JNEST EISSN: 2961-8738 ● PISSN: 2961-8916 ● DOI: 10.56741/jnest.v5i03.2193 238
Article Received 28 March 2026, Revised 28 August 2026

# Early-Age Strength Development and Ultimate Mechanical Performance of Ternary Blended Self-Compacting Concrete

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***Abstract*—Portland cement production contributes significantly to global carbon emissions, encouraging the development of sustainable Self-Compacting Concrete (SCC) incorporating Supplementary Cementitious Materials (SCMs). This study investigated fresh properties, early-age strength development, and 28-day mechanical performance of ternary SCC blends containing Ground Granulated Blast-Furnace Slag (GGBFS) and fly ash. Workability was evaluated using slump flow and flow-time tests, while mechanical performance was assessed through strength testing. Results showed that 40% GGBFS reduced flowability, whereas incorporating 10–20% fly ash improved workability within SF1–SF2 classes through its spherical particle morphology and ball-bearing effect, maintaining adequate viscosity (VS2) without segregation. The G20-F20 mixture, containing 20% GGBFS and 20% fly ash, achieved the highest 28-day compressive strength of 41.08 MPa, representing a 22.02% improvement over the control. However, SCM replacement exceeding 40% reduced binder efficiency and compressive strength. The highest flexural strength, 7.54 MPa, was obtained with the G20-F0 mixture, potentially reflecting improved interfacial transition zone characteristics through pozzolanic and latent hydraulic reactions. These findings suggest that conventional predictive models, including ACI 318, may underestimate flexural performance. Overall, the optimized ternary blend with 40% SCM replacement demonstrated a favorable balance between workability, mechanical performance, and reduced cement consumption. This study contributes to sustainable concrete development by identifying suitable GGBFS–fly ash combinations for high-performance construction applications.**

***Index Terms*— Flexural Strength, Fly Ash, Ground Granulated Blast-Furnace Slag (GGBFS), Interfacial Transition Zone (ITZ), Self-Compacting Concrete (SCC), Ternary Blend.**

## I. Introduction

Concrete remains one of the most widely used construction materials because of its versatility, mechanical performance, durability, and economic efficiency. However, conventional concrete generally requires mechanical vibration to achieve adequate consolidation, particularly in structural elements with congested reinforcement. Inadequate vibration may result in incomplete compaction, increased void content, and non-uniform material properties. Self-Compacting Concrete (SCC) was developed to overcome these limitations by providing sufficient flowability, passing ability, and segregation resistance to allow concrete to fill formwork and consolidate under its own weight without external vibration. These characteristics improve construction efficiency, placement quality, and working conditions, particularly in densely reinforced structural members. The fresh-state performance of SCC is commonly evaluated through parameters such as slump flow diameter, flow time, V-funnel flow time, and L-box passing ability, as recommended by the European Guidelines for Self-Compacting Concrete [1].

Despite these advantages, SCC commonly requires a high volume of powder materials to achieve the rheological stability necessary for self-compaction. Consequently, the extensive use of Portland cement may increase environmental impacts associated with carbon emissions and energy consumption during cement production. The growing demand for sustainable construction materials has encouraged the incorporation of Supplementary Cementitious Materials (SCMs) as partial cement replacements. Among various SCMs, fly ash (FA) and Ground Granulated Blast Furnace Slag (GGBFS) have received considerable attention due to their availability, pozzolanic/hydraulic characteristics, and potential contribution to fresh, mechanical, and durability properties of concrete [2]–[4].

Fly ash is widely used in SCC because its fine and spherical particles can improve particle packing and reduce internal friction between cementitious particles, thereby enhancing flowability and stability of fresh concrete. Hameed et al. demonstrated that fly ash can effectively function as a viscosity-modifying component in SCC by improving flow characteristics while maintaining segregation resistance [5]. Similarly, previous studies have reported that the incorporation of fly ash can improve the workability of SCC, although excessive replacement levels may reduce early-age strength due to slower pozzolanic reactions compared with Portland cement hydration [5]–[6].

In contrast, GGBFS possesses latent hydraulic properties and contributes to strength development through secondary hydration reactions. The incorporation of GGBFS can refine the microstructure of cementitious composites through additional formation of calcium silicate hydrate (C–S–H) products, resulting in improved later-age mechanical performance and durability. However, the influence of GGBFS is strongly dependent on its replacement level, fineness, chemical composition, and interaction with other binder components [7]–[8]. Previous investigations have shown that moderate GGBFS replacement levels may enhance compressive and flexural strength, whereas excessive replacement may lead to reduced early-age strength due to insufficient Portland

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cement hydration products [9]–[10].

The combined utilization of FA and GGBFS in ternary binder systems has attracted significant research interest because their complementary characteristics may provide a balance between workability, early-age strength development, and later-age mechanical performance. Fly ash contributes mainly through particle morphology and delayed pozzolanic reaction, while GGBFS provides additional hydraulic activity and calcium-rich compounds that accelerate later-age strength development [11]. Qu et al. investigated concrete containing different proportions of FA and GGBFS and reported that SCM incorporation significantly affected compressive, tensile, and flexural strength development depending on replacement level and curing age [11]. Their findings indicate that the mechanical response of SCM-based concrete cannot be generalized solely based on cement replacement percentage because the interaction between different SCMs plays an important role in strength evolution.

Although previous studies have confirmed the potential of FA and GGBFS as sustainable alternatives for Portland cement replacement, the optimum SCM replacement level remains dependent on mixture composition, binder characteristics, curing conditions, and targeted performance requirements. Differences in water-to-binder ratio, cement content, SCM proportion, particle characteristics, and chemical composition may result in different mechanical responses among studies. Therefore, the performance of FA–GGBFS-based SCC should not be evaluated solely based on the percentage of cement replacement, but also considering the interaction among binder components and the resulting hydration mechanisms.

Previous investigations have demonstrated that moderate GGBFS incorporation can improve the mechanical performance of SCC. Ofuyatan et al. reported that partial replacement of cement with GGBFS contributed to improved compressive and flexural strength, with approximately 20% GGBFS providing favorable mechanical performance [9]. Similarly, Sahoo et al. investigated SCC mixtures containing different GGBFS replacement levels and found that moderate GGBFS incorporation resulted in improved structural performance, while further increases in GGBFS content did not provide proportional strength enhancement [7]. These findings suggest that an optimum balance between Portland cement hydration and secondary hydration reactions from GGBFS is necessary to achieve enhanced mechanical properties.

However, the beneficial effects of SCM incorporation are not always consistent across different mixture systems. Elsayed et al. reported that incorporating FA and GGBFS in eco-friendly SCC could provide environmental benefits and improve fresh concrete characteristics, but excessive SCM replacement may negatively influence mechanical properties because of reduced Portland cement availability and slower hydration development [12]. Similarly, Abbas and Qureshi demonstrated that the mechanical response of SCC containing FA and GGBFS was strongly influenced by SCM proportion, indicating that increasing SCM content does not necessarily result in continuous improvement in strength performance [10]. These variations among previous studies highlight that the optimum FA–GGBFS combination is mixture-specific and requires evaluation based on the desired balance between sustainability and mechanical performance.

