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Influence of Graphene Oxide (GO) and Fly Ash (FA) on the workability and mechanical properties of self-compacting concrete

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Abstract: Self-compacting concrete (SCC) is an advanced material for complex construction applications requiring accurate formwork, high reinforcement density, and superior surface finishes. The ability to flow and consolidate under its weight eliminates the need for mechanical vibration, thereby improving construction efficiency, reducing labor costs, and ensuring greater homogeneity. SCC is widely employed in underground structures, high-rise buildings, and load-bearing elements where strength, durability, and workability are critical. Graphene oxide (GO) and fly ash (FA) enhance SCC's performance. GO enhances compressive strength, crack resistance, and durability through microstructural refinement and crack propagation inhibition, while FA improves workability, reduces water demand, and increases durability by lowering permeability and shrinkage. The partnership between GO and FA meets SCC performance standards and enhances its applicability in high-performance and sustainable construction. This study examined the effects of GO content (0% and 0.03% by binder weight) and FA content (15%, 25%, and 35%) on the workability and mechanical qualities of SCC. A series of studies were performed to assess the workability features of SCC, together with two principal mechanical properties: compressive strength and flexural tensile strength at 28 days. The findings demonstrate that while an increase in GO content diminishes flowability owing to its elevated specific surface area, the appropriate incorporation of FA mitigates this effect, leading to a combination with enhanced mechanical properties. SCC with 0.03% GO and 25% FA attained the maximum compressive strength at 28 days.

Keywords: GO, fly ash, workability, strength, self-compacting concrete.

1. Introduction

SCC has emerged as a revolutionary material in contemporary construction, providing exceptional workability, improved mechanical qualities, and decreased labor demands. In contrast to traditional concrete, SCC can flow and consolidate under its weight, negating the necessity for mechanical vibration and improving efficiency and structural integrity. The SCC prototype was initially finalized in 1988 in Japan from commercially available materials. This concrete was first designated as "High-Performance Concrete" and subsequently referred to as "Self-Consolidating High-Performance

Concrete" [1]. Since then, other countries globally, including Japan, Europe, North America, and Australia, have demonstrated a keen interest in exploring, enhancing, and implementing this concrete form.

In 2007, the American Concrete Institute (ACI) assessed SCC as an innovative technology and advocated its implementation in the United States. A survey indicated that 22 of the 25 counties in Columbia in 2008 utilized or contemplated using SCC [2]. The Virginia Department of Transportation (VDOT) allocates over 13 million USD yearly for prefabricated constructions utilizing SCC, achieving a 5% cost reduction [3]. The walls of the acoustic vibration testing facility at NASA's Plum Brook station were constructed with SCC, exhibiting a flowability of SF = 650 mm, ensuring the structure's requisite surface quality. SCC is characterized by high strength (> 40 MPa), low porosity, extended durability, and excellent water resistance [4]. SCC is produced utilizing active mineral additives, a low water-to-binder ratio, a reduction in the coarse aggregate, and a substantial quantity of superplasticizers [5].

Active mineral additions are employed to augment the powder content (cement + active mineral additives) to enhance the paste volume and optimize the rheological qualities of the concrete mixture. The low water-to-binder ratio and little cement usage improve the SCC mixture's cohesion while maintaining the concrete's necessary strength. Furthermore, reducing the quantity of coarse aggregate enhances workability, while a substantial dosage of superplasticizer guarantees the requisite flowability of the concrete mixture. It must fulfill the following two criteria to generate the appropriate self-compacting concrete. Initially, SCC should attain elevated aggregate resistance by reducing the water-to-powder ratio, imposing coarse aggregate restrictions of up to 28%, a maximum size of 12.5 mm, and using mineral admixtures. FA and silica fume were taken into account. PCE-based superplasticizers and viscosity modifying agents (VMA) were incorporated to achieve elevated deformability [6], [7].

The plasticizing action of PCE additive primarily results from two distinct repulsive forces between cement particles, leading to their dispersion. Electrostatic repulsion arises from the adsorption of negative charges contributed by the carboxylic groups in the molecule's main chain. The dispersion effect of the comb-shaped side chains of polymer molecules in the mixture inhibits the agglomeration of cement particles. This combination can decrease water content by 30-40%. A Viscosity-Modifying Admixture (VMA) is employed to modify the viscosity of the concrete mixture. VMA is used to raise concrete viscosity, regulate the rheological characteristics of the mix, improve uniformity, minimize water segregation and bleeding, and avert layering, hence facilitating the management of the Self-Consolidating Concrete (SCC) mixture [2].

GO, a two-dimensional graphene derivative has attracted considerable interest in the construction sector because of its exceptional mechanical properties, extensive surface area, and highly reactive functional groups. The characteristics of GO contribute to its effectiveness as a nano-reinforcement for cement-based materials, improving their mechanical strength, durability, and microstructural integrity. Studies have shown that GO notably enhances compressive strength, flexural strength, and fracture resistance, positioning it as a promising material for future sustainable construction applications [8], [9], [10].

GO and FA have been thoroughly examined for their effects on concrete's mechanical performance, durability, and sustainability. Graphene oxide, characterized by its extensive surface area, presence of oxygen-functional groups, and reinforcement capabilities, has demonstrated enhancements in compressive and flexural strength, microstructural refinement, and the facilitation of hydration reactions. [11]. Studies show that GO improves the compressive strength of cementitious composites by as much as 21.5% and flexural strength by 14%. This enhancement is primarily attributed to its ability to densify the interfacial transition zone (ITZ) and promote the formation of calcium-silicate-hydrate (C-S-H) gel [12].

Meanwhile, FA is commonly utilized as a supplementary cementitious material (SCM) because of its capacity to enhance workability, minimize early-age shrinkage, and improve durability. Research has shown that FA enhances the rheological properties of cement paste by counteracting the increased viscosity induced by GO [11]. Nonetheless, an overabundance of FA replacement (exceeding 30%) may adversely impact early-age strength, necessitating careful mix design [12]. The observed synergistic effect of GO and FA leads to balanced enhancements in mechanical and rheological performance, rendering this combination especially advantageous for SCC and high-performance concrete (HPC) [13], [14].

Despite these benefits, obstacles remain, especially regarding dispersion and workability. The strong van der Waals forces present in GO lead to agglomeration, which diminishes its effectiveness as a nano-reinforcement. To address this issue, polycarboxylate ether (PCE) superplasticizers are frequently employed to improve the dispersion of GO and preserve fluidity [12]. Furthermore, research indicates that FA alleviates the adverse effects of GO on workability by lowering yield stress and plastic viscosity, thereby promoting a more uniform concrete mix [11].

