in place of sand. It has been observed by Mahendran and Arunachelam (2016) that CSA minimised the crack and voids formation in GPC by producing more polymerisation gels, which assisted in the development of a compacter and denser structure with higher strength. The effect of the composition of various oxides on the compressive strength of GPC was studied by Reddy et al. (2016), and the optimum composition for oxides was reported as 50.5%, 26.5%, and 15.9% for SiO2, Al2O3, and Fe2O3 & CaO, respectively. In this current study, the SiO2 content of fly ash, alccofine and CSA was 51.81, 32.54 and 35.64%, the high SiO2 content was also responsible for the increased GPC strength. The results of the current study were supported by the abovementioned previous studies.

3.2.2. WATER ABSORPTION AND VOLUME OF PERMEABLE VOIDS

Water absorption tests give an indication of the water absorbed by GPC specimens under aggressive environments and the volume of voids presence in the hardened GPC. The outcomes of the water absorption tests at the ages of 28, 90 and 365 days of various GPC mixes are shown in Fig. 4. The water absorption of control Mix (0CSA-GPC) was 7.34, 6.53 and 5.55% at the respective ages. The lowest water absorption was observed for Mix 20CSA-GPC, which were 6.52, 5.95 and 4.93% at the respective ages. Lowest water absorption were observed at the age of 365 days for all mixes (5.55, 5.12, 4.93 and 5.72% for the mixes 0CSA-GPC, 10CSA-GPC, 20CSA-GPC and 30CSA-GPC, respectively).

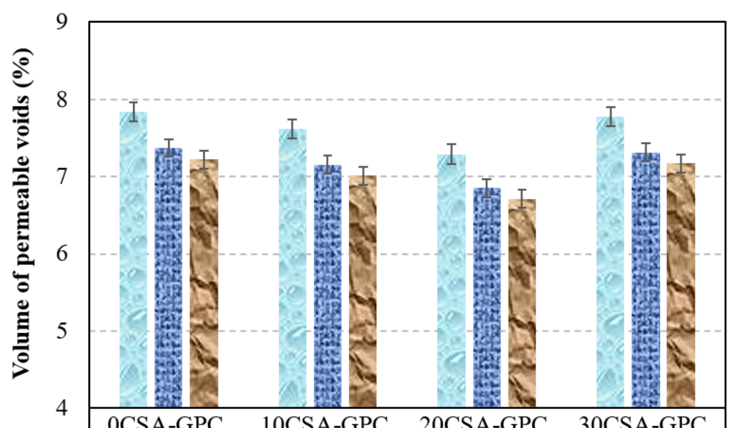


	0CSA-GPC	10CSA-GPC	20CSA-GPC	30CSA-GPC
28 days	7.34	7.11	6.52	7.28
90 days	6.53	6.25	5.95	6.45
365 days	5.55	5.12	4.93	5.72

Figure 4 Water absorption of GPC mixes

The reduction in pores and the improvement in bonding of GPC ingredients due to the CSA inclusion led to a decrease in water absorption, up to 20% CSA substitution. Similar factors governing the increment in the compressive strength also caused a reduction in the water absorption. However, when excessive CSA was used (i.e., higher than 20%), new voids were formed due to the rise in excess free water content caused by low water absorption of CSA (0.42%). This, in turn, increased the overall water absorption of the GPC (presence of more voids to absorb water). There was also a possibility of bleeding with higher CSA content, resulting in the formation of capillary channels and a degradation in GPC quality. The other reason was the fineness of CSA, which led to the release of excess heat, causing cracking and providing a path for the ingress of water. The water absorption of Mix 30CSA-GPC was similar to the water absorption of the control mix.

The volume of permeable voids was also estimated as illustrated in Fig. 5. A decline in the values was observed with increasing CSA% in GPC. For the control mixes, the values were 7.84, 7.37 and 7.22% at the curing ages of 28, 90 and 365 days, respectively, which decreased to 7.29, 6.85 and 6.71%, with 20% CSA. With further substitution (i.e., more than 20%), higher permeable void volume was noticed.



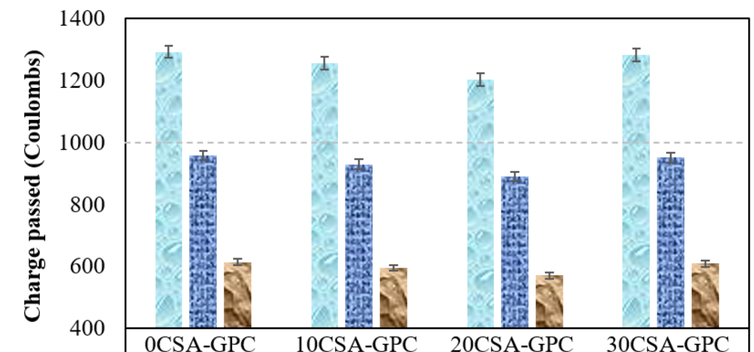
	0CSA-GPC	10CSA-GPC	20CSA-GPC	30CSA-GPC
28 days	7.84	7.61	7.29	7.78
90 days	7.37	7.15	6.85	7.31
365 days	7.22	7.01	6.71	7.17