The interaction between FA and GGBFS is particularly important in ternary binder systems because both materials contribute through different reaction mechanisms. Fly ash generally contributes to long-term strength development through pozzolanic reactions, whereas GGBFS provides latent hydraulic activity that promotes additional hydration products at later curing ages. The simultaneous incorporation of these materials may generate synergistic effects through improved particle packing, reduced pore connectivity, and refinement of the cementitious matrix [8], [11], [13]. Blikharskyy et al. reported that the incorporation of SCMs can modify hydration kinetics and promote matrix densification through the formation of additional hydration products, contributing to improved hardened concrete properties [13].

Despite the advantages of ternary SCM systems, high-volume SCM replacement commonly results in slower early-age strength development compared with conventional Portland cement concrete. This behavior is primarily associated with the dilution effect caused by reduced clinker content and the slower reaction kinetics of supplementary materials during the initial curing period. Qu et al. reported that concrete containing FA and GGBFS exhibited different strength development patterns depending on SCM proportion and curing age, indicating that early-age and later-age strength responses should be evaluated separately [11]. Similarly, Pang et al. observed that high-volume fly ash SCC could achieve satisfactory long-term mechanical performance, although early-age strength development was delayed due to the slower pozzolanic contribution of fly ash [6].

Early-age strength development is particularly important for SCC applications because construction activities often depend on early demoulding, load transfer, and construction scheduling. However, many previous studies have focused primarily on 28-day compressive strength, while the transition of strength development from early curing ages to later ages remains less extensively evaluated. A comprehensive assessment of strength evolution at multiple curing ages is therefore necessary to determine whether ternary FA–GGBFS SCC mixtures experience delayed strength gain, continuous strength improvement, or limitations in early mechanical performance.

In addition to compressive strength, flexural strength represents an important parameter for evaluating concrete performance because it reflects resistance against tensile cracking and the quality of the hardened cement matrix. However, the relationship between compressive and flexural strength may become more complex when SCMs are incorporated because changes in hydration products, pore structure, and interfacial transition zone (ITZ) characteristics may influence these properties differently. Previous studies have demonstrated that modifications in binder composition through the incorporation of supplementary cementitious materials (SCMs), such as fly ash and GGBFS, can significantly influence the

mechanical response, including tensile-related properties and flexural performance of SCC mixtures [10], [14].

The development of empirical relationships between compressive and flexural strength is therefore challenging for SCM-based SCC systems. Although simple regression equations are commonly used in concrete engineering practice, their applicability may be limited when applied to mixtures with different SCM contents and hydration characteristics. Faraj et al. demonstrated that compressive strength prediction of environmentally friendly SCC containing GGBFS requires multiple input parameters, including binder composition, water-to-binder ratio, aggregate proportions, superplasticizer dosage, and curing age [15]. Similarly, Deneme developed a prediction model for fly ash SCC using a large dataset and demonstrated that strength development is influenced by several interacting parameters rather than a single material variable [16].

Consequently, a low correlation coefficient in a simple compressive–flexural relationship does not necessarily indicate poor mechanical behavior, but may reflect the complexity of SCM-based concrete systems and the limited number of mixtures used for model development. Asaad and Morcous emphasized that empirical prediction models may experience reduced accuracy when applied to SCC containing different SCM combinations because conventional equations may not adequately capture the influence of binder interactions and mixture characteristics [17]. Therefore, relationships between compressive and flexural strength developed from limited experimental datasets should be interpreted as mixture-specific correlations rather than universal prediction equations.

Based on these limitations, further investigation is required to clarify the combined effects of FA and GGBFS on fresh properties, early-age strength development, and ultimate mechanical performance of ternary SCC. In particular, the influence of different FA–GGBFS proportions on strength evolution from 1 to 28 days, flexural performance, and the applicability of compressive–flexural strength relationships require further investigation.

Therefore, this study investigates the performance of ternary blended self-compacting concrete incorporating fly ash and GGBFS as partial cement replacements. Nine concrete mixtures were evaluated, consisting of a Portland cement control mixture and SCM-modified mixtures with different FA and GGBFS proportions. The experimental program included fresh concrete evaluation through slump flow and measurements, compressive strength testing at 1, 3, 7, and 28 days, and flexural strength evaluation at 28 days.

The objectives of this study are: (1) to evaluate the influence of FA and GGBFS proportions on the fresh properties of SCC; (2) to investigate early-age and ultimate compressive strength development of ternary SCM-based SCC; (3) to evaluate the effect of ternary binder composition on flexural strength performance; and (4) to examine the relationship between compressive and flexural strength while identifying the limitations of empirical prediction for high-volume SCM-based SCC.

The contribution of this research lies in the systematic evaluation of ternary FA–GGBFS SCC mixtures across multiple curing ages while integrating fresh properties, compressive strength evolution, and flexural performance within a single experimental framework. The findings provide further insight into the optimization of high-volume SCM replacement by identifying the balance between sustainable cement reduction and mechanical performance enhancement.

### *A. Mix Proportions*

The experimental program consisted of nine concrete mix variations, including one control mixture (100% Portland cement) and eight ternary blend mixtures incorporating different percentages of GGBFS and fly ash. The mix design was formulated based on the absolute volume method to achieve the requirements of Self-Compacting Concrete (SCC). The total binder content (cement + GGBFS + fly ash) was kept constant at 600 kg/m³ for all mixtures. The water-to-binder (w/b) ratio was fixed at 0.262 to ensure high mechanical performance.

The substitutions of SCMs were calculated by weight of the total binder. The GGBFS replacement levels were 0%, 20%, and 40%, while the fly ash replacement levels were 0%, 10%, and 20%. To isolate the variables and ensure that any changes in fresh and hardened properties were solely attributed to the ternary binder interactions, the quantities of water (157.20 kg/m³), fine aggregate (888.70 kg/m³), coarse aggregate (792.20 kg/m³), and high-range water-reducing admixture or superplasticizer (6.00 kg/m³) were maintained constantly across all variations. The detailed mix proportions are presented in Table I.

