

Influence of Mix Design Parameters on the Fresh and Compressive Strength of Steel Fiber-Reinforced Self-Compacting Geopolymer Concrete

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Abstrak

Self-Compacting Geopolymer Concrete (SCGC) merupakan alternatif ramah lingkungan pengganti beton berbasis semen Portland (*Ordinary Portland Cement*, OPC) karena menggabungkan keunggulan bahan pengikat geopolimer dengan kemampuan alir yang tinggi. Penelitian ini bertujuan mengkaji pengaruh rasio air terhadap bahan pengikat (W/B), rasio aktivator alkali terhadap *fly ash* (AAS/FA), dan dosis *superplasticizer* terhadap kinerja beton segar dan kuat tekan SCGC berbasis *fly ash* yang diperkuat 1% serat baja lurus pada kondisi perawatan suhu ruang. Dua formulasi campuran diuji. Sifat beton segar dievaluasi menggunakan pengujian *slump flow*, *V-funnel*, dan *L-box* sesuai EFNARC (2005), sedangkan kuat tekan diuji pada umur 7, 28, dan 56 hari berdasarkan ASTM C39. Campuran SCGC-B (W/B = 0,075; AAS/FA = 0,35; *superplasticizer* = 4,5%) menunjukkan kinerja terbaik dengan nilai *slump flow* 705 mm, waktu alir *V-funnel* 9 detik, rasio *L-box* 0,89, serta kuat tekan 15,08 MPa, 26,40 MPa, dan 33,52 MPa pada umur 7, 28, dan 56 hari. Hasil penelitian menunjukkan bahwa optimasi komposisi campuran menghasilkan SCGC mutu struktural yang memenuhi persyaratan EFNARC pada kondisi *ambient curing*. Selain itu, penelitian ini memberikan dasar eksperimental bagi pengembangan dan optimasi beton geopolimer berkelanjutan berbasis *fly ash* Kelas F lokal.

Abstract

Self-compacting geopolymer concrete (SCGC) is a sustainable alternative to ordinary Portland cement (OPC)-based concrete because it combines the environmental benefits of geopolymer binders with the superior workability of self-compacting concrete. This study investigated the effects of the water-to-binder (W/B) ratio, alkaline activator-to-fly ash (AAS/FA) ratio, and superplasticizer dosage on the fresh and compressive strength performance of fly ash-based SCGC reinforced with 1% straight steel fibers under ambient curing conditions. Two mixture formulations were evaluated. Fresh properties were assessed using slump flow, V-funnel, and L-box tests in accordance with EFNARC (2005), while compressive strength was determined at 7, 28, and 56 days. SCGC-B (W/B = 0.075, AAS/FA = 0.35, superplasticizer = 4.5%) exhibited the best performance, achieving a slump flow of 705 mm, a V-funnel flow time of 9 s, an L-box ratio of 0.89, and compressive strengths of 15.08, 26.40, and 33.52 MPa at 7, 28, and 56 days, respectively. The results demonstrate that optimizing mixture composition enables the production of structural-grade SCGC satisfying EFNARC requirements under ambient curing conditions. This study also provides an experimental basis for the development and optimization of sustainable geopolymer concrete using locally available Class F fly ash.

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INTRODUCTION

The construction industry is one of the major contributors to global greenhouse gas emissions because of its extensive dependence on ordinary Portland cement (OPC). Cement production generates substantial carbon dioxide (CO₂) emissions through limestone calcination and energy-intensive manufacturing processes, prompting the development of environmentally sustainable cementitious materials. Among the available alternatives, self-compacting geopolymer concrete (SCGC) has attracted considerable attention because it combines the environmental advantages of geopolymer binders with the superior workability of self-compacting concrete. The utilization of industrial by-products such as Class F fly ash as the primary aluminosilicate precursor significantly reduces Portland cement consumption while promoting sustainable construction and carbon emission mitigation (Ghafoor & Fujiyama, 2023; Ghafoor et al., 2021; Moodi et al., 2025; Kumar et al., 2025).