Moreover, GO significantly influences flexural strength, especially in regulating crack formation and propagation. Research has shown that GO functions as a nano-bridge between cement particles, successfully limiting the formation of microcracks within the concrete matrix. This leads to a notable enhancement in tensile strength and the material's capacity to absorb stress before failure [15]. Furthermore, GO significantly contributes to improving the long-term durability of SCC. The substantial surface area and superior binding characteristics of GO contribute to the filling of microvoids formed by FA, leading to a decrease in overall porosity and an enhancement in the concrete’s resistance to water penetration and chemical assaults [16].

To attain the best performance, it is essential to meticulously regulate the dosage of GO and FA to avoid any negative impacts on the workability of concrete. Studies indicate that excessive GO may result in poor dispersion, which can diminish the fluidity of the concrete mixture and complicate the working process. In a similar vein, incorrect proportions of FA can adversely affect the workability of the mix, leading to agglomeration and a decrease in homogeneity [17]. Consequently, identifying the ideal ratio of GO and FA is essential for ensuring that SCC attains superior mechanical strength and sufficient flowability for construction purposes.

Integrating FA and GO offers a new approach to improving the workability, strength, durability, and sustainability of SCC. GO enhances viscosity, which may decrease flowability, while improving mechanical properties via accelerated hydration and crack-bridging. FA, an often utilized supplementary cementitious material, enhances flowability, improves long-term strength, and mitigates the environmental impact of cement usage. This research investigates the effects of GO and FA on both the fresh and hardened properties of SCC, clarifying their interaction and providing dosage recommendations for practical use. The densification of the concrete's pore volume increases SCC's strength.

This study contributes to the existing body of knowledge by addressing a significant gap in understanding the combined effects of GO and FA on the fresh and hardened properties of self-compacting concrete (SCC). While previous studies have separately investigated the influence of GO and FA on concrete performance, comprehensive investigations into their synergistic interaction, particularly in SCC systems, remain limited. The novelty of this research lies in its systematic evaluation of multiple FA replacement levels (15%, 25%, and 35%) and GO dosages (0%, 0.03%, and 0.06%) within a controlled SCC framework using standardized workability and strength assessment protocols.

Key contributions of this research include:

(1) Establishing the optimal combination of FA and GO to enhance both the workability and mechanical performance of SCC without compromising its self-consolidating characteristics.

(2) Quantitatively assessing the trade-offs between increased viscosity due to GO and improved flowability due to FA, providing a balanced mix design strategy.

(3) Demonstrating the microstructural benefits of GO for strength enhancement while highlighting the rheological improvements introduced by FA in mitigating GO's adverse effects on fresh properties.

(4) Offering practical mix proportioning recommendations for high-performance, durable, and sustainable SCC applicable in real-world construction scenarios.

(5) These findings are particularly relevant for developing advanced concrete materials that meet sustainability and structural performance requirements.

2. Materials and Methods

2.1. Materials

Cement: PC40 cement of the But Son brand, complying with TCVN 2682:2020 [18]. The characteristics of the cement are displayed in Table 1. For SCC, a larger quantity of paste content is necessary; hence, a portion of the cement was consistently substituted with silica fume, FA, and powder content

Water: Clean water suitable for construction applications.

FA: Sourced from Vung Ang I, a fine waste material with spherical particles ranging from 10µm to 100µm, meeting the technical requirements of Type F FA as per ASTM C618.

Table 1. Binder Materials Properties

Oxide/Property	Cement	FA	Silica Fume
% SiO_2	21.77	58.26	95.85
% Fe_2O_3	4.14	5.76	0.05
% Al_2O_3	6.56	31.74	0.26
% CaO	60.13	1.96	0.21
% MgO	2.09	0.15	0.45
% Na_2O	0.38	0.78	-
% K_2O	0.43	0.73	-
% SO_3	2.17	0.17	1.00
% LOI	2.39	0.31	2.80
Specific Gravity (g/cm^3)	3.15	2.25	2.07
Consistency (%)	33	-	-
Fineness (m²/Kg)	307	350	-

According to recommendations [19], [20], [21], aggregate with a maximum size (D_{max}) of 10-15 mm ensures more excellent SCC stability. In high-strength concrete applications, aggregate sizes between 9.5 mm and 12.7 mm are preferred, with limestone sourced from Kien Khe, Ha Nam. The properties of the aggregate are presented in Table 2.

Table 2. Physical and Mechanical Properties of Coarse Aggregate [22]

No	Test Parameter	Result	TCVN 7570:2006	Test Method
1	Bulk Density (g/cm³)	2.75	-	TCVN 7572-4:06
4	Loose Bulk Density (kg/m³)	1540	-	TCVN 7572-6:06
5	Porosity (%)	44.2	-	TCVN 7572-6:06
6	Dust, Clay, Silt Content (%)	0.1	≤ 1.0	TCVN 7572-8:06
7	Cylinder Crushing Strength (%)	11.9	-	TCVN 7572-11:06
8	Nominal Aggregate Size, Dmax (mm)	10	-	TCVN 7572-2:06

The yellow sand used for SCC in this study is sourced from the Lo River, ensuring it is dry, clean, and impurities-free. The maximum particle size does not exceed 5 mm, with several physical and mechanical properties presented in Table 3.

Table 3. Physical and Mechanical Properties of Fine Aggregate [22], [23]

No	Test Parameter	Result	TCVN 7570:2006	Test Method
1	Bulk Density (g/cm³)	2.60	-	TCVN 7572-4:06
2	Loose Bulk Density (kg/m³)	1450	-	TCVN 7572-6:06
3	Fineness Modulus	2.62	2.0 ÷ 3.3	TCVN 7572-2:06
4	Dust, Clay, Silt Content (%)	0.12	≤ 1.50	TCVN 7572-8:06
5	Mica Content (%)	0.1	-	TCVN 7572-8:06
6	Cl^- Content (%)	0.15	-	TCVN 7572-8:06

The mineral powder for producing self-compacting concrete (SCC) typically consists of finely ground limestone and dolomite powders. The compressive strength of the stone should not be less than 200 daN/cm². The material used for mineral powder must be clean, free of impurities, and should not contain more than 5% clay or contaminants. Limestone powder plays a crucial role in SCC by enhancing the viscosity and stability of the mixture, reducing segregation, and improving workability. It also contributes to optimizing the particle packing density, leading to a denser cementitious matrix. Additionally, limestone powder acts as a secondary nucleation site, promoting better hydration of cement and improving early-age strength development.