TABLE I. CONCRETE MIX PROPORTIONS (KG/M³)

| Mix ID | Cement | GGBFS | FA | Sand | Gravel | Water | SP |
|---|---|---|---|---|---|---|---|
| Control | 600 | 0 | 0 | 761.2 | 929.2 | 157.2 | 2.4 |
| G0-F10 | 540 | 0 | 60 | 761.2 | 929.2 | 157.2 | 2.4 |
| G0-F20 | 480 | 0 | 120 | 761.2 | 929.2 | 157.2 | 2.4 |
| G20-F0 | 480 | 120 | 0 | 761.2 | 929.2 | 157.2 | 2.4 |
| G20-F10 | 420 | 120 | 60 | 761.2 | 929.2 | 157.2 | 2.4 |
| G20-F20 | 360 | 120 | 120 | 761.2 | 929.2 | 157.2 | 2.4 |
| G40-F0 | 360 | 240 | 0 | 761.2 | 929.2 | 157.2 | 2.4 |
| G40-F10 | 300 | 240 | 60 | 761.2 | 929.2 | 157.2 | 2.4 |
| G40-F20 | 240 | 240 | 120 | 761.2 | 929.2 | 157.2 | 2.4 |

### *B. Fresh Concrete Properties Testing*

The fresh properties of the SCC mixtures were evaluated immediately after the mixing process. The slump flow test and $T_{500}$ flow time were conducted in accordance with the Indonesian National Standard (SNI) 9024:2021 [18] and the European Guidelines for Self-Compacting Concrete (EFNARC) recommendations [1]. The slump flow test measures the unconfined flowability and filling ability of the concrete, while the $T_{500}$ time indicates the flow rate and relative viscosity by measuring the time required for the concrete spread to reach a 500 mm diameter. Furthermore, a visual stability index (VSI) was observed to ensure the mixtures had adequate cohesion without severe bleeding or aggregate segregation.



**Fig. 1.** Visual observation of the slump flow tests: (a) inadequate flowability in the G40-F0 mixture, (b) acceptable flowability in the G0-F10 mixture, and (c) excellent flowability and cohesiveness in the G20-F10 ternary blend.

*C. Compressive Strength Testing*

The compressive strength test was performed to evaluate the mechanical development of the concrete mixtures. The specimens were cast in standard molds measuring 150 mm in diameter and 300 mm in without any external vibration, relying entirely on the self-consolidating characteristics. Following 24 hours of casting, the specimens were demolded and cured in a standard water tank at room temperature until the designated testing age. The compressive strength was tested using a Universal Testing Machine (UTM) at curing ages of 1, 3, 7, and 28 days, according to the SNI 1974:2011 [19] standard. For each mixture and testing age, three identical specimens were tested, and the average value was recorded to ensure data reliability.

*D. Flexural Strength Testing*

The flexural strength test was conducted to evaluate the tensile-related mechanical performance and strength development of the SCC mixtures at different curing ages. Beam specimens with dimensions of 150 mm × 150 mm × 600 mm were prepared without external vibration, relying on the self-compacting characteristics of the concrete mixtures. After casting, the specimens were demolded after 24 hours and cured in a water tank at room temperature until the designated testing ages.

The flexural strength of the SCC mixtures was evaluated at 1, 3, 7, and 28 days using a Universal Testing Machine (UTM) under a two-point loading configuration in accordance with SNI 4431:2011 [20]. The specimens were subjected to two symmetrical loading points until failure, and the maximum applied load was recorded to determine the flexural strength. The flexural strength was calculated based on the maximum load, span length, and specimen dimensions according to the applicable flexural testing procedure. For each mixture and curing age, three identical beam specimens were tested, and the average value was reported to ensure data reliability and minimize experimental variability.

## III. Result and Discussions

*A. Fresh Concrete Properties*

The fresh properties of the developed Self-Compacting Concrete (SCC) mixtures were evaluated through slump flow diameter and $T_{500}$ flow time, as summarized in Table I and illustrated in Fig. 1. The slump flow test was performed to evaluate the filling ability and unconfined flowability of fresh SCC mixtures. According to the EFNARC guidelines [1], most of the developed mixtures satisfied the recommended SCC workability requirements, achieving slump flow classifications within the SF1 (550–650 mm) and SF2 (660–750 mm) categories. The SF1 classification is generally suitable for structural applications with moderate reinforcement, whereas the SF2 classification is more appropriate for structures with congested reinforcement requiring higher flowability. In this study, the G20-F10 and G40-F20 mixtures achieved SF2 classification, indicating that an appropriate combination of GGBFS and fly ash can maintain sufficient flowability despite the high level of cement replacement.

However, the experimental results revealed that the incorporation of high GGBFS content without fly ash adversely affected the fresh properties of SCC. The G40-F0 mixture exhibited a slump flow diameter of only 345 mm, which was below the minimum requirement for SCC classification. This reduction in flowability may be associated with the influence of GGBFS characteristics on the rheological behavior of the mixture, including particle morphology, surface characteristics, fineness, and interaction with the cementitious paste. A higher proportion of GGBFS may increase particle interaction and paste resistance, resulting in reduced flowability when adequate modification of the binder system is not provided. Similar effects of GGBFS incorporation on SCC rheology have been reported by Mohammed et al. [21] and Larsen et al. [22], who demonstrated that SCM characteristics and their interaction with chemical admixtures significantly influence the viscosity and flow behavior of SCC mixtures. Nevertheless, the magnitude of flowability reduction observed in the present study was more pronounced than some previous reports, which may be attributed to differences in GGBFS fineness, chemical composition, particle size distribution, binder proportion, and superplasticizer dosage among different mixture designs.

Interestingly, the addition of fly ash effectively improved the flowability of mixtures containing high GGBFS content. The incorporation of 10% and 20% fly ash into the 40% GGBFS mixture increased the slump flow diameter from 345 mm (G40-F0) to 630 mm (G40-F10) and 665 mm (G40-F20), respectively. This improvement can be explained by the spherical particle morphology and smoother surface characteristics of fly ash, which enhance particle packing efficiency and reduce internal friction between solid particles. The spherical fly ash particles

provide a ball-bearing effect that improves paste mobility and facilitates aggregate movement during flow [5]–[6].

TABLE II. FRESH CONCRETE PROPERTIES

| Mix ID | Slump Flow (mm) | $T_{500}$ (s) | SF Class | VS Class | Status |
|---|---|---|---|---|---|
| Control | 600 | 2.79 | SF1 | VS2 | Pass |
| G0-F10 | 590 | 3.77 | SF1 | VS2 | Pass |
| G0-F20 | 635 | 2.50 | SF1 | VS2 | Pass |
| G20-F0 | 650 | 2.46 | SF1 | VS2 | Pass |
| G20-F10 | 670 | 3.82 | SF2 | VS2 | Pass |
| G20-F20 | 625 | 2.90 | SF1 | VS2 | Pass |
| G40-F0 | 345 | - | Fail | - | Fail |
| G40-F10 | 630 | 2.19 | SF1 | VS2 | Pass |
| G40-F20 | 665 | 2.10 | SF2 | VS2 | Pass |

Hameed et al. [5] reported that fly ash can function as a viscosity-modifying component in SCC by improving flow characteristics while maintaining mixture stability. Similarly, Pang et al. [6] demonstrated that high-volume fly ash SCC exhibited improved fresh-state performance due to the beneficial physical characteristics of fly ash particles. Compared with these previous studies, the present findings provide further evidence that fly ash can effectively compensate for the adverse rheological effects associated with high GGBFS incorporation, demonstrating the synergistic role of FA in ternary FA–GGBFS SCC systems.