Figure 5 Volume of permeable voids of GPC mixes

These outcomes could also be related to the compressive strength results. The primary reasons that were responsible for the increment in the compressive strength also caused the reduction in water absorption since an GPC mix with higher strength absorbed less water due to a denser and compacter matrix structure. The water absorption of concrete mixes incorporating CSA was studied by Afshoon and Sharifi (2017), and a decrease in the water absorption was observed with the inclusion of CSA in concrete. Al-Jabri et al. (2011) used CSA to replace fine aggregates at varying levels from 0 to 100%, and it was concluded that CSA substitution (up to 40%) decreased the water absorption. Prem et al. (2018) reported improvement in the water absorption capabilities of concrete, even up to 100% CSA incorporation. Singh and Mehta (2020) observed that porousness and water absorption of GPC decreased due to CSA inclusion. In summary, the CSA content affected the water absorption capabilities of concrete, but different researchers reported different thresholds. Such discrepancies could be caused by the physical and chemical features of other ingredients. In addition, materials utilised in different studies were obtained from different sources. Variation in physical and chemical properties were unavoidable.

3.2.3. CHLORIDE ION RESISTANCE

The outcomes of the RCPT at the ages of 28, 90 and 365 days are displayed in Fig. 6. A decrease in RCPT values was noticed with an increment in CSA% in GPC, which indicated a better chloride penetration resistance. The RCPT values relate to the chloride resistance of GPC, with higher values indicated lower resistance (lower durability) to chloride penetration and vice versa. The RCPT values were 1293, 958 and 614 Coulombs at the respective ages for the control Mix (0CSA-GPC). As mentioned earlier, the CSA substitution up to 20% reduced the pore content, which also reduced the permeability of the GPC mixes. This blocked the path of penetration of chloride ions. The RCPT values at 90 and 365 days were significantly lower than RCPT than that of 7 days, and those GPC mixes exhibited comparatively higher chloride penetration resistance. The range of RCPT values was 890 - 958 Coulombs and 571 - 614 Coulombs for curing ages of 90 and 365 days, respectively.



	0CSA-GPC	10CSA-GPC	20CSA-GPC	30CSA-GPC
28 days	1293	1256	1202	1284
90 days	958	930	890	951
365 days	614	596	571	609

Figure 6 RCPT results of GPC mixes

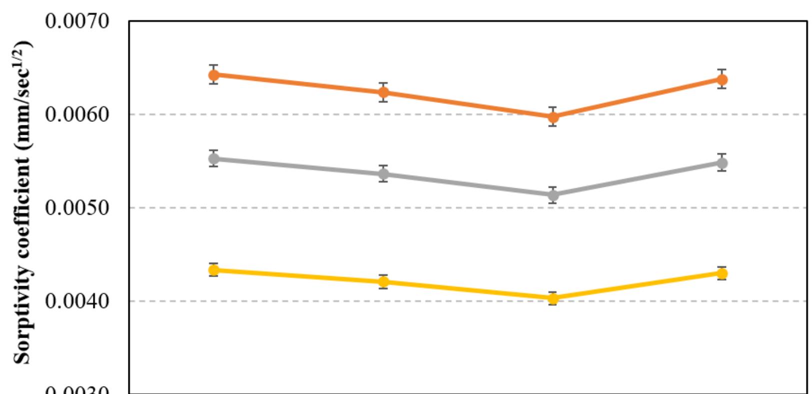
The decrease in charge passed due to CSA substitution (up to 20%) can be attributed to a combination of a few factors, namely (a) reduction in pore conductivity, (b) improvement of pore structure (i.e., decline of pore connectivity due to the combined reaction of fly ash, and alccofine, which filled the voids, and reduction of chances of chloride penetration and, (c) improvement in cohesion among various GPC ingredients. This could be confirmed from the outcomes of the compression tests. Also, the water absorption decreased with up to CSA% of 20%. Beyond 20% substitution, a poor GPC matrix was formed, as earlier mentioned in this study. The reasons responsible for the decrease in matrix strength at higher CSA substitution were also responsible for the increase in charge passed.