Unlike OPC concrete, geopolymer concrete develops its binding matrix through the alkali activation of aluminosilicate materials, producing sodium aluminosilicate hydrate (N-A-S-H) gel as the primary reaction product. This geopolymerization process generates a dense microstructure with excellent chemical stability and high resistance to sulfate attack, chloride penetration, and aggressive environments. Furthermore, previous life-cycle assessment studies have demonstrated that fly ash-based geopolymer concrete can reduce greenhouse gas emissions by approximately 40–60% compared with conventional OPC concrete while maintaining satisfactory engineering performance (Samuel et al., 2020; Kumar et al., 2025; Sbahieh et al., 2023).

Despite these advantages, geopolymer concrete generally exhibits relatively brittle behavior and limited tensile capacity. The incorporation of steel fibers has therefore been widely adopted to improve crack resistance, toughness, and post-cracking behavior through crack-bridging mechanisms. Numerous studies have reported significant improvements in compressive, tensile, and flexural strengths after steel fiber addition. However, increasing the fiber dosage generally reduces workability because fibers increase internal friction and obstruct the flow of fresh concrete, particularly in self-compacting systems. Consequently, achieving an appropriate balance between fresh concrete performance and mechanical properties remains one of the primary challenges in the development of steel fiber-reinforced SCGC (Dhanalakshmi et al., 2023; D. Wang et al., 2019; Rahimpour & Esmaili, 2025; Joshi & Sawant, 2025; Kumar et al., 2025).

The fresh and hardened performance of SCGC is governed by several mixture parameters, among which the water-to-binder (W/B) ratio, alkaline activator-to-fly ash (AAS/FA) ratio, and superplasticizer dosage are considered the most influential. These parameters control both the rheological behavior of fresh concrete and the geopolymerization process responsible for strength development. Fresh concrete performance is commonly evaluated using slump flow, V-funnel, and L-box tests in accordance with EFNARC (2005). Previous investigations have demonstrated that optimizing the interaction among these mixture parameters is essential for producing SCGC with satisfactory workability and mechanical performance (Ghafoor, Fujiyama, et al., 2021; Ghafoor & Fujiyama, 2022).

Although considerable progress has been achieved in the development of steel fiber-reinforced SCGC, several research gaps remain. Most previous studies have focused on optimizing individual mixture parameters, such as the activator composition, superplasticizer dosage, or fiber content, whereas the combined influence of the W/B ratio, AAS/FA ratio, and superplasticizer dosage has received relatively limited attention. Furthermore, studies utilizing locally available Indonesian Class F fly ash together with straight steel wire fibers under ambient curing conditions remain scarce. Consequently, comprehensive evaluations integrating fresh concrete performance and compressive strength development under practical curing conditions are still limited, despite their importance for structural applications (Pelisser et al., 2018; Onn et al., 2019; Sbahieh et al., 2023; Hafez et al., 2019).

To address these gaps, the present study systematically investigates the combined effects of the W/B ratio, AAS/FA ratio, and superplasticizer dosage on the fresh and compressive strength performance of steel fiber-reinforced SCGC under ambient curing conditions. The novelty of this research lies in the combined evaluation of these key mixture parameters using locally available Indonesian Class F fly ash and straight steel wire fibers without heat curing. In addition, the study establishes an experimental database that can support future mixture optimization, microstructural characterization, and durability investigations.

Accordingly, this study aims to evaluate the influence of mixture composition on the fresh and compressive strength performance of steel fiber-reinforced SCGC. Fresh concrete properties were evaluated using slump flow, V-funnel, and L-box tests in accordance with EFNARC (2005), while compressive strength was determined after 7, 28, and 56 days. The findings are expected to provide practical guidance for the development of sustainable structural geopolymer concrete utilizing locally available industrial by-products.

