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Effect of Silica Fume on the Engineering Properties of Fly Ash-Based Geopolymer Concrete Using 100% Recycled Concrete Aggregate

Rudra Pratap Singh[1],*, Bijayananda Mohanty[2]

Abstract

Construction and demolition (C&D) waste has generated an enormous amount in developing countries like India due to explosive infrastructures and increasing urbanization, causing numerous concerns regarding the environment and economy. Recycling of aggregate from C&D debris is a beneficial approach to sustainable development and a circular economy. In contrast, numerous drawbacks of the integration of recycled concrete aggregates are due to adhered mortar remaining on their surfaces, reducing the strength compared to that obtained with natural aggregates (NA), inhibiting the extensive application of such concretes. This study assesses the viability of integrating 100% recycled concrete aggregates (RCA) into fly ash (FA) based geopolymer concrete (GPC) with the addition of silica fume (SF) cured at elevated temperatures (85°C). The present research examined the compressive strength, ultrasonic pulse velocity (UPV), water permeability, and rapid chloride penetration test (RCPT) of FA-based GPC with and without 100% RCA substituted to natural aggregate. The results showed that the properties of GPC diminished when RCA was used. Interestingly, adding SF showed a positive influence on the overall properties of GPC. The compressive strength decreased by about 24% with the inclusion of 100% RCA. On the other hand, adding SF (5-20%) enhanced the compressive strength by 7.5-22%. Conclusively, this research shows the feasibility of employing 100% RCA to produce GPC, providing a sustainable approach to converting waste to useful construction materials.

Keywords: Geopolymer concrete, recycled concrete aggregate, silica fume, compressive strength, chloride permeability

INTRODUCTION

Concrete is often utilized in the construction sector since it is simple to work with and adaptable to different shapes. The increasing global population and rising industry have led to rapid urbanization [1]. The construction industry has undergone enormous expansion globally; subsequently, the construction industry exploits substantial amounts of renewable assets and produces endless waste [2]. Concrete production requires massive raw materials and causes depletion of natural resources [3]. Hence, research must focus on finding ways to reduce the use of traditional cement and natural aggregate. Over the past several years, industrial by-products have been used as alternatives to cement. Several studies documented that industrial by-products such as fly ash, slag, and silica fume have great potential to substitute traditional cement [4-6], which must be used mainly in developing nations like India. Unlike conventional cement, these materials provide several environmental advantages, such as reduced carbon footprints, sustainably utilized waste, and conserving natural assets [7-10].

***Author for Correspondence**
Rudra Pratap Singh

[1]PhD Scholar, Department of Civil Engineering, National Institute of Technology, Mizoram, India
[2]Associate Professor, Department of Civil Engineering, National Institute of Technology, Mizoram, India

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The generation of construction and demolition (C&D) waste leads to significant troubles with storage and dumping in the ground, necessitating initiatives to mitigate the challenges of dumping issues and adverse environmental effects with sustainable utilization [11]. The investigators are looking at potential possibilities for the utilization of C&D wastes in concrete [12]. Among the many potential alternatives to natural aggregates, recycled aggregates derived from C&D debris are among the most abundant. The utilization of recycled aggregates provides beneficial ecological consequences. In contrast, numerous studies showed the drawbacks of recycled concrete aggregates [13]. For instance, adhered mortar remains on RCA surfaces, reducing the strength compared to that obtained with natural aggregates (NA), inhibiting the extensive application of such concretes [14]. RCA exhibits increased porosity and water absorption compared to NA [15].

Interestingly, using geopolymer binders, efforts have been undertaken in the published literature to address the unfavourable characteristics of recycled aggregate. To encourage the utilization of 100% RCA, Singh et al. [16] studied the utilization of FA, GGBS, and SF. In order to achieve the highest possible mechanical performance and environmental friendliness in geopolymer concrete, the authors attempted to optimize the combination of FA, GGBS, and SF proportions. The author also investigated the potential of ternary blended optimized FA, GGBS, and SF containing 100% recycled aggregates to mitigate the adverse impact of recycled aggregate against acid and sulphate resistance of GPC [17].