In addition to flowability, the viscosity and flow rate characteristics of the mixtures were evaluated through the $T_{500}$flow time test. As presented in Table I, all mixtures that achieved adequate slump flow values exhibited $T_{500}$values ranging from 2.10 s to 3.82 s, corresponding to the VS2 viscosity class according to EFNARC specifications [1]. The VS2 classification indicates that the mixtures possessed sufficient viscosity to maintain stability during placement while minimizing the risk of segregation and bleeding. This balance between flowability and viscosity is particularly important for SCC containing high volumes of SCMs because excessive reduction in viscosity may compromise stability, whereas excessive viscosity may limit filling ability.

The obtained $T_{500}$results indicate that the combination of FA and GGBFS successfully balanced the rheological behavior of the SCC mixtures. Hameed et al. [5] reported that fly ash contributes to viscosity control through improved particle packing and reduced friction among binder particles, while Mohammed et al. [21] demonstrated that the interaction between fly ash, GGBFS, and chemical admixtures plays an important role in controlling SCC rheology. In the present study, the improved $T_{500}$performance of FA-containing mixtures confirms that fly ash not only enhances flowability but also contributes to maintaining sufficient cohesion and stability in high-volume GGBFS-based SCC.

Overall, the fresh concrete results demonstrate that the performance of ternary FA–GGBFS SCC is strongly dependent on the balance between different supplementary cementitious materials. Although high GGBFS replacement alone reduced flowability, the incorporation of fly ash successfully restored the rheological performance by improving particle packing and reducing internal friction. Unlike previous studies that mainly investigated FA or GGBFS separately, the present study highlights the importance of optimizing the interaction between FA and GGBFS to achieve sustainable SCC mixtures with reduced cement consumption while maintaining the fresh-state requirements necessary for practical construction applications.

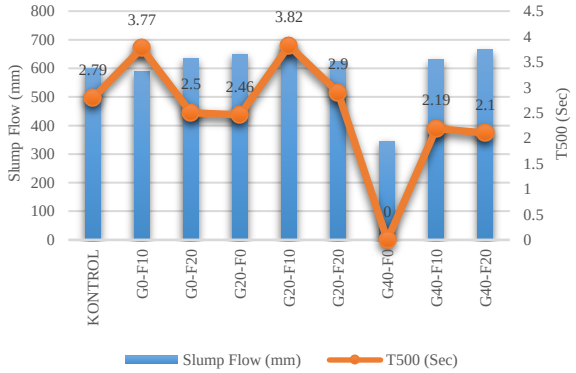



**Fig. 2.** Slump flow and T500 time of the SCC mixtures

*B. Compressive Strength Development*

The development of compressive strength of the SCC mixtures at curing ages of 1, 3, 7, and 28 days is summarized in Table III and illustrated in Fig. 3. All mixtures exhibited a continuous increase in compressive strength with increasing curing age, indicating the progressive hydration of cementitious materials and the gradual refinement of the hardened concrete matrix. At early curing ages (1 and 3 days), the CONTROL mixture exhibited higher compressive strength compared with the SCM-containing mixtures. The lower early-age strength observed in the ternary blended SCC mixtures can be attributed primarily to the dilution effect caused by replacing Portland cement with fly ash and GGBFS, which reduces the amount of clinker available for rapid hydration. In addition, the slower reaction kinetics of supplementary cementitious materials contribute to delayed strength development during the initial curing period. Fly ash requires sufficient calcium hydroxide (CH), generated from Portland cement hydration, to initiate pozzolanic reactions, while GGBFS develops strength through latent hydraulic reactions that occur progressively depending on the availability of alkaline activation and calcium sources. Similar early-age strength reduction trends have been reported in previous studies, where high-volume SCM incorporation resulted in slower initial strength development due to delayed dissolution and reaction of SCM particles compared with Portland cement hydration [6], [11].

As the curing period increased to 7 days, the strength development of the ternary blended mixtures became more pronounced, indicating that secondary hydration mechanisms had become increasingly active. The pozzolanic reaction of fly ash and the latent hydraulic reaction of GGBFS contributed to the formation of additional calcium silicate hydrate (C–S–H) products, which gradually improved matrix densification and reduced internal pore connectivity. Consequently, the compressive strength difference between the SCM-containing mixtures and the CONTROL mixture decreased significantly at this intermediate curing age. This behavior is consistent with the findings of Qu et al. [11], who demonstrated that the mechanical performance of FA–GGBFS blended concrete is strongly influenced by the interaction between SCM type, replacement level, and curing age. However, differences in strength development

rates among studies may occur due to variations in water-to-binder ratio, SCM fineness, chemical composition, particle size distribution, and curing conditions.

At later curing ages, particularly at 28 days, the beneficial effect of the ternary binder system became increasingly evident. Several SCM-containing mixtures achieved higher compressive strength than the CONTROL mixture, which reached 33.67 MPa. Among all mixtures investigated, the G20-F20 mixture exhibited the optimum performance with a 28-day compressive strength of 41.08 MPa, representing an improvement of approximately 22.02% compared with the CONTROL mixture. This superior performance indicates the presence of a synergistic interaction between fly ash and GGBFS when used at an appropriate proportion. GGBFS contributes to strength enhancement through its latent hydraulic activity and continuous formation of hydration products, whereas fly ash improves particle packing efficiency and contributes to long-term pozzolanic reactions. The balanced combination of these two SCMs provides sufficient reactive components to promote additional C–S–H formation while simultaneously reducing micro-voids within the cementitious matrix. Similar synergistic effects of FA and GGBFS combinations have been reported by Abbas and Qureshi [10] and Qu et al. [11], who demonstrated that properly optimized SCM proportions can improve mechanical performance compared with single SCM replacement systems.

TABLE III. COMPRESSIVE STRENGTH RESULT (MPA)

| Mix ID | 1 Day | 3 Days | 7 Days | 28 Days |
|---|---|---|---|---|
| CONTROL | 12.39 | 20.50 | 29.65 | 33.67 |
| G0-F10 | 8.54 | 20.41 | 25.22 | 30.92 |
| G0-F20 | 7.83 | 14.69 | 31.09 | 36.39 |
| G20-F0 | 11.17 | 20.30 | 28.63 | 39.18 |
| G20-F10 | 6.90 | 15.47 | 29.56 | 40.69 |
| G20-F20 | 5.55 | 14.41 | 24.56 | 41.08 |
| G40-F0 | 6.62 | 14.86 | 30.99 | 33.90 |
| G40-F10 | 4.68 | 16.00 | 24.96 | 36.27 |
| G40-F20 | 3.60 | 9.96 | 20.49 | 27.94 |

The improvement in long-term compressive strength observed in the present study also highlights that the performance of ternary SCM-based SCC cannot be predicted solely based on the total replacement level of Portland cement. Instead, the interaction between different SCM components plays an important role in controlling hydration kinetics, pore structure development, and final mechanical performance. Although high-volume SCM incorporation may reduce early-age strength due to reduced cement content and slower reaction rates, appropriate optimization of the FA–GGBFS ratio can effectively compensate for this limitation through enhanced secondary hydration and microstructural refinement. Unlike previous studies that mainly focused on either fly ash or GGBFS individually or evaluated only ultimate strength at 28 days, this study systematically investigated strength evolution from early-age curing (1 day) to later-age performance (28 days) using nine ternary FA–GGBFS SCC mixtures. Therefore, the findings provide further insight into the role of SCM interaction in achieving a balance between sustainability and mechanical performance in high-volume SCM-based SCC.