The GO used in the experiment has a surface area of 110-250 m²/g, a specific gravity of 0.121 g/cm³, is an odorless, fine brown powder, very lightweight, with a particle size of 0.8-2 nm, and a carbon content of 60-80%. The Polycarboxylate (PCE) admixture is a new generation of environmentally friendly concrete additives at an advanced global level. PCE is a light yellow, transparent, soluble liquid (Figure 1). The VMA Commercial admixture meets the ASTM C 494 / C 494M requirements for Type S.

Figure 1. GO Powder and Aqueous PCE Solution

2.2. Mix Design

The literature review demonstrates that a 0.03% incorporation of GO and a 30% substitution of cement with FA yield optimal results in self-compacting concrete. This conclusion aligns completely with prior findings regarding the effects of combining GO and FA in self-compacting concrete, as documented in studies referenced in [11], [16], [17]. This research has shown that substituting 30% of cement with fly ash and using 0.03% graphene oxide enhances the workability and strength of self-compacting concrete. However, to verify the feasibility and optimize the practical application, this study extensively investigated various SCC mixtures with different FA replacement levels (15%, 25%, 35%) and GO dosages ranging from 0.01% to 0.05%. This broader investigation was essential to identify the optimal balance between workability, mechanical strength, and durability while addressing potential material interaction effects.

Based on the mix design parameters of SCC from Europe, Japan, and the US, combined with a preliminary review of materials, the technical specifications for the SCC mixture are determined as follows:

The air content in concrete is 2% [24].

The water-to-binder ratio (Water/Binder) basing volume ranges from 0.9 to 1.14, with a mass-based ratio of 0.256-0.374, selected based on surveys [24], [25], [26].

The sand-to-aggregate ratio is selected as 0.526 by volume based on surveys [25] and guidelines [24].

FA replaces 15%, 25%, and 35% of the binder mass to enhance the workability of the SCC mixture, with a surveyed ratio (Fly Ash/Binder) of 0.081-0.418.

Superplasticizer is used at 1% of the binder mass [25].

The VMA content is 0.0346% of the binder mass [25].

The GO content is used at 0%, 0.03%, and 0.06% of the binder mass (note that the binder consists of cement and FA).

The experimental method based on the absolute volume principle was used to calculate the mix proportions for SCC. Table 4 presents the mix design results for mixes), utilizing the materials mentioned in Section 2.1.

This study involved formulating many SCC mixtures with systematic modifications to various constituents to assess their effects on workability, durability, and mechanical qualities. The experiment was organized around three primary factors: the cement-to-fly ash ratio, the influence of GO, and the regulation of superplasticizer (PCE) and viscosity-modifying additive (VMA), as outlined in Table 4.

The variation in cement and FA content throughout the mixes (ranging from 344.5 kg to 397.5 kg of cement and from 132.5 kg to 185.5 kg of fly ash) was intended to evaluate the impact of the cement-to-fly ash ratio on the workability and strength of SCC. An increased fly ash content can enhance flowability and diminish hydration heat but may reduce early-age strength. On the other hand, augmenting cement content might improve strength but may adversely impact workability.

The experiment examines the impact of GO at varying dosages of 0% to 0.06% weight of binder equivalent 0 kg, 0.16 kg, and 0.32 kg. GO is a nanomaterial recognized for augmenting durability, strengthening adhesion between the matrix and particles, and affecting concrete microstructure. Nonetheless, the incorporation of GO may influence the workability of SCC. This experiment seeks to identify the ideal GO dosage that improves strength while maintaining the self-compacting properties of the mixture.

Table 4. Quantities of Materials per m^3

Mixes	%FA	%GO	Cement (kg)	FA (kg)	GO (kg)	Silica Fume (kg)	Mineral Powder (kg)	Sand (kg)	Coarse Aggregate (kg)	VMA (kg)	PCE (kg)	Water (kg)
SCC0	0	0	530	0	0	25	50	860	755	0.23	5.3	160
SCC1	35	0	344.5	185.5	0	25	50	860	755	0.23	5.3	160
SCC2	25	0	397.5	132.5	0	25	50	860	755	0.23	5.3	160
SCC3	15	0	450.5	79.5	0	25	50	860	755	0.23	5.3	160
SCC4	35	0.03	344.5	185.5	0.159	25	50	860	755	0.23	5.3	160
SCC5	25	0.03	397.5	132.5	0.159	25	50	860	755	0.23	5.3	160
SCC6	15	0.03	450.5	79.5	0.159	25	50	860	755	0.23	5.3	160
SCC2	25	0	397.5	132.5	0	25	50	860	755	0.23	5.3	160
SCC5	25	0.03	397.5	132.5	0.159	25	50	860	755	0.23	5.3	160
SCC7	25	0.06	397.5	132.5	0.318	25	50	860	755	0.23	5.3	160

A crucial element of the mix design is the uniform water content (160 kg), PCE (5.3 kg), and VMA (0.23 kg) in all mixtures. This method enables the author to assess the effects of acceptable material variations without the influence of alterations in workability modifiers. Maintaining a continuous superplasticizer (PCE) guarantees the desired flowability of SCC, while VMA aids in preserving viscosity and segregation resistance.

This study seeks to determine the ideal SCC mix design that harmonizes workability, mechanical strength, and durability. The experimental results may elucidate the optimal material ratios for formulating SCC with enhanced workability, elevated durability, and practical utility in construction endeavors.

This table outlines the proportions of materials used for different SCC mixes, ensuring the optimal balance of mechanical properties and workability.

2.3. Mixing SCC

The mixing process of SCC containing GO and other supplementary components was carried out according to the steps outlined in Table 5.

Table 5. SCC Mixing Procedure

Step	Mixing Procedure	Mixing Time
1	Preheat the mixing drum (if necessary, especially in cold conditions)	-
2	Prepare GO suspension: Dilute GO with 30% of the total water content, add PCE (Sika-PCE) with a GO:PCE ratio of 1:1, stir at 400 rpm for 15 minutes, then use an ultrasonic probe at 30% power for 30 minutes to ensure uniform dispersion	45 minutes
3	Add 100% of the coarse aggregates (gravel, crushed stone) into the mixing drum	-
4	Add 40% of the remaining total water + the remaining superplasticizer (PCE) into the mixing drum, mix thoroughly	1 minute
5	Gradually add cement + mineral admixtures (FA, silica fume) into the mixture, continue mixing to avoid clumping	1.5 minutes
6	Add 100% sand + 30% of the remaining water, and mix thoroughly	5 minutes
7	Gradually pour the pre-prepared GO suspension into the main mixture, continue mixing	2 minutes
8	If necessary, add viscosity-modifying admixture (VMA), continue mixing	2 minutes
9	Pause and check the consistency of the SCC mix	1 minute
10	If the mixture does not meet the required workability, remix	2 minutes
11	Discharge the SCC mix into the chute	-

Figure 2. Some images from the specimen casting experiment process.