Research indicated that SF may decrease concrete's porosity and water absorption. Kurad et al. [18] recognized the potential to utilize RCA and FA to mitigate the adverse effects of its manufacturing phase without compromising the durability characteristics of concrete. Akthar et al. [19] indicated in their investigation that the characteristics of concrete with RCA improved positively when silica fume was utilized at concentrations ranging from 5% to 20%. Sasanipour et al. [20] utilized SF in their investigation to minimize the detrimental impacts influenced by RCA. Wang et al. [15] demonstrated that concrete containing up to 20% FA and 15% SF in a ternary blend had superior compressive strength. The current research aims to examine the impact of SF on the properties of FA-based GPC with 100% RCA cured at elevated temperatures. The behaviour of GPC incorporating SF was evaluated employing numerous criteria, including compressive strength, ultrasonic pulse velocity (UPV), water permeability, and chloride ingress.

METHODOLOGY AND TESTING

Class-F fly ash (FA) was obtained from Vindhyanchal Tarmal Power Station, Madhya Pradesh, India. The physical properties of binders were determined using standard testing protocols under IS: 4031-1988, 2005 [21]. The FA was used as the primary binder material with a specific gravity of 2.26, and the specific gravity of SF was 2.40. The average particle size of FA and SF was 21.04 and 8.0 μm, and the specific surface area was 2360 and 17600 cm^2/g. The oxide composition of FA and SF is depicted in Table 1, and Fig. 1 illustrates the morphology of FA and SF. Showing that FA particles predominantly exhibit a spherical shape, whereas SF possesses an irregular shape with sharp edges. The 12M sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solutions (14.7% Na_2O, 29.4% SiO_2, and 55.9% H_2O) were used to prepare the alkaline solution as an alkali activator. The ratio of Na_2SiO_3/NaOH is 2.0. River sand was used as fine aggregate with a fineness modulus of 2.64, and RCA was used as a coarse aggregate to substitute for natural aggregates. The obtaining process and characteristics of RCA were reported in a previous study [16].

In this study, the six mixed proportions of FA-based GPC incorporating SF (0-20%) at 5% intervals, with and without RCA. The Na_2SiO_3 and NaOH were taken to be 146 kg/m^3 and 74 kg/m^3, and solution/binder ratios were 0.5 for all mixes. Initially, the fly ash (440 kg/m^3), RCA (1148 kg/m^3), and fine aggregate (586 kg/m^3) were mixed in the dry state for 2-3 minutes, and then the alkali solution was added and mixed for the next 3-4 minutes until the mixture looked homogeneous and consistent. Finally, the fresh GPC was filled in the 150mm^3 cube mould and then cured at elevated temperature (80°C) for 24 hours in the oven. After that, the specimens were demoulded and kept at ambient temperature until the age of testing (28 days). The production process of GPC is illustrated in Figure 2.

The slump cone test was carried out to measure the workability of fresh GPC mixtures as per the guidelines of ASTM C143/C143M-09 [22]. The compressive strength of GPC specimens was determined at 28 days of curing period in accordance with IS 516-1959 [23] using the 2000 kN capacity of the CTM machine. As per the IS 13311-1 [24], the ultrasonic pulse velocity (UPV) test was performed to assess the homogeneity and integrity of the concrete structure. The water permeability test was conducted on 150 mm^3 specimens placed in a water permeability machine under the guidelines of IS 516-2 [25]. The water was applied forcefully on the top surface of the specimens for 72 hours at a constant pressure of 0.5 N/mm^2. After 48 hours, the sample was taken out and split into two parts to measure the water penetration depth. The rapid chloride penetration test (RCPT) was performed according to the ASTM C1202 [26] to evaluate the chloride permeability and measure the depth of penetrated chloride.

RESULTS AND DISCUSSION

Workability

The slump cone test determined the workability of FA-based GPC with and without RCA mixes incorporating SF. When the NA was substituted with the RA, the workability diminished by 12% due to adhered mortar on the surface of the RA, which required more liquid than the NA, as shown in Figure 3. A similar finding was reported regarding the impact of RA on the rheological behaviours of GPC [16]. Moreover, the slump value decreased by 4.5, 9.2, 13.6, and 22.7%, with the substitution of FA with SF by 5, 10, 15, and 20%. The reduction in the flowability of geopolymer due to the addition of silica fume was attributed to the greater specific surface area of silica fume, leading to inadequate water for particle wetting [27]. Similarly, Okoye et al. [28] indicated that the slump of fly ash-based geopolymer concrete diminished by incorporating silica fume. Ou et al. [29] showed that substituting 10% of slag with silica fume in slag-based geopolymer concrete reduced its slump from 190 mm to 185 mm. Zhang et al. [30] observed that the slump flow consistently diminished when the silica fume level increased from 5% to 25%.