The results in this study showed that the effect of CSA inclusion was more pronounced at higher ages, which was similarly observed in other previous study (Najimi et al. 2011b). With the increase in CSA% up to 15%, an increase in the chloride penetration resistance was observed by Boakye and Uzoegbo (2014). Rajasekar et al. (2019a) also observed that CSA substitution up to 60% enhanced the chloride penetration resistance. In contrast, it has been shown in a previous study that the inclusion of CSA in concrete did not significantly affect the RCPT values (Prem et al. 2018). Since the experimental outcomes were mainly based on the interaction between CSA and other GPC constituents, which differed across different studies, a variation in results was expected. As per the guidelines of ASTM C1202 (2012), the probability of chloride permeation for all GPC mixes at 28 days was classified as 'low'; while at 90 and 365 days, it was classified as 'very low'.

3.2.4. SORPTIVITY

The sorptivity test is used to measure the susceptibility of exposed, unsaturated GPC to water permeation. It depends on various factors, including the characteristics of aggregates, admixture type, placement method, and mix proportions. Fig. 7 presents the sorptivity coefficient of various GPC mixes. The collective action of fly ash, OPC-alccofine and CSA successfully reduced the sorptivity coefficient. A decline in sorptivity coefficient was observed up to 20% CS substitution, beyond which the values started to increase. For the control mix, the respective sorptivity coefficient at the ages of 28, 90 and 365 days were 0.0064, 0.0055, and 0.0043 mm/sec1/2. The highest values were observed at 28 days (0.0060-0.0064 mm/sec1/2), while the lowest values were identified at 365 days (0.0040-0.0043 mm/sec1/2).

The reduction in sorptivity could be related to the combined contribution of fly ash, OPC-43, alccofine and CSA, which improved the pore structure of the GPC. This reduced the size and quantity of permeable pores (Lotfy et al. 2016). At higher age, the bonding among various GPC constituents became stronger, leading to a denser structure with lower sorptivity coefficient. The results obtained were also in agreement with the outcomes of the water absorption tests, as an increase in the water absorption was also observed when the amount of CSA exceeded 20%.



	0CSA-GPC	10CSA-GPC	20CSA-GPC	30CSA-GPC
28 days	0.0064	0.0062	0.0060	0.0064
90 days	0.0055	0.0054	0.0051	0.0055
365 days	0.0043	0.0042	0.0040	0.0043

Figure 7 Sorptivity coefficient of various GPC mixes

Rajasekar et al. (2019b) observed a decrease in sorptivity coefficient for concrete mixes up to 60% CSA, indicating impermeable concrete. In an investigation conducted by Sharma and Khan (2017), a reduction in sorptivity coefficient was noticed when CSA% was increased. The results of the above-discussed studies justified the general trend observed in the present investigation. Yet, it was again noted that the threshold could vary due to the interaction of CSA with other constituents, as mentioned in Clause 3.2.2.

3.3. STATISTICAL ANALYSIS

The variance approach, known as the method of Analysis of Variance (ANOVA) was used to investigate the statistical significance of selected parameters used in this study. The effects of varying levels of CSA in GPC mixes at various ages were investigated, and the findings obtained from Post Hoc Tukey tests are shown in Table 6.

The substitution levels of CSA i.e., 0, 10, 20 and 30%, were chosen as dependent variables. The curing ages were set as the independent variables (i.e., 7, 28, 90 and 365 days). The results were classified as statistically significant when p-value was less than or equal to 0.05. In the case of compressive strength, the p-value was less than 0.05 at all ages, indicating that the values were classified as statistically significant. Multiple comparisons were also made between the mean strength of the GPC mixes using Post Hoc Tukey tests, as shown in Table 6.

Table 6: Comparisons for compressive strength using Post Hoc Tukey method.

Dependent variable	(I) mix	(J) mix	p-value
0	7 days	28 days	0.000*
		90 days	0.000*
		365 days	0.000*
	28 days	7 days	0.000*
		90 days	0.000*
		365 days	0.000*
	90 days	7 days	0.000*
		28 days	0.000*
		365 days	0.018*
	365 days	7 days	0.000*
		28 days	0.000*
		90 days	0.018*
10	7 days	28 days	0.000*
		90 days	0.000*
		365 days	0.000*
	28 days	7 days	0.000*
		90 days	0.001*
		365 days	0.000*
	90 days	7 days	0.000*
		28 days	0.001*
		365 days	0.009*
	365 days	7 days	0.000*
		28 days	0.000*
		90 days	0.009*
20	7 days	28 days	0.000*
		90 days	0.000*
		365 days	0.000*
	28 days	7 days	0.000*
		90 days	0.000*
		365 days	0.000*
	90 days	7 days	0.000*
		28 days	0.000*
		365 days	0.002*
	365 days	7 days	0.000*
		28 days	0.000*
		90 days	0.002*
30	7 days	28 days	0.000*

		90 days	0.000*
		365 days	0.000*
	28 days	7 days	0.000*
		90 days	0.000*
		365 days	0.000*
	90 days	7 days	0.000*
		28 days	0.000*
		365 days	0.004*
	365 days	7 days	0.000*
		28 days	0.000*
		90 days	0.004*

(Note: p-value < 0.05 indicates significant)

The durability parameters were also compared using Post Hoc Tukey tests. The durability parameters include water absorption, RCPT, and sorptivity, which were considered as dependent variables. The curing ages were considered as independent variables. Multiple comparisons were conducted, and the findings are summarised in Table 7. Highly significant results were observed for the durability parameters at curing ages of 28, 90 and 365 days (p-value < 0.05). The findings were then compared to those previously reported in the literature.