This mixing procedure ensures proper dispersion of materials and homogeneous consistency, optimizing the workability and performance of the SCC mixture. Experiment using the initial optimal water content, subsequently adjusting according to the outcomes of flowability and viscosity assessments. Prioritise increasing PCE or adjusting the FA ratio before reducing water to maintain the workability of SCC without compromising its strength, should adjustments be necessary.

Some experimental images below (Figure 2) include the mixing of GO, trial mixing of SCC for preliminary slump adjustment, the paddle mixer, and specimen preparation.

2.4. Testing the Workability Parameters of SCC

Both ASTM and EN standards establish testing methods for evaluating the workability parameters of SCC mixtures. The results obtained from applying both standards are considered highly consistent. The EN 12350:2010 Testing Fresh Concrete standard provides specific guidance on determining six key workability parameters of SCC [27]. SF (slump flow), T500 (flow time), V-funnel, J-ring, L-box, and SR (segregation resistance) facilitate accurate and convenient evaluation. The workability of the SCC mixture is characterized by three key technical parameters: filling ability, passing ability, and segregation resistance (**Figure 3**) [2].

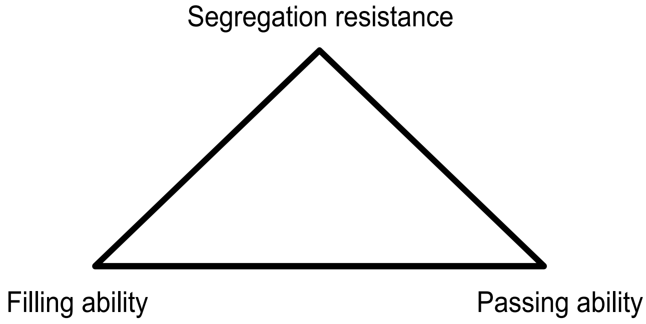

Figure 3. Diagram of the fundamental workability parameters of SCC [2].

This study adopts the EN standard for identifying and assessing SCC workability parameters (Figure 4), while also referring to the ASTM method, which evaluates SCC workability visually based on the visual stability index (VSI) (Figure 4).

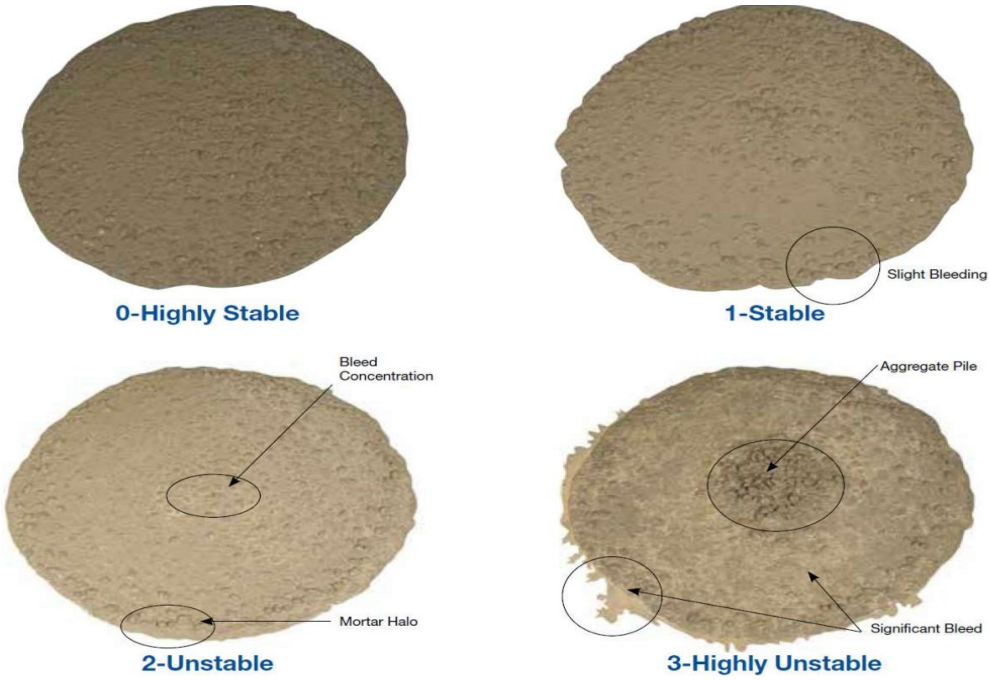

Figure 4. Visual Workability Assessment of Mortar Based on ASTM VSI Rating [28]

VSI (Visual Stability Index) Evaluation Criteria

VSI = 0: No signs of segregation or bleeding.

VSI = 1: Stable; no apparent segregation, with slight bleeding visible as small water droplets on the surface.

VSI = 2: Some segregation, with slight mortar separation at the edges (≤10 mm) or coarse aggregates stacking at the center of the mortar spread.

VSI = 3: Strong segregation, with significant mortar separation at the edges (>10 mm) or coarse aggregates heavily concentrated at the center of a wide mortar spread.

Determining Slump Flow (SF) and T500 Time

The SCC mixture is poured into a cone and then lifted vertically. The time taken for the concrete mix to flow outward and reach a circular diameter of 500 mm is recorded as T500 (Figure 5). Once the SCC mixture completes its flow, the final diameter of the mortar ring is measured as the slump flow (SF) value. The typical SF value ranges from 650-800 mm, while the T500 time generally falls within 2-5 seconds.

Determination of Passing Ability (Flow Through Ability)

The passing ability through the L-box is determined using the L-box apparatus, which measures the ratio of the heights of two mortar columns (Hz/H1) after the SCC mixture flows through the L-box (Figure 6). The passing ability through the V-funnel is evaluated by pouring the SCC mixture into the funnel until it is filled. The bottom gate of the funnel is then opened, and a timer is used to record the time taken for the concrete to flow out (ultimately measured as Tv).

Specimen Preparation

The specimens were prepared following ASTM C192 [29] For molding and curing. Compressive strength was tested according to ASTM C39 [30] Using 150 × 300 mm cylindrical specimens. Flexural tensile strength was determined per ASTM C78 [31], utilizing 150 × 150 × 600 mm beam specimens under third-point loading. All specimens were demolded after 24 hours and cured in water at 23 ± 2°C until testing at 28 days**.** Self-compacting concrete (SCC) was placed in molds without vibration to maintain its self-consolidating properties.