MATERIALS AND METHODS

Materials and Mix Design

Natural fine and coarse aggregates, Class F fly ash, alkaline activators, a polycarboxylate ether (PCE)-based superplasticizer, and straight steel wire fibers were used in this study. Fine and coarse aggregates were obtained from local quarries in Central Java, Indonesia, and characterized in accordance with the relevant ASTM and Indonesian National Standards (SNI). Class F fly ash collected from the Tanjung Jati coal-fired power plant, Jepara, Indonesia, was used as the geopolymer precursor.

The alkaline activator consisted of a 14 M sodium hydroxide (NaOH) solution and commercial sodium silicate (Na_2SiO_3) with a $\text{Na}_2\text{SiO}_3/\text{NaOH}$ mass ratio of 2.5. A polycarboxylate ether (PCE)-based superplasticizer (Consul SS-8) was used to improve the workability of the geopolymer mixtures. Straight steel wire fibers with a length of 25 mm, an average diameter of approximately 0.5 mm, and an aspect ratio of approximately 50 were incorporated at a constant dosage of 1% by concrete volume.

Concrete mixtures were designed using the absolute volume method for 1 m³ of concrete. Two mixture formulations (SCGC-A and SCGC-B) were prepared to investigate the combined effects of the water-to-binder (W/B) ratio, alkaline activator-to-fly ash (AAS/FA) ratio, and superplasticizer dosage on the fresh and compressive strength performance of steel fiber-reinforced self-compacting geopolymer concrete under ambient curing conditions. To isolate the influence of the investigated variables, the alkaline activator dosage (10% of binder mass), NaOH concentration (14 M), $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio (2.5), and steel fiber content (1% by volume) were maintained constant for all mixtures. The mixture proportions and experimental variables are summarized in Table 1.

Table 1. Mixture Proportions and Experimental Variables of SCGC Mixtures

Mixture	W/B	AAS/FA	SP (%)
SCGC-A	0.15	0.40	2.5
SCGC-B	0.075	0.35	4.5

Concrete specimens were prepared at PT. Kembar Jaya Mandiri Mulya, Demak, Indonesia. Cylindrical specimens (150 mm × 300 mm) were used for compressive strength testing. Three specimens were tested for each mixture at curing ages of 7, 28, and 56 days, resulting in a total of 18 specimens.

Test Methods

Fresh concrete properties were evaluated in accordance with EFNARC (2005) using the slump flow, V-funnel, and L-box tests to determine flowability, viscosity, and passing ability, respectively.

Compressive strength was determined using cylindrical specimens (150 mm × 300 mm) after 7, 28, and 56 days of ambient curing. Three specimens were tested at each curing age, and the average compressive strength and standard deviation were calculated.

RESULTS AND DISCUSSION

The fresh properties of self-compacting geopolymer concrete (SCGC) were evaluated through the slump flow, V-funnel, and L-box tests following the recommendations of EFNARC (2005). These tests collectively represent the flowability, viscosity, filling ability, and passing ability of self-compacting concrete, which are essential parameters for ensuring adequate placement without external vibration.

Table 2. Fresh properties of SCGC mixtures and comparison with EFNARC (2005) requirements

Parameter	SCGC-A	SCGC-B	(EFNARC, 2005) Requirement
Slump flow test (mm)	660 (Complies with SF2)	705 (Complies with SF2)	SF1: 550–650 SF2: 660–750 SF3: 760–850
V-funnel test (detik)	16 (Complies with SF2)	9 (Complies with VF2)	VF1: ≤ 8 VF2: 9–25
L-box test	0,73 (Does not comply)	0,89 (Complies)	PA1: ≥ 0,80 (2 reinforcing bars) PA2: ≥ 0,80 (3 reinforcing bars)

The experimental results indicate that both SCGC mixtures satisfied the EFNARC slump flow requirement for the SF2 class, with average slump flow values of 660 mm for SCGC-A and 705 mm for SCGC-B. Although both mixtures exhibited satisfactory filling ability, SCGC-B demonstrated noticeably higher flowability despite possessing a significantly lower water-to-binder ratio. This observation indicates that the increased dosage of the polycarboxylate ether (PCE)-based superplasticizer effectively compensated for the reduced free-water content by improving particle dispersion and minimizing interparticle friction. Similar behavior has been reported by (Ghafoor, Fujiyama, et al., 2021) and (Ghafoor & Fujiyama, 2022), who demonstrated that PCE-based superplasticizers remain highly effective in geopolymer systems containing highly alkaline activator solutions.