The importance of various variables, such as the CSA content and the water-cement ratio with compressive strength, was considered in this analysis.

Table 7: Statistical significance of durability parameters.

Dependent variable	(I) mix	(J) mix	p-value		
			Water absorption	RCPT	Sorptivity
0	28 days	90 days	0.011*	0.000*	1.000
		365 days	0.000*	0.000*	0.000*
	90 days	28 days	0.011*	0.000*	1.001
		365 days	0.015*	0.000*	0.000*
	365 days	28 days	0.000*	0.000*	0.000*
		90 days	0.015*	0.000*	0.000*
10	28 days	90 days	0.102	0.000*	1.000
		365 days	0.005*	0.000*	0.000*
	90 days	28 days	0.102	0.000*	1.002
		365 days	0.121	0.000*	0.000*
	365 days	28 days	0.005*	0.000*	0.000*
		90 days	0.121	0.000*	0.000*
20	28 days	90 days	0.025*	0.000*	1.000
		365 days	0.009*	0.000*	0.000*
	90 days	28 days	0.025*	0.000*	1.000
		365 days	0.001*	0.000*	0.000*
	365 days	28 days	0.009*	0.000*	0.000*
		90 days	0.001*	0.000*	0.000*
30	28 days	90 days	0.035*	0.000*	1.000

		365 days	0.001*	0.000*	0.000*
	90 days	28 days	0.035*	0.000*	1.002
		365 days	0.041*	0.000*	0.000*
	365 days	28 days	0.001*	0.000*	0.000*
		90 days	0.041*	0.000*	0.000*

(Note: p-value < 0.05 indicates significant)

In a study by Mavroulidou (2017), Khushal-Wallis analysis and ANOVA test were performed, and the results showed that the most significant parameter affecting the compressive strength was the water-cement ratio, followed by the cement type. The p-value for CSA was found to be 0.208, which was deemed insignificant. In the Khushal-Wallis analysis, similar results were found. Also, it was noted that the use of CSA improved the mechanical and the durability characteristics, but its significance was relatively minor as compared to that of the water-cement ratio.

To analyse the experimental results, Minitab software was used in a study by Hari and Mini (2019). The dependent variables were water absorption, RCPT and sorptivity, while the independent variables were Portland cement (PC) with fly ash, PC with crumb rubber, and crumb rubber. All of them were found to be statistically significant. The effect of hybridisation and the volume of fibres on the mechanical properties was also described. Other researchers have also employed statistical analysis, as in the current study, to investigate the relationship between the various parameters stated above.

4. CONCLUSIONS

In this study, the feasibility of utilising CSA as alternate aggregate for the production of composite GPC was investigated. The experimental results showed that an enhancement in the strength and durability properties of GPC was observed when sand was replaced by CSA, up to a maximum of 20%. CSA helped in the formation of additional polymerisation gels, which improved the bonding among various GPC ingredients. The following conclusions could be made based on the present study:

1) The workability of GPC improved with the substitution of CSA due to the smooth and glassy surface of CSA, which enhanced the flowability of GPC. Highest slump was achieved by Mix 20CSA-GPC (155 mm).
2) The presence of CSA increased the density of matrix, which reduced the number of voids and thus the air content in GPC.
3) The density of GPC increased by 0.51% with every 10% increase in the CSA content.
4) With up to 20% of CSA replacement binding among GPC ingredients was enhanced, resulting in a denser matrix structure with higher strength. However, with further substitution, strength declined due to formation of cracks and voids in GPC.
5) The water absorption and sorptivity tests results were directly related to the compressive strength. A denser structure with improved properties was produced due to the presence CSA, resulting in lower water absorption and sorptivity values.
6) CSA substitution also helped in improving the resistance against chloride ion penetration into GPC mixes. Yet, this was limited to 20% replacement.
7) A strong statistical relationship was discovered among fresh properties, compressive strength, and durability parameters.

Finally, it can be concluded that the CSA can be utilised as a substitution for natural sand (up to 20%) in the production of GPC as a sustainable construction material with the significantly lower than other studies.

CONFLICT OF INTERESTS

None.

ACKNOWLEDGMENTS

The authors wish to thank Raicon Labs Private Limited, Haryana, India for giving support to test the samples in their laboratory.

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