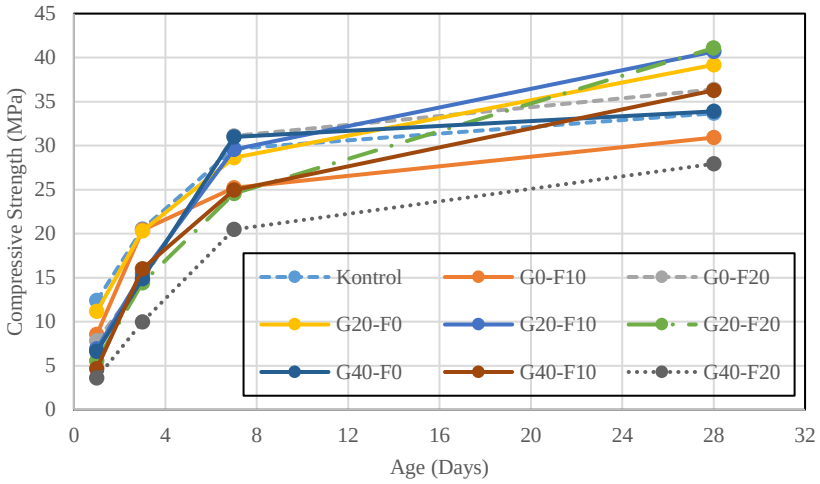



**Fig. 3.** Compressive strength development of the SCC mixtures over time

*C. Flexural Strength Performance*

The development of flexural strength of the SCC mixtures at curing ages of 1, 3, 7, and 28 days is summarized in Table IV and illustrated in Fig. 4. Similar to the compressive strength behavior, all mixtures exhibited continuous improvement in flexural strength with increasing curing age, indicating the progressive development of the hardened cementitious matrix and enhancement of the bonding characteristics between cement paste and aggregate particles. However, the influence of SCM incorporation on flexural strength development showed a different trend compared with compressive strength, indicating that tensile-related properties are governed by additional mechanisms associated with crack initiation and propagation, particularly within the interfacial transition zone (ITZ).

At early curing ages (1 and 3 days), mixtures containing high proportions of fly ash and GGBFS exhibited lower flexural strength compared with the CONTROL mixture. For instance, the G40–F20 mixture achieved a flexural

strength of 1.06 MPa at 1 day, whereas the CONTROL mixture reached 2.56 MPa. The reduction in early-age flexural performance can be attributed to the slower reaction kinetics of SCMs, which limits the formation of sufficient hydration products during the initial curing period. The replacement of Portland cement with FA and GGBFS reduces the amount of primary hydration products generated at early ages, resulting in a weaker binder matrix and lower resistance against crack initiation. Similar observations have been reported by Pang et al. [6] and Qu et al. [11], who demonstrated that high-volume SCM incorporation may delay early-age mechanical development due to slower pozzolanic and latent hydraulic reactions compared with Portland cement hydration.

As curing progressed, the flexural strength of SCM-containing mixtures increased significantly due to the activation of secondary hydration mechanisms. At 28 days, all mixtures containing FA and GGBFS exhibited higher flexural strength than the CONTROL mixture (6.07 MPa). The highest flexural strength was obtained by the G20–F0 mixture, reaching 7.54 MPa, followed by G40–F0 (7.43 MPa) and G20–F10 (7.20 MPa). The superior flexural performance of GGBFS-dominant mixtures suggests that GGBFS played a significant role in improving the tensile-related behavior of SCC through enhanced hydration products and improved interfacial bonding. This observation is consistent with the findings of Ofuyatan et al. [9], who reported that moderate GGBFS replacement levels could improve the mechanical performance of SCC by providing additional calcium-rich phases that contribute to matrix refinement.

The improvement in flexural strength at later ages can be primarily associated with the continuous formation of secondary calcium silicate hydrate (C–S–H) products from pozzolanic and hydraulic reactions. The additional C–S–H phases generated by GGBFS and fly ash contribute to reducing pore connectivity, refining the interfacial transition zone (ITZ), and improving the bond strength between aggregate and cement paste. Since flexural failure is strongly influenced by microcrack development within the ITZ, improvements in interfacial bonding can produce a significant effect on flexural performance. Previous studies have demonstrated that GGBFS and fly ash incorporation can modify fracture behavior and improve tensile-related properties of SCC through enhanced matrix refinement and improved interfacial characteristics [10]–[11], [14].

TABLE VI
FLEXURAL STRENGTH RESULTS (MPA)

| Mix ID | 1 Day | 3 Days | 7 Days | 28 Days |
|---|---|---|---|---|
| CONTROL | 2.56 | 3.43 | 3.71 | 6.07 |
| G0-F10 | 2.88 | 3.14 | 4.84 | 6.17 |
| G0-F20 | 2.96 | 2.77 | 4.48 | 6.41 |
| G20-F0 | 2.52 | 3.21 | 4.68 | 7.54 |
| G20-F10 | 1.52 | 3.35 | 4.05 | 7.20 |
| G20-F20 | 1.19 | 2.70 | 4.91 | 6.60 |
| G40-F0 | 1.61 | 3.77 | 4.93 | 7.43 |
| G40-F10 | 1.48 | 3.58 | 4.79 | 6.88 |
| G40-F20 | 1.06 | 2.04 | 4.95 | 6.48 |

Interestingly, the optimum flexural strength obtained from G20–F0 differs from the optimum compressive strength observed in the G20–F20 mixture. This difference indicates that compressive strength and flexural strength do not necessarily respond identically to SCM incorporation. While compressive strength is primarily governed by overall matrix densification and bulk strength development, flexural strength is more sensitive to ITZ quality, crack resistance, and aggregate–paste interaction. Therefore, the presence of a higher fly ash proportion, although beneficial for compressive strength improvement through enhanced particle packing and long-term pozzolanic activity, does not necessarily provide the maximum flexural resistance.

Furthermore, the G40–F20 mixture provides an important indication regarding the role of high-volume SCM incorporation. Although the replacement of 60% Portland cement resulted in a dilution effect and limited early strength development, the mixture still achieved a flexural strength of 6.75% higher than the CONTROL mixture at 28 days. This behavior suggests that the improvement of flexural performance is not solely dependent on cement content but also on the quality and distribution of hydration products within the binder matrix. Similar behavior has been reported in SCM-based and geopolymer systems, where the incorporation of reactive materials such as GGBFS promotes the formation of a denser and more cohesive binder network, resulting in improved resistance against tensile cracking [23]–[24].

Overall, the flexural strength results demonstrate that the influence of FA and GGBFS on SCC mechanical performance is property-dependent. The optimum mixture for compressive strength development does not necessarily correspond to the optimum flexural strength performance, highlighting the importance of evaluating multiple mechanical indicators when designing sustainable SCC mixtures. The present study contributes further understanding of the distinct roles of FA and GGBFS in controlling compressive and flexural behavior, particularly by demonstrating that optimized ternary SCM systems can enhance long-term mechanical performance while reducing Portland cement consumption.