On the contrary, some contradictory results were also documented in earlier studies. According to Liu et al. [31], the workability might be enhanced by including 10% to 25% silica fume. Wetzel et al. [32] found that workability substantially improved with the addition of 12.5% silica fume. As far as the component list goes, silica fume is crucial. The impact of silica fume on the rheological properties of geopolymer systems is mainly regulated by interparticle repulsion or attraction. The working properties of the material could be enhanced with an adequate amount of silica fume, owing to its lubricating properties and the alteration of the activator characteristic induced by its quick dissolution [33].

Table 1. Chemical composition of FA and SF.

Chemical composition (%)	FA	SF
SiO_2	54.91	93.74
Al_2O_3	28.72	0.19
CaO	2.36	0.40
MgO	0.37	0.17
Fe_2O_3	3.05	0.95
Na_2O	0.00	0.00
SO_3	0.12	0.34
K_2O	1.34	0.62
TiO_2	2.95	0.48
SrO	0.39	0.34
P_2O_5	0.48	1.10
MnO	0.04	0.73

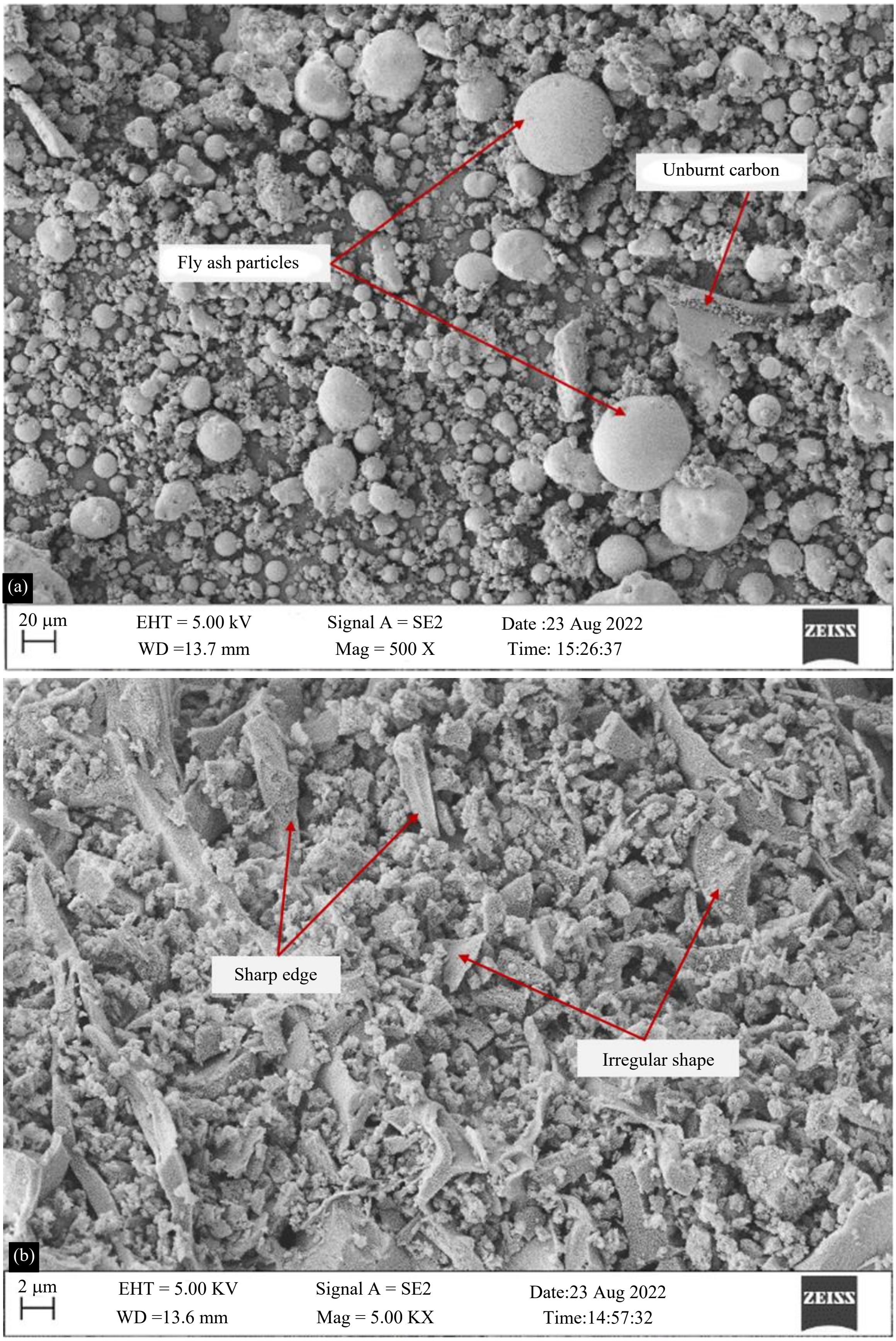

Figure 1. SEM Images of a) FA and b) SF.

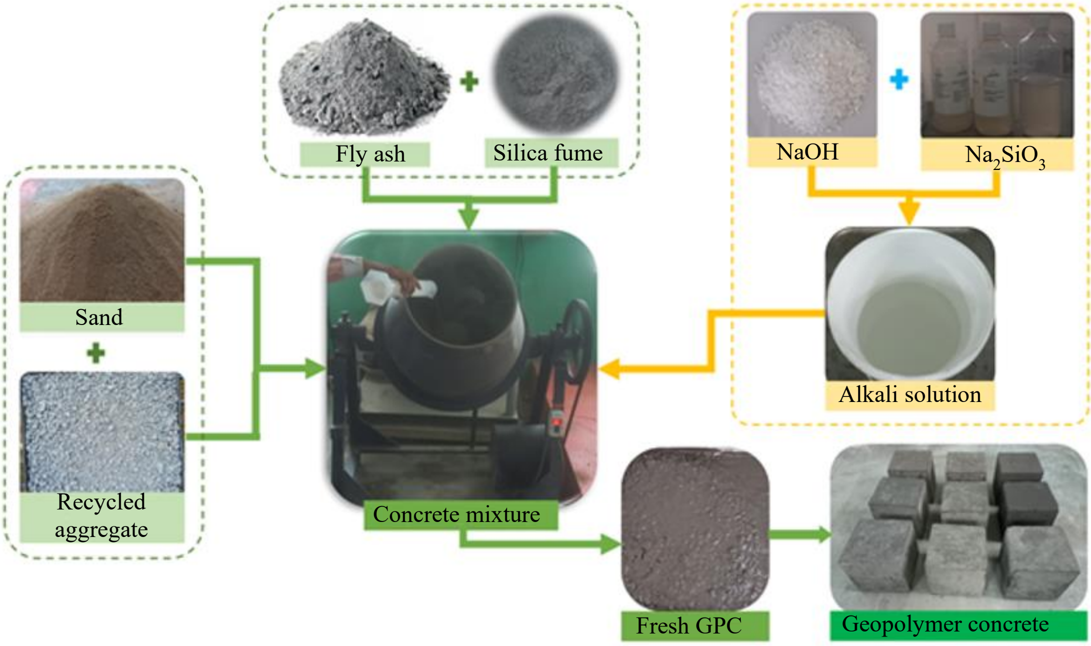

Figure 2. Process for the preparation of GPC.