The V-funnel test further confirmed the improved rheological characteristics of SCGC-B. The discharge time decreased from 16 s for SCGC-A to 9 s for SCGC-B while remaining within the VF2 classification specified by EFNARC (2005). Lower V-funnel flow time indicates reduced plastic viscosity and more efficient movement of the fresh mixture through confined spaces. The improvement can be attributed to enhanced lubrication between fly ash particles resulting from the higher superplasticizer dosage. Previous investigations have similarly reported that PCE-based admixtures effectively reduce viscosity without inducing segregation when appropriate dosages are employed (Ghafoor, Fujiyama, et al., 2021).

The most significant improvement was observed in the L-box test. SCGC-A produced an H_2/H_1 ratio of 0.73, which failed to satisfy the minimum EFNARC requirement (≥ 0.80), whereas SCGC-B achieved a ratio of 0.89, indicating satisfactory passing ability through reinforcing bars. The improved performance of SCGC-B suggests that the optimized rheological characteristics successfully reduced blocking caused by the presence of steel fibers. Adequate particle dispersion promoted more uniform flow through restricted openings, thereby enhancing the self-compacting capability of the mixture.

Overall, the fresh property results demonstrate that the simultaneous reduction of the W/B ratio and increase in superplasticizer dosage successfully produced a balanced rheological performance. Despite the lower water content, SCGC-B exhibited superior flowability, lower viscosity, and

improved passing ability compared with SCGC-A. These findings confirm that optimizing the interaction between mixture composition and chemical admixtures is essential for maintaining the self-compacting characteristics of steel fiber-reinforced geopolymer concrete, particularly when low water contents are employed to enhance mechanical performance (Kumar et al., 2025).

Compressive Strength Development

Figure 3 illustrates the evolution of compressive strength for both SCGC mixtures at curing ages of 7, 28, and 56 days. Regardless of mixture composition, compressive strength increased continuously throughout the curing period, confirming that geopolymerization remained active under ambient curing conditions. Nevertheless, SCGC-B consistently produced higher compressive strength than SCGC-A at every testing age, indicating that optimization of the W/B ratio, AAS/FA ratio, and superplasticizer dosage substantially improved mechanical performance.

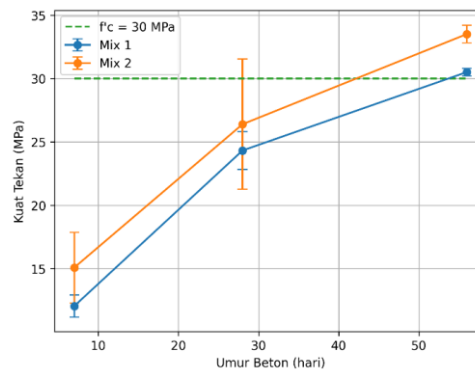


Figure 1. Development of compressive strength of SCGC mixtures under ambient curing conditions

At 7 days, SCGC-A achieved an average compressive strength of 12.07 MPa, whereas SCGC-B reached 15.08 MPa, corresponding to an increase of approximately 25%. This improvement is primarily attributed to the lower W/B ratio adopted in SCGC-B, which reduced capillary porosity and enhanced the packing density of fly ash particles. Similar observations were reported by (Nath & Sarker, 2013) and (Ghafoor, Khan, et al., 2021), who demonstrated that reducing excess water facilitates the formation of a denser aluminosilicate network during the early stages of geopolymerization.

The compressive strength continued to increase at 28 days, reaching 24.35 MPa for SCGC-A and 26.40 MPa for SCGC-B. This gradual strength development differs from conventional Portland cement concrete because geopolymer concrete continues forming additional N-A-S-H gel through ongoing dissolution of aluminosilicate particles. Consequently, matrix densification continues beyond the early curing period, leading to progressive improvements in mechanical performance (Yun-Ming et al., 2012; Nath & Sarker, 2013).