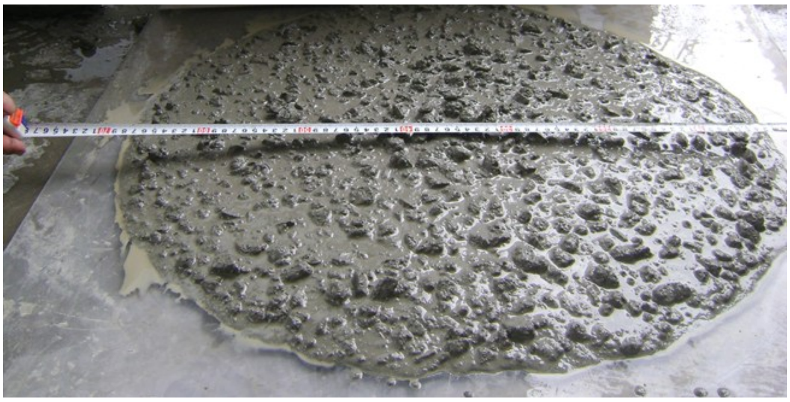

Figure 5. Slump Flow Test Experiment

Figure 6. Experiment for Determining Passing Ability Using the L-box, V-funnel

3. Results

Based on the experimental standards [25], [26], [27], [28], [29], Table 6 presents the workability characteristics of fresh SCC, including slump flow, T-500 flow time, V-funnel time, and L-Box ratio, which indicate the mixture's fluidity, filling ability, and stability. The values shown in the table ensure consistency and statistical robustness by taking multiple measurements and averaging them.

The compressive strength test was conducted according to ASTM C39 standard [30]. The test was performed on three specimens at 28 days of age for each type of self-compacting concrete. Meanwhile, the flexural tensile strength was determined according to ASTM C78 [31]. Each flexural strength result is the average of three specimens. Figure 7 presents self-compacting concrete's compressive and flexural tensile strength results, along with the corresponding standard deviations.

The accuracy and consistency of building materials research depend on the reliability of experimental data. Standard deviation (σ) measures data dispersion relative to the mean, while the coefficient of variation (CV) assesses data stability: CV ≤ 5%: High reliability with minimal variation; 5% < CV < 10%: Moderate reliability with slight variations; CV ≥ 10%: Significant variation, requiring further investigation into the experimental method. Utilizing these criteria allows for the evaluation of the reliability of the experimental results.

Table 6. Fresh SCC Workability Characteristics

Mixes	Slump Flow (mm)	T-500 (s)	V-funnel (s)	L-Box Ratio
SCC0	725	3	6	0.95
SCC1	765	2	7	1
SCC2	745	2	6	1
SCC3	730	2	6	0.96
SCC4	730	4	10	1
SCC5	716	3	9	0.92
SCC6	698	3	8	0.9
SCC2	745	2	6	1
SCC5	716	3	9	0.92
SCC7	645	5	12	0.89

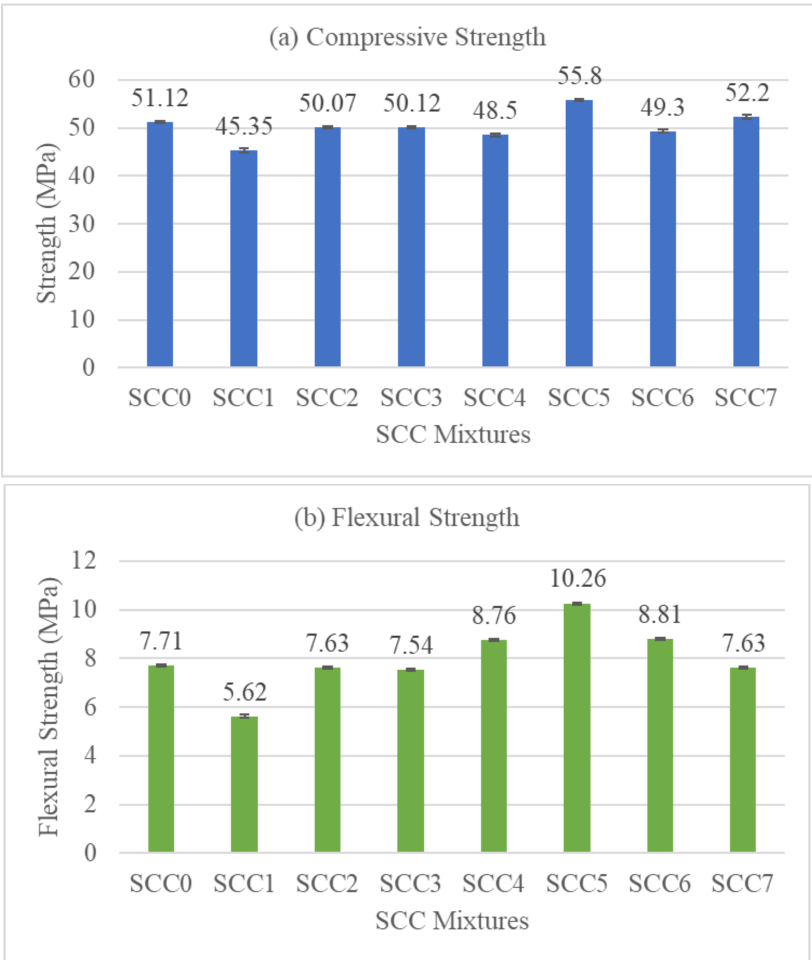

Figure 7. Experimental results: (a) Compressive strength; (b) Flexural strength

Compressive strength at 28 days ranged from 45.35 MPa to 55.8 MPa across the mixtures, with standard deviations between 0.2 and 0.43 MPa. All results exhibited low coefficients of variation (CV < 1%), indicating reliable measurements (Figure 7a).

Flexural strength at 28 days ranged from 5.62 MPa to 10.26 MPa, with low standard deviations (0.04–0.063 MPa) and coefficients of variation (CV < 1.1%), demonstrating high repeatability (Figure 7b). These results provide a strong basis for further interpretation of the effects of GO and FA in Section 4.

4. Discussion

SCC can flow and compact independently, eliminating the necessity for mechanical vibration, which significantly improves construction quality and structural durability. Nonetheless, the integration of nano-materials like GO can affect the fresh properties of SCC, especially slump flow, viscosity (V-Funnel), spreading time (T500), and passing ability through reinforcement (L-Box Ratio). Furthermore, FA significantly enhances workability by lowering viscosity and boosting the fluidity of the mixture. The examination of data from Tables 4 and 6 indicates notable alterations in SCC's workability upon the incorporation of GO and FA, corroborating earlier research

4.1. Impact of FA and GO on the Slump Flow

The slump flow test serves as a crucial metric for assessing the flowability and self-compaction characteristics of SCC. The integration of FA and GO significantly impacts the rheological properties of SCC, affecting its fluidity, cohesiveness, and segregation resistance. The experimental findings demonstrate a positive correlation between FA content and slump flow, while GO shows an inverse relationship, resulting in a decreased spread diameter.