### *D. Effect of SCM on Strength*

The ultimate mechanical performance of SCC mixtures is strongly influenced by the level of cement replacement and the interaction between different supplementary cementitious materials (SCMs). To evaluate the effect of SCM incorporation, the 28-day compressive and flexural strengths of the developed mixtures were compared at different FA and GGBFS replacement levels, as presented in Fig. 5. The results demonstrate that the influence of SCMs was highly dependent on replacement proportion, where an appropriate balance between GGBFS and fly ash enhanced mechanical performance, whereas excessive replacement reduced the effectiveness of the binder system.

The compressive strength results indicate that the 20% GGBFS replacement level provided the optimum condition for strength enhancement. Among all mixtures, the G20-F20 and G20-F10 mixtures achieved the highest compressive strengths, reaching 41.08 MPa and exceeding the CONTROL mixture by approximately 22.02% and 18.16%, respectively.

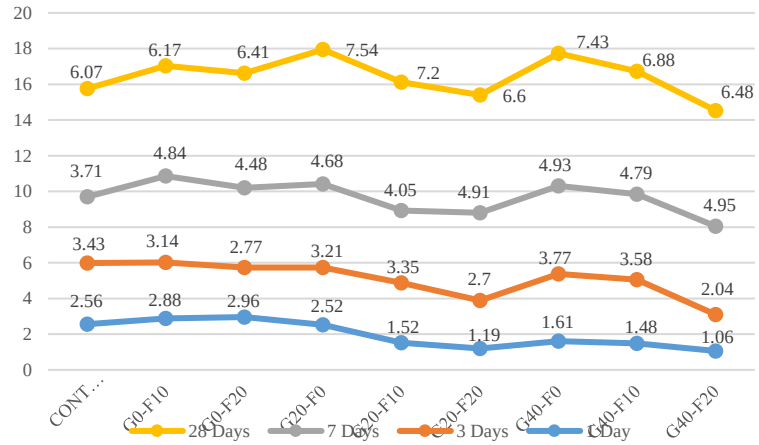



**Fig. 4.** Flexural strength development of the SCC mixtures over time

The superior performance of these mixtures suggests that a moderate amount of GGBFS combined with fly ash provides a favorable balance between cement hydration, secondary reactions, and particle packing effects. The presence of GGBFS contributes through latent hydraulic reactions, producing additional calcium silicate hydrate (C–S–H) phases, while fly ash improves particle packing efficiency due to its fine and spherical morphology. The combination of these mechanisms reduces internal porosity and promotes a denser cementitious matrix, resulting in enhanced compressive strength development.

This behavior is consistent with previous studies reporting that moderate GGBFS replacement levels can improve mechanical performance by promoting secondary hydration reactions and microstructural refinement. Ofuyatan et al. [9] reported that approximately 20% GGBFS replacement provided favorable mechanical performance in SCC mixtures. Similarly, Qu et al. [11] demonstrated that the mechanical properties of FA–GGBFS blended concrete are strongly dependent on the interaction between SCM type, replacement ratio, and curing age. However, the optimum replacement level may vary among studies due to differences in SCM characteristics, binder composition, water-to-binder ratio, and curing conditions.

In contrast, excessive SCM incorporation resulted in a reduction in compressive strength. The G40-F20 mixture, containing a total SCM replacement level of 60% (40% GGBFS and 20% fly ash), exhibited a 17.03% reduction in compressive strength compared with the CONTROL mixture. This reduction can be primarily attributed to the dilution effect caused by the significant reduction in Portland cement content. At this high replacement level, the amount of cement available to provide early hydration products and calcium hydroxide (CH) becomes limited, reducing the activation efficiency of the remaining SCM particles. Consequently, a larger proportion of fly ash and GGBFS particles may remain partially unreacted during the investigated curing period and contribute mainly through filler effects rather than through complete pozzolanic and hydraulic reactions. Similar strength reduction trends at excessive SCM replacement levels have been reported by Pang et al. [6] and Qu et al. [11], who emphasized that the beneficial effect of SCMs depends strongly on maintaining an appropriate balance between cement hydration products and secondary reactions.

Interestingly, the influence of SCM incorporation on flexural strength exhibited a different trend compared with compressive strength. Unlike compressive strength, where G20-F20 represented the optimum mixture, the highest flexural strength was obtained from the G20-F0 mixture, reaching 7.54 MPa, followed by G40-F0 (7.43 MPa) and G20-F10 (7.20 MPa). All SCM-containing mixtures showed higher 28-day flexural strength than the CONTROL mixture (6.07 MPa), including mixtures with reduced compressive strength such as G40-F20. This observation indicates that flexural strength is not solely governed by the overall strength of the cementitious matrix but is also strongly influenced by microstructural characteristics, particularly the quality of the interfacial transition zone (ITZ) and resistance against crack propagation.

The improvement in flexural performance can be attributed to the ability of GGBFS and fly ash to refine the ITZ through the formation of additional hydration products. The secondary C–S–H gels generated from SCM reactions can reduce pore connectivity, improve aggregate–paste bonding, and enhance the resistance of the matrix against microcrack initiation and propagation. Since flexural failure is highly dependent on crack development within the ITZ, improvements in this critical region may provide a greater contribution to flexural strength than to compressive strength. Similar observations regarding the influence of SCMs on fracture behavior and tensile-related properties of SCC have been reported by Salehi and Mazloom [14] and Abbas and Qureshi [10].

The different optimum mixtures for compressive and flexural strength highlight an important finding of this study. While the G20-F20 mixture achieved superior compressive strength due to enhanced matrix densification and balanced secondary hydration, the G20-F0 mixture exhibited the highest flexural strength due to the dominant contribution of GGBFS-derived hydration products and improved interfacial bonding. This indicates that the mechanical response of SCM-based SCC is property-dependent and cannot be evaluated solely based on compressive strength. Therefore, optimizing ternary SCM mixtures requires consideration of multiple mechanical indicators to achieve a balanced performance between compressive resistance, flexural capacity, and sustainability objectives.

Overall, the results demonstrate that the incorporation of FA and GGBFS provides significant potential for improving the mechanical performance of SCC while reducing Portland cement consumption. However, the effectiveness of SCM incorporation depends strongly on the replacement level and the interaction between different SCM components. The findings of this study provide further evidence that optimized FA–GGBFS combinations can achieve high-performance SCC by balancing hydration kinetics, microstructural refinement, and mechanical performance.