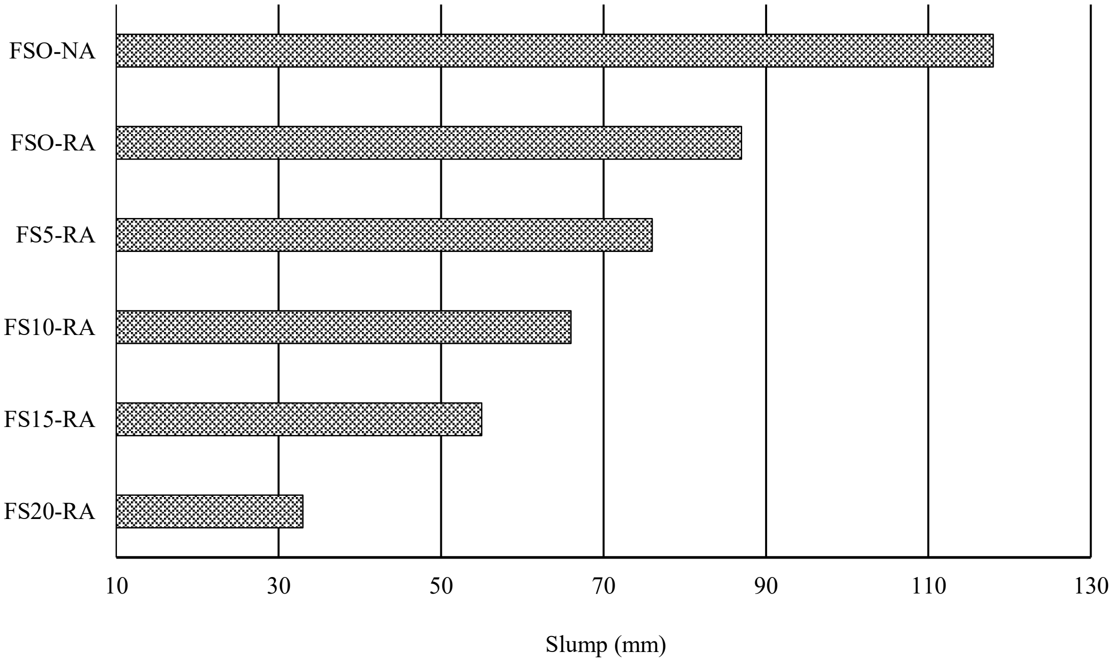

Figure 3. Slump of GPC with RCA and SF.

Compressive Strength and Ultrasonic Pulse Velocity

The compressive strength of FA-based GPCs incorporating SF with 100% RCA was determined at 28 days of curing period. As shown in Figure 4, the compressive strength was reduced by 24% with the replacement of NA by RA. However, the strength improved by 7.5, 18.4, 24.8, and 22.2%, incorporating 5, 10, 15, and 20% SF in FA-based GPC containing RCA. Using an adequate amount of SF in the FA-based GPC enhances the geopolymerization process, and the strength performance improves because SF is a highly reactive pozzolanic material that has greater strength due to the formation of aluminosilicate gel [28]. Jena et al. [34] reported that blending silica fume with fly ash in geopolymer concrete improves strength, reaching up to 42.6 MPa at 70°C curing temperature. Silica fume-modified geopolymer concrete achieved a compressive strength of 59.59 MPa after 28 days [35]. Adding silica fume improves the compressive strength of fly ash-based geopolymer concrete. This enhancement is attributed to the refinement of the pore structure and the microstructure optimization, which increases the material's density and strength [36].

The UPV test is utilized to assess the homogeneity, quality, and structural integrity of hardened concrete [37]. The influence of RA and SF on the UPV of FA-based GPC samples is illustrated in Figure 4. Similar to the compressive strength results, the UPV decreased (24.7%) when replacing the NA with RCA, but was enhanced by adding SF up to 15%, after which it began to decline. This enhancement was 9.2, 21.5, 27.2, and 23.7% by adding 5, 10, 15, and 20% SF. The 10-20% of SF showed significant results when using 100% RCA in FA-based GPC, and it is a good quality of concrete as per the designated range for UPV value according to the IS 13311-1 [24]. Gupta et al. indicated that incorporating 10% silica fume into GGBS-based GPC enhanced UPV values, signifying reduced voids and filling empty spaces with the fine grains of silica fume. Singh et al. [37] reported that the incorporation of 20% WGP in FA-GGBS-based GPC enhanced the UPV value by 23%. Compressive strength and Ultrasonic Pulse Velocity (UPV) are intimately associated; thus, concrete with greater compressive strength typically exhibits greater UPV.