The rise in slump flow associated with elevated FA content can be explained by the spherical shape of FA particles, which act as micro-ball bearings, minimizing internal friction and improving the mobility of the cementitious paste. From Figure 8, the findings indicate that SCC1 (35% FA) achieved the highest slump flow of 765 mm, highlighting the effective lubricating properties of FA in enhancing workability. Similarly, SCC2 (25% FA) and SCC3 (15% FA) demonstrated satisfactory slump flow values of 745 mm and 730 mm, respectively. This indicates that moderate FA replacement (25%-35%) optimizes SCC flowability while avoiding excessive dilution of the cementitious phase. The results are consistent with earlier research, indicating that FA replacement levels of up to 40% improve workability by augmenting paste volume and decreasing water demand [32].

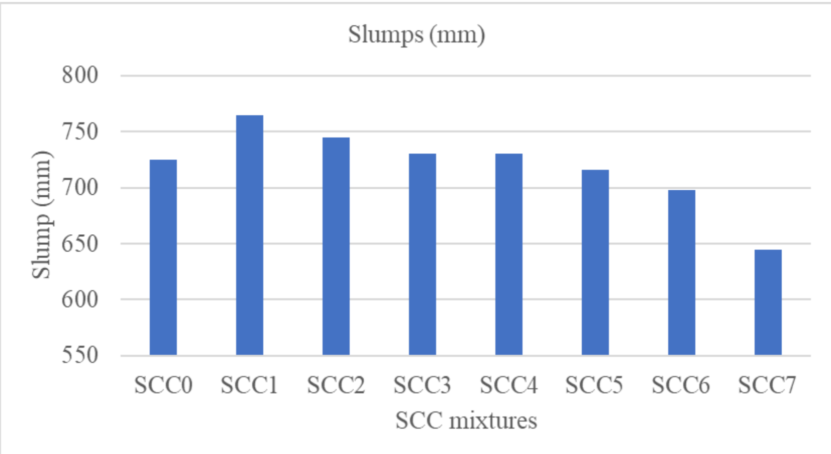

Figure 8. Slump chart of SCC mixtures

On the other hand, the addition of GO adversely affects slump flow, as seen in SCC5, SCC6, and SCC7, where a rise in GO content led to a gradual decrease in spread diameter. SCC7 (0.06% GO) demonstrated the lowest slump flow (645 mm), suggesting that GO considerably enhances the viscosity of the cement matrix. This phenomenon results from the extensive surface area and hydrophilic characteristics of GO, resulting in enhanced water adsorption, interparticle interactions, and the establishment of a more compact hydration network. Prior studies have shown that GO particles aid in the nucleation of hydration products, enhancing early-age densification while concurrently limiting flowability [33]. The reduction in slump flow associated with the incorporation of GO is attributed to the robust van der Waals forces present between GO nanosheets. These forces encourage particle aggregation, which in turn diminishes dispersion efficiency and elevates the yield stress of the SCC mixture [34].

The observations underscore the differing impacts of FA and GO on the rheological properties of SCC. FA improves flowability by minimizing interparticle friction and augmenting paste volume, whereas GO contributes to increased viscosity owing to its elevated surface energy and ability to absorb water. This highlights the importance of meticulously refining FA-GO combinations in SCC mix designs. For optimal workability, keeping FA replacement between 25%-35% is advisable, and ensuring that GO content remains below 0.03%-0.05%. Furthermore, employing high-range water-reducing admixtures (HRWR) like polycarboxylate ether (PCE) is crucial for alleviating the negative impacts of GO on flowability, thereby achieving an ideal equilibrium between workability and mechanical performance [35].

4.2. Impact of FA and GO on T500 and V-Funnel Viscosity

The T500 and V-Funnel tests play a vital role in evaluating the viscosity and flow time of SCC, offering valuable information regarding the spreadability and resistance to flow obstruction. The integration of FA and GO markedly affects the rheological properties of SCC by modifying its fluidity, cohesion, and internal friction in the cementitious matrix. The experimental results indicate that increased FA content promotes quicker spreading and reduces viscosity, while adding GO raises viscosity, resulting in extended flow durations.

The T500 test assesses the duration needed for SCC to extend to a diameter of 500 mm, indicating the initial flow properties. Figure 9 demonstrates that increased FA content leads to a decrease in T500 time, as shown in SCC1 (35% FA), which recorded the quickest flow time of 2 seconds, thereby affirming the contribution of FA in enhancing fluidity and minimizing flow resistance. The spherical nature of FA particles is responsible for enhancing paste lubricity and reducing internal particle friction, which facilitates the more rapid spreading of SCC [32]. Similarly, SCC2 (25% FA) and SCC3 (15% FA) demonstrated T500 values of 2 seconds, reinforcing the observation that a moderate replacement of FA improves the flowability of SCC while avoiding excessive viscosity. This trend aligns with earlier investigations, which have indicated that FA enhances SCC workability by augmenting the paste volume and diminishing interparticle interactions within the cementitious matrix [33].

On the other hand, incorporating GO markedly enhances T500 times, as seen in SCC5, SCC6, and SCC7, where an increased GO content led to a slower spreadability. SCC7 (0.06% GO) demonstrated the longest T500 time (5 seconds), indicating that GO impedes the flow of SCC by elevating yield stress and viscosity. The observed effect is attributed to the robust hydrogen bonding between GO nanosheets and cement particles. This interaction facilitates the development of a more compact hydration network, thereby limiting the mobility within the mixture [34]. The elevated surface area and reactive functional groups of GO promote water adsorption, resulting in increased cohesion and diminished fluidity, thereby prolonging T500 times. Earlier investigations have shown that even minimal GO dosages (<0.05%) can notably influence SCC rheology by enhancing cohesion and restricting the movement of free particles [34].

Similarly, the V-Funnel test evaluates the flow duration of SCC through a constricted passage, offering a straightforward evaluation of viscosity and resistance to blockage. Figure 9 also indicates that including FA leads to decreased viscosity, exemplified by SCC1 (35% FA), which achieved a

V-Funnel time of 7 seconds, reflecting minimal internal friction and improved workability. Nevertheless, the addition of GO led to a significant rise in V-Funnel times, with SCC7 (0.06% GO) showing the peak value recorded at 12 seconds. This underscores the viscosity-enhancing properties of GO, attributed to its capacity to bind free water molecules and facilitate early-age hydration densification [36].