The highest compressive strengths were obtained after 56 days, where SCGC-A and SCGC-B achieved 30.52 MPa and 33.52 MPa, respectively. Both mixtures exceeded the target design strength of 30 MPa, confirming that structural-grade self-compacting geopolymer concrete can be successfully produced under ambient curing conditions. The superior performance of SCGC-B demonstrates that simultaneous optimization of the W/B ratio, alkaline activator content, and superplasticizer dosage effectively improves compressive strength while preserving satisfactory fresh concrete performance.

The strength gain between 28 and 56 days was approximately 25–27% for both mixtures, indicating that geopolymerization remained active during the later curing period. Unlike OPC concrete, where hydration gradually decreases after 28 days, fly ash-based geopolymer concrete continues to develop additional aluminosilicate gel, producing a progressively denser microstructure. Similar long-term strength development has been reported by (Rehman & Kim, 2021).

The relatively small standard deviations obtained from repeated testing indicate good mixture homogeneity and satisfactory repeatability of the experimental procedure. Although minor variations were observed during early-age testing, they did not alter the overall trend of continuous strength development. Comparable experimental variability has been reported by (Dhanalakshmi et al., 2023), who attributed such variations primarily to differences in fiber orientation and distribution within the geopolymer matrix.

From a mechanistic perspective, the superior performance of SCGC-B resulted from the synergistic interaction among the three investigated mixture parameters. The lower W/B ratio reduced pore volume within the hardened matrix, whereas the reduced AAS/FA ratio minimized excess activator solution that could otherwise increase porosity after evaporation. Simultaneously, the increased dosage of PCE-based superplasticizer enhanced particle dispersion, ensuring adequate workability despite the lower water content. Consequently, fly ash particles were more uniformly distributed, promoting more efficient geopolymerization and the formation of a denser N-A-S-H gel network. Similar mechanisms have been described by (Ghafoor, Khan, et al., 2021) and (Basha et al., 2023).

Furthermore, the incorporation of 1% straight steel fibers contributed to crack-bridging mechanisms that delayed microcrack propagation during compressive loading. Although steel fibers generally provide greater improvements in tensile and flexural behavior than in compressive strength, they enhance the integrity of the geopolymer matrix by redistributing stresses and reducing crack localization. Comparable findings have been reported by (Dhanalakshmi et al., 2023), (Joshi & Sawant, 2025), and (Kumar et al., 2025).

Overall, the compressive strength results demonstrate that careful optimization of mixture parameters enables the production of steel fiber-reinforced SCGC possessing both satisfactory workability and structural-grade compressive strength under ambient curing conditions.

CONCLUSIONS

This study investigated the combined influence of the water-to-binder (W/B) ratio, alkaline activator-to-fly ash (AAS/FA) ratio, and superplasticizer dosage on the fresh and compressive strength performance of steel fiber-reinforced self-compacting geopolymer concrete (SCGC) under ambient curing conditions. The results demonstrated that optimizing these mixture parameters significantly improved both fresh concrete properties and compressive strength. Among the investigated mixtures, SCGC-B exhibited the best overall performance by satisfying all EFNARC (2005) requirements while achieving the highest compressive strength under ambient curing conditions.

The continuous increase in compressive strength up to 56 days confirmed that geopolymerization remained active beyond the conventional curing period, indicating that structural-grade SCGC can be successfully produced without heat curing. Furthermore, the successful use of locally available Indonesian Class F fly ash demonstrates its potential as a sustainable alternative to ordinary Portland cement for self-compacting concrete applications.

Although the present work was limited to two mixture formulations, it provides an experimental basis for the development and optimization of sustainable SCGC. Future studies should employ broader experimental designs and investigate additional mechanical properties, durability performance, and microstructural characteristics to support the development of practical mixture design guidelines.

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