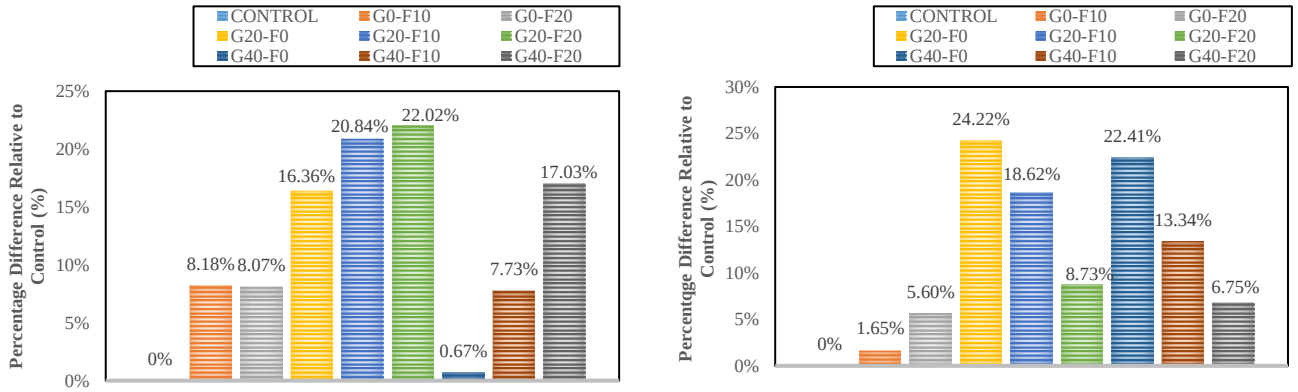



**Fig. 5. (a)** Percentage difference of 28-day compressive strength for all SCC mixtures relative to the control flexural strength development of the SCC mixtures over time, **(b)** Percentage difference of 28-day flexural strength for all SCC mixtures relative to the control.

### *E. Relationship Between Compressive and Flexural Strength*

In structural engineering practice, flexural strength is commonly estimated from compressive strength using empirical relationships developed primarily from conventional concrete systems. However, the applicability of these relationships to high-volume supplementary cementitious material (SCM)-based self-compacting concrete (SCC) remains uncertain because SCM incorporation modifies hydration kinetics, pore structure development, and interfacial transition zone (ITZ) characteristics. Therefore, the relationship between the 28-day compressive strength and flexural strength of all investigated SCC mixtures was evaluated, as illustrated in Fig. 6.

Unlike a conventional linear regression approach, a second-order polynomial regression model was adopted in this study to describe the relationship between compressive strength and flexural strength. This approach was selected because the relationship between these two mechanical properties is not necessarily proportional, particularly in SCM-modified concrete systems. Compressive strength is mainly governed by the overall densification of the cementitious matrix, hydration degree, and pore refinement, whereas flexural strength is more sensitive to localized characteristics, including ITZ quality, aggregate–paste bonding, and resistance against microcrack initiation and propagation. Therefore, a quadratic function was considered more suitable to capture possible variations in the strength development trend caused by the complex interaction between SCM reactions and microstructural modification.

Based on the experimental data, the developed second-order polynomial relationship for the ternary FA–GGBFS SCC mixtures is expressed as:

$$fr = -6 \times 10^{-6}(f'c)^2 + 0.0582(f'c) + 4.6932 \quad (1)$$

where $f_r$ represents the flexural strength and $f_c'$ represents the compressive strength of the SCC mixtures.

The obtained polynomial model exhibited a relatively low coefficient of determination ($R^2 = 0.2259$), indicating that compressive strength alone cannot sufficiently explain the variation in flexural strength of the investigated ternary FA–GGBFS SCC mixtures. Although the quadratic model was introduced to capture possible nonlinear behavior, the low $R^2$ value demonstrates that the relationship between these two mechanical properties is strongly affected by additional factors beyond bulk compressive resistance. This behavior is expected in SCM-based SCC because modifications in hydration products and microstructural characteristics influence compressive and flexural responses differently.

The different optimum mixtures obtained for compressive and flexural strength further support this interpretation. The G20-F20 mixture achieved the highest compressive strength of 41.08 MPa, whereas the highest flexural strength was obtained from the G20-F0 mixture with a value of 7.54 MPa. This discrepancy indicates that an increase in compressive strength does not necessarily result in a proportional improvement in flexural performance. While compressive strength reflects the overall load-bearing capacity and densification of the concrete matrix, flexural strength is more strongly influenced by crack development mechanisms, ITZ refinement, and the quality of bonding between aggregate and cement paste [10], [14]. Similar differences between compressive and tensile-related properties have been reported in SCM-based concrete systems, where the contribution of supplementary materials depends on their influence on hydration products, pore structure, and failure mechanisms [10]–[11], [14].

To further assess the applicability of the proposed relationship, the experimental flexural strength values were compared with the prediction equation recommended by ACI 318 [23] for normal-weight concrete. The comparison revealed that the ACI-based prediction provided lower flexural strength values than those experimentally obtained from the FA–GGBFS SCC mixtures. For the investigated compressive strength range of approximately 27–41 MPa, the ACI equation predicted flexural strength values of approximately 3.4–4.0 MPa, whereas the measured flexural strengths ranged from 6.07 to 7.54 MPa.

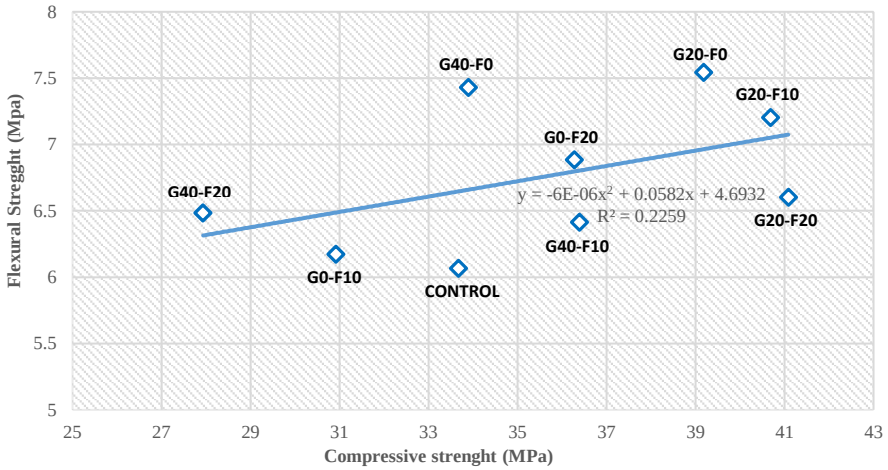



**Fig. 6.** Scatter Plot Compressive vs Flexural Strength

The higher flexural strength observed experimentally compared with the ACI prediction can be attributed to the microstructural modification induced by SCM incorporation. The fine particles of fly ash and GGBFS improve particle packing and reduce internal voids, while secondary hydration reactions generate additional calcium silicate hydrate (C–S–H) products that contribute to matrix refinement and ITZ improvement [10]–[11]. These mechanisms enhance aggregate–paste interaction and increase resistance against crack propagation, resulting in higher flexural performance compared with values predicted using conventional concrete-based relationships.

Nevertheless, the low $R^2$value represents an important limitation of the proposed empirical relationship. The developed equation should not be interpreted as a universal predictive model for all SCM-based SCC mixtures because flexural behavior is influenced by multiple parameters, including SCM type, replacement ratio, binder composition, curing age, aggregate properties, and interfacial characteristics. Instead, the proposed polynomial relationship should be considered as a preliminary empirical correlation applicable within the range of FA–GGBFS SCC mixtures investigated in this study.