The findings validate the differing impacts of FA and GO on the rheological properties of SCC. FA improves flowability by minimizing internal friction and augmenting paste volume, whereas GO contributes to increased viscosity through its ability to absorb water and its interactions at the nanoscale. Consequently, achieving an ideal equilibrium between workability and viscosity management is essential. To address the excessive viscosity caused by GO, it is advisable to restrict the GO content to a range of 0.03%-0.05%. Additionally, the replacement of FA should be kept between 25%-30% to ensure sufficient flowability. Furthermore, employing polycarboxylate-based superplasticizers is crucial to mitigate the viscosity rise caused by GO, thereby achieving a well-optimized SCC mix that satisfies both workability and mechanical performance standards [37].

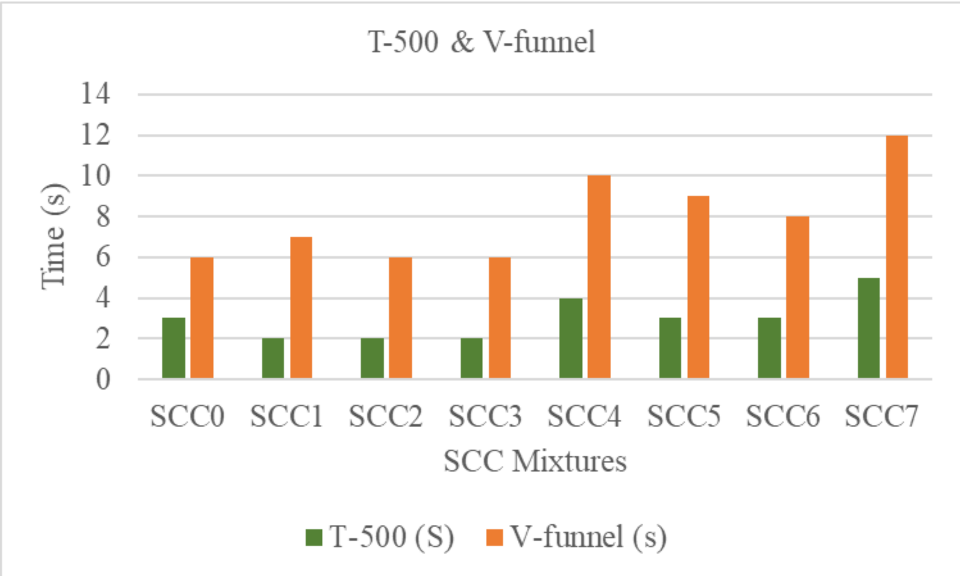

Figure 9. T-500 and V-funnel charts of SCC mixtures

4.3. Impact of FA and GO on L-Box Ratio

The L-Box test is an essential measure of SCC's capacity to navigate through reinforcement without obstruction, demonstrating its flowability in constrained environments and its resistance to segregation. Incorporating FA and GO is crucial in altering this property by affecting the concrete matrix's viscosity, cohesion, and particle dispersion. The experimental results demonstrate that FA improves passing ability by minimizing internal friction, while GO adversely impacts passing ability by elevating viscosity and diminishing flow continuity.

Figure 10 indicates that increased FA content enhances SCC's capacity to navigate through reinforcement, as shown by SCC1 (35% FA), which attained an L-Box ratio of 1.00, reflecting outstanding flowability and low resistance to movement. The enhancement observed can be linked to the spherical shape of FA particles, which serve as lubricants, minimizing friction between particles and improving the material's capacity to move through confined areas [32]. The L-Box ratios of SCC2 (25% FA) and SCC3 (15% FA) were 1.00 and 0.96, respectively. This further confirms that FA enhances the passing ability of SCC by increasing the volume of paste and minimizing coarse aggregate interlocking. The results align with earlier research, indicating that FA replacement levels of 20%-35% improve SCC flow properties, especially in confined areas like reinforced sections [13], [33].

On the other hand, the addition of GO has an adverse impact on L-Box performance, as seen in SCC5, SCC6, and SCC7, where increased GO content led to a gradual decline in L-Box ratios. SCC7 (0.06% GO) demonstrated the lowest L-Box ratio (0.89), indicating that increased GO concentrations hinder SCC's capacity to flow through reinforcement. The observed behavior is linked to the significant surface area and water-absorbing characteristics of GO, resulting in heightened viscosity and cohesion. This, in turn, causes SCC to demonstrate enhanced resistance to movement when under constrained condition [34]. Furthermore, GO promotes the development of a more compact hydration network, enhancing interparticle bonding and decreasing flowability, which further restricts SCC's capacity to navigate through reinforcement [35].

The observations highlight the differing impacts of FA and GO on SCC's passing capability. FA improves flowability and passing ability by minimizing particle friction and augmenting the volume of free paste. In contrast, GO contributes to increased viscosity, hindering movement through dense reinforcement. For optimal L-Box ratio maintenance, limiting GO content to ≤0.03% is advisable and keeping FA replacement within the range of 25%-30%. Furthermore, employing high-range water-reducing admixtures (PCE-based superplasticizers) is crucial to mitigate the viscosity increase caused by GO, thereby ensuring that SCC maintains its self-compacting properties while also gaining from the mechanical improvements provided by GO [36].

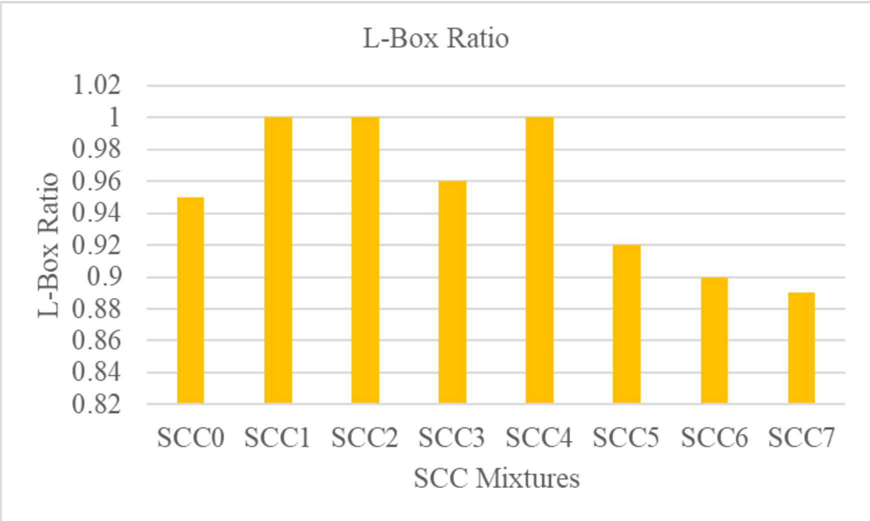

Figure 10. L-Box ratio chart of SCC mixtures

4.4. Impact of FA and GO on the Compressive Strength

Compressive strength is a critical feature of concrete that dictates its load-bearing capability and structural integrity. The integration of FA and GO markedly affects the hydration process, microstructural densification, and mechanical properties of SCC. The experimental findings indicate that moderate FA substitution (15%-30%) improves long-term compressive strength, whilst GO is a nano-reinforcement, optimizing microstructure and enhancing mechanical properties to an ideal limit. Excessive FA or GO might result in a decrease in strength due to microstructural defects.