Water Permeability and RCPT

The water permeability and rapid chloride penetration tests (RCPT) of GPC specimens were evaluated after 28 days of curing period, and test results are presented in Figure 5. Permeability properties are directly related to the other durability aspects of concrete. Results indicated that, by incorporating RCA instead of NA, the water penetration depth is increased from 12mm to 20mm. The permeability increased with RCA in GPC is related to the development of the voids and pores due to adhesive mortar in the surface of RCA, which creates the double interfacial zone among the paste and RA [16]. Interestingly, SF plays a vital role in compensating for the adverse impact of RA due to its pozzolanic reaction and fineness of particles. Incorporating 5, 10, 15, and 20% of SF, reducing the depth of water penetration to 17, 14, 13, and 15mm, respectively. Reactive silica from silica fume can substantially improve microstructural refinement by efficiently reducing water permeability in the initial phase. This effect was equally significant at prolonged periods [38]. However, over 15% of SF shows negative results due to excessive SF content, resulting in a very high Si/Al ratio [37]. Although the GPC specimens containing RA had a water penetration depth below 30 mm, they were classified as having low permeability according to the permeability criteria designated by IS:516 (part 2) [25].

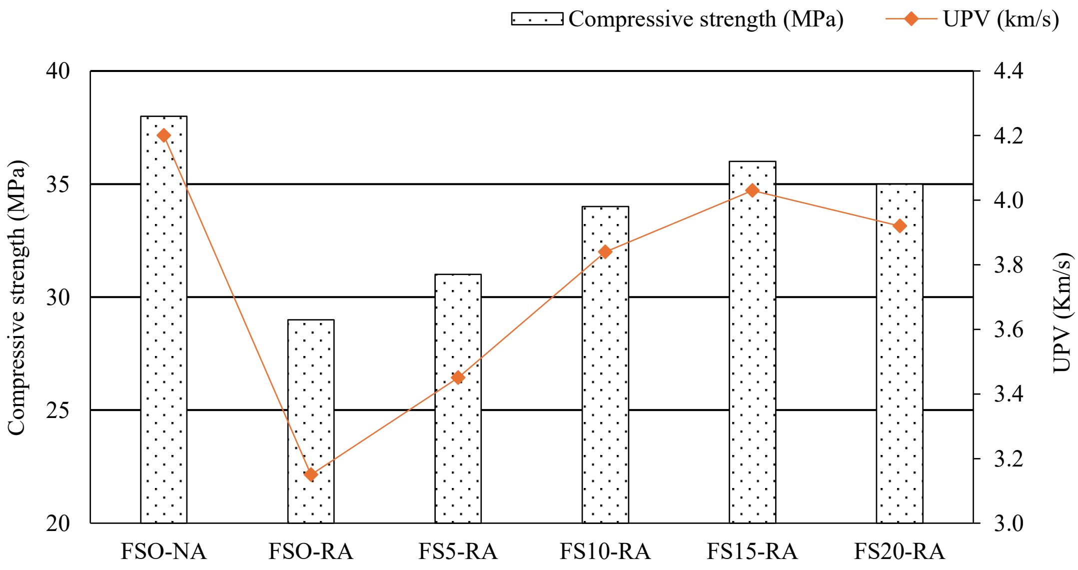

Figure 4. Compressive strength and UPV of GPC with RCA and SF.