Overall, these findings demonstrate that conventional compressive–flexural relationships developed for ordinary concrete may not fully represent the mechanical behavior of high-volume FA–GGBFS SCC. The results highlight the necessity of developing mixture-specific relationships for sustainable concrete systems, where changes in hydration mechanisms and microstructural characteristics significantly influence tensile-related performance.

*F. Optimum SCC Mix*

Determining the optimum mixture for high-volume SCM-based Self-Compacting Concrete (SCC) requires consideration of multiple performance indicators rather than relying on a single mechanical parameter[10]. In this study, the optimum mixture was evaluated based on the combined performance of fresh properties, early-age strength development, 28-day compressive strength, flexural strength, and the level of ordinary Portland cement (OPC) replacement. Based on this comprehensive evaluation, the G20-F20 mixture, consisting of 20% GGBFS and 20% fly ash replacement, was identified as the most balanced ternary SCC mixture.

The G20-F20 mixture achieved the highest 28-day compressive strength of 41.08 MPa, representing an improvement of 22.02% compared with the CONTROL mixture. In addition, this mixture maintained adequate fresh properties and achieved a flexural strength of 6.60 MPa, demonstrating that the enhancement in compressive strength was not achieved at the expense of overall mechanical performance. The superior performance of G20-F20 indicates that a 40% total SCM replacement level provides an effective balance between cement reduction and mechanical efficiency.

The enhanced performance of the G20-F20 mixture can be attributed to the synergistic interaction between GGBFS and fly ash. The incorporation of 20% GGBFS provides sufficient latent hydraulic activity, promoting the formation of additional calcium silicate hydrate (C–S–H) products that contribute to matrix densification and improvement of the interfacial transition zone (ITZ). Previous studies have demonstrated that SCM incorporation can enhance mechanical performance through additional hydration products and microstructural refinement [11], [24]. Meanwhile, the addition of 20% fly ash improves particle packing efficiency due to its spherical particle morphology and contributes to long-term strength development through pozzolanic reactions [5], [11]. The combined effects of hydraulic reaction from GGBFS and pozzolanic activity from fly ash promote the formation of a denser and more homogeneous cementitious matrix compared with mixtures containing only a single SCM.

The selection of 40% total SCM replacement as the optimum level also demonstrates the importance of maintaining an appropriate balance between SCM utilization and available Portland cement content. Although higher SCM incorporation can provide greater cement reduction, excessive replacement may reduce strength development due to the dilution effect caused by insufficient clinker hydration products and limited calcium hydroxide availability for secondary reactions. This behavior was observed in the G40-F20 mixture, which contained 60% SCM replacement and exhibited reduced compressive strength compared with the G20-F20 mixture. Similar observations have been reported in previous studies, where excessive SCM replacement resulted in reduced mechanical performance due to the dilution effect,

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reduced clinker availability, and slower hydration kinetics of supplementary materials compared with Portland cement [6], [11], [25].

From a sustainability perspective, replacing 40% of OPC with SCMs provides significant potential for reducing cement consumption and associated environmental impacts from cement production. However, because this study did not include a detailed life-cycle assessment, the environmental benefit should be interpreted as a potential reduction rather than a quantified carbon reduction. Previous studies have demonstrated that SCM incorporation can improve the sustainability performance of concrete by reducing clinker content while maintaining acceptable mechanical performance [2].

Interestingly, the optimum mixture for flexural performance was different from that for compressive strength. The G20-F0 mixture, containing 20% GGBFS without fly ash, achieved the highest flexural strength of 7.54 MPa, representing an improvement of 24.22% compared with the CONTROL mixture. This finding indicates that the optimum SCM composition depends on the targeted mechanical performance. While fly ash contributes significantly to compressive strength enhancement through improved particle packing and long-term pozzolanic activity, GGBFS appears to provide a greater contribution to flexural resistance through enhanced hydration products and improved ITZ characteristics. Similar behavior was reported by Ofuyatan et al. [9], who identified approximately 20% GGBFS replacement as an effective level for improving the mechanical performance of SCC.

Therefore, the findings of this study demonstrate that there is no single optimum SCM proportion for all mechanical properties. The G20-F20 mixture represents the optimum overall SCC design when considering a balance between flowability, compressive strength, flexural performance, and cement reduction. Meanwhile, G20-F0 may be preferred for applications where flexural resistance is the dominant design requirement. This distinction highlights the importance of performance-based optimization rather than simply maximizing SCM replacement in the development of sustainable high-performance SCC.

## V. Conclusion

Based on the comprehensive experimental investigation evaluating the fresh properties, early-age development, and ultimate mechanical performance of ternary blended Self-Compacting Concrete (SCC) incorporating high volumes of fly ash and GGBFS, the following principal conclusions are drawn:

1. Rheological Recovery via Micro-Lubrication: The utilization of a high GGBFS volume (40%) without fly ash severely deteriorates the flowability of SCC (slump flow of 345 mm) due to the high interparticle friction caused by its angular morphology. However, the introduction of 10% to 20% fly ash effectively restores workability, satisfying the SF1 and SF2 criteria. The spherical fly ash particles act as a micro-lubricant (ball-bearing effect) that reduces yield stress while maintaining an adequate VS2 viscosity class, ensuring a cohesive and segregation-free mixture.
2. Optimum Threshold and Dilution Effect: High-volume SCM mixtures exhibit a characteristic "slow-starter" behavior during early-age curing (1 and 3 days) due to delayed secondary hydration. By 28 days, a 20% GGBFS substitution threshold emerges as the optimum level for compressive strength. The G20-F20 ternary blend achieved the maximum compressive capacity of 41.08 MPa (+22.02% over the CONTROL). Conversely, excessive total SCM replacement up to 60% (G40-F20) triggers a severe dilution effect due to binder starvation, resulting in a 17.03% reduction in compressive strength.
3. Microstructural ITZ Densification: Flexural strength demonstrates a remarkably higher sensitivity and universally positive response to SCM inclusion compared to compressive strength. The binary G20-F0 mixture recorded the peak flexural strength of 7.54 MPa (+24.22%). The secondary C-S-H gels precipitated from the pozzolanic and latent hydraulic reactions selectively densify the Interfacial Transition Zone (ITZ), significantly enhancing tensile crack resistance and causing all SCM-blended mixtures to substantially outperform the standard ACI 318 predictive model.
4. Optimum Sustainable Configuration: The G20-F20 mixture (comprising 20% GGBFS and 20% fly ash) is established as the optimum ternary configuration for high-performance SCC. By successfully replacing 40% of conventional ordinary Portland cement, this specific blend provides an exceptional synergy of superior ultimate mechanical strength, excellent structural ductility, and significantly reduced carbon footprint, making it highly viable for sustainable construction applications.

## Acknowledgment

The authors express their sincere gratitude to the Department of Civil Engineering at Universitas Brawijaya for providing the necessary facilities and institutional support for this research.

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