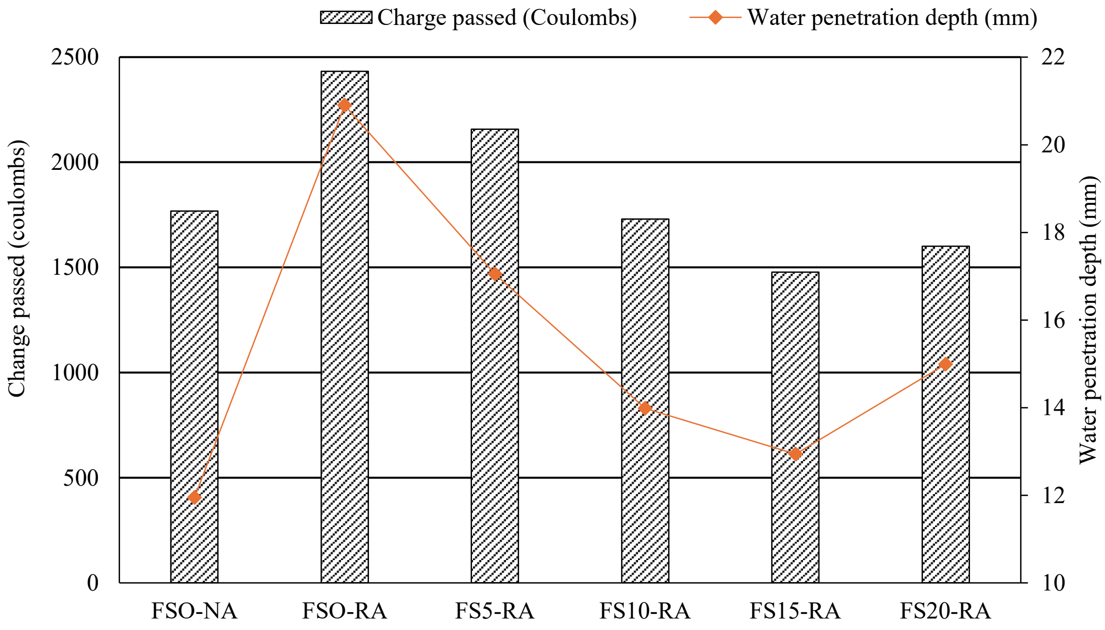

Figure 5. Chloride penetration and water permeability of GPC specimens with RCA and SF.

Chloride ion penetration plays a major role in the deterioration of reinforced structures, which comprises pavements, bridges, and offshore platforms. The chloride ingress accelerates the corrosion of embedded steel bars used as GPC reinforcing bars [39]. The chloride permeability of the FA-GPC, containing RCA and incorporating 0-20% of SF, was evaluated using the RCPT method. The test results at 28 days showed that chloride permeability increased by about 37.6% when NA was replaced with the RCA. However, adding 5, 10, 15, and 20% of SF reduced the chloride permeability by 11, 28.3, 38.8, and 33.7% compared to that without SF in GPC with 100% RCA. The SF-15% in GPC containing RCA had the lowest chloride permeability. Liu et al. [40] indicated that incorporating silica fume into fly ash/slag alkali-activated materials refines microstructures and diminishes mesopore volume due to the presence of reactive SiO_2, which facilitates gel formation and enhances chloride resistance. Silica fume may significantly improve the resistance of the water and the rapid chloride permeability of concrete [38]. However, continuously increasing the SF content beyond 15% led to a subsequent increase in the charge passed. Due to the excessive amount of SF, the development of a strong aluminosilicate gel was hindered, and structural integrity was negatively impacted because Si was raised and Al was significantly lowered [16]. Consequently, the matrix turned weaker, and ions were transported into the concrete significantly faster. For comparison, Mehta and Siddique [41] reported that the chloride permeability decreased when RHA was utilized as a replacement for GGBS by up to 15%; thereafter, it increased. The strength reduction was another indicator of the degradation of structural integrity. These findings demonstrate that replacing FA with SF enhances corrosion resistance and reduces degradation caused by chloride penetration in GPC containing recycled aggregate. Incorporating SF into concrete enhanced its microstructure, promoting hydration and pozzolanic reaction, resulting in decreased chloride permeability [28].

CONCLUSION

This study experimentally assessed the impact of substituting FA with silica fume at different ratios on the fresh and hardened characteristics of FA-based GPC utilizing 100% recycled aggregate, cured at elevated temperatures (85°C) for 24 hours. Numerous substantial conclusions were derived from the test results:

- The compressive strength of GPC decreased by 23.9% by adding 100% RCA, and monotonically improved from 7.5-22.1% by increasing SF levels by up to 15%.

- UPV of GPC was reduced by 24.7% including 100% RCA, and dramatically increased by 9-23.7% with the addition of silica fume from 5-20%, compared to the reference specimens.
- The water permeability was reduced by increasing SF by up to 15%; it decreased from 20mm to 13mm for optimized specimens, i.e., FS15-RA, compared to the control specimen (FS0-RA).
- Similarly, chloride permeability was reduced with increasing SF up to 15%; the maximum reduction of 38.8% was observed for the optimized (i.e., FS15-RA) sample compared to the FS0-RA.
- SF improved the packing density of GPC matrix by forming additional C-S-H and C-(N)-A-S-H products, and reaction product development became more robust, which compensated for the adverse impact of RCA.
- The offered GPC option to traditional concrete is incredibly adaptable and effectively works with the envisioned sustainability aims of businesses engaged in sustainable construction approaches. Today's problems with waste management, climate change, and durability are all directly addressed with geopolymer concrete. When combined with digital construction technology, the circular economy, and smart city projects, it will eventually emerge as a key component of sustainable infrastructure.

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