The findings demonstrate that FA enhances compressive strength primarily via its pozzolanic reaction, which generates secondary calcium silicate hydrate (C-S-H) gel, hence enhancing the interfacial transition zone (ITZ) between the cement paste and aggregates [31]. SCC5 (25% FA) demonstrated the greatest compressive strength (55.8 MPa), indicating that moderate FA inclusion optimizes the binder formulation and improves long-term strength development. Nonetheless, SCC1 (35% FA) exhibited the lowest compressive strength (45.35 MPa), indicating that a high FA content compromises the cement matrix, diminishing early-age strength. This corresponds with prior research suggesting that FA replacement above 30% may impede initial hydration, resulting in postponed strength progression due to reduced availability of cementitious materials [13], [33].

The incorporation of GO significantly influences compressive strength by improving microstructural densification and crack resistance. GO particles promote nucleation sites for hydration, expediting C-S-H gel formation and enhancing particle packing density [33]. SCC7 (0.06% GO) demonstrated a compressive strength of 52.2 MPa, exceeding SCC1 (45.35 MPa), although falling just short of SCC5 (55.8 MPa). The diminished strength at elevated GO concentrations (>0.05%) is ascribed to GO agglomeration, which impedes uniform particle distribution and engenders localized weak regions within the matrix [35]. Previous research has found analogous findings, indicating that an ideal GO content of 0.02%-0.05% enhances compressive strength by as much as 20%, whereas high GO concentrations over 0.06% result in diminished strength due to particle aggregation [36].

These findings validate that FA and GO exert complementary influences on the compressive strength of SCC. FA promotes long-term strength growth via pozzolanic action, whilst GO bolsters microstructural integrity by reducing microcrack propagation. Excessive FA (>30%) diminishes early-age strength due to diluting effects, while excessive GO (>0.05%) decreases efficiency due to agglomeration. To enhance compressive strength, an optimized SCC formulation should include 25%-30% FA and 0.03%-0.05% graphene oxide, maintaining a balance among workability, hydration efficiency, and structural integrity [37]

4.5. Impact of FA and GO on the Flexural Strength

Flexural strength is an essential mechanical parameter that influences the tensile resistance and fracture propagation characteristics of SCC, especially under bending loads. The integration of FA and GO markedly affects the tensile stress distribution, microstructural reinforcement, and fracture resistance of SCC. The experimental findings indicate that moderate FA substitution (25%-30%) improves flexural performance, whereas GO aids in matrix densification and crack bridging, enhancing tensile capacity to an optimal limit. Excessive FA or GO can reduce flexural performance due to compromised interfacial bonding and particle agglomeration.

The findings indicate that FA augments flexural strength by enhancing the interfacial transition zone (ITZ) and facilitating subsequent hydration processes. FA interacts with calcium hydroxide (CH) to generate supplementary calcium silicate hydrate (C-S-H), hence enhancing the pore structure and augmenting the adhesion between cement paste and aggregates [32]. SCC5 (25% FA) demonstrated the greatest flexural strength (10.26 MPa), indicating that modest FA substitution optimizes tensile load distribution and improves fracture resistance. Nonetheless, SCC1 (35% FA) exhibited a markedly decreased flexural strength (5.62 MPa), suggesting that excess FA compromises the cohesiveness between the paste and aggregates, impairing tensile performance. This finding corroborates previous studies indicating that FA replacement over 30% can enhance brittleness due to diminished cementitious binder content and protracted hydration effects [13], [33].

Likewise, GO markedly affects SCC's flexural strength by serving as a nano-reinforcement, inhibiting the beginning and spread of microcracks. GO promotes the establishment of a thick hydration network, improving the mechanical interlocking among cementitious phases and augmenting the tensile stress capacity of the matrix [35]. SCC7 (0.06% GO) had a flexural strength of 8.64 MPa, indicating that the inclusion of GO enhances SCC by optimizing the microstructure and augmenting fracture resistance. SCC5 (0.03% GO) exhibited greater flexural strength (10.26 MPa) than SCC7, indicating that high GO (>0.05%) may cause agglomeration, creating stress concentration spots that adversely affect crack resistance [35]. The findings align with prior research indicating that a GO level of 0.02%-0.05% improves flexural strength by 10%-20%, but elevated concentrations diminish efficacy due to inadequate dispersion and localized weak areas [36].

These findings highlight the synergistic impact of FA and GO on the flexural strength of SCC. FA enhances ductility and tensile load distribution via pozzolanic activity and interfacial transition zone refinement, whereas GO fortifies the microstructure by reducing crack propagation. Excess fatty acid (FA) beyond 30% diminishes flexural capacity because of reduced binder availability, while excessive GO beyond 0.05% causes agglomeration, impairing stress transmission efficiency. To enhance the flexural strength of SCC, the proposed mix design should include 25%-30% FA and 0.03%-0.05% GO, achieving a balance among tensile reinforcement, crack resistance, and overall structural efficacy [37].

5. Conclusion

This investigation offers an in-depth assessment of how FA and GO influence both the fresh and hardened characteristics of SCC. The results indicate that FA significantly enhances workability, whereas GO improves mechanical performance by facilitating microstructural refinement and crack-bridging mechanisms. The replacement of FA by 25%-30% leads to a notable enhancement in slump flow, a reduction in viscosity, and an improvement in passing ability, collectively promoting fluidity and cohesiveness in SCC. Nonetheless, an increased FA content exceeding 30% compromises the compressive strength at early ages, attributed to the effects of cement dilution and the postponement of hydration reactions. On the other hand, incorporating GO up to 0.05% optimally improves compressive strength, flexural resistance, and ITZ densification, thereby validating its potential as a nano-reinforcement. However, an excessive amount of GO (greater than 0.05%, namely in this study 0.06% GO by weight of bender) results in an increase in viscosity, which causes agglomeration, stress concentration, and ultimately a reduction in strength.

The research demonstrates that FA and GO show a synergistic but contrasting effect on SCC performance. FA enhances flowability but compromises early-age strength, while GO improves mechanical properties yet adversely impacts fresh-state rheology. The ideal SCC formulation must include 25%-30% FA and 0.03%-0.05% GO by weight of bender, achieving a harmonious balance of workability, mechanical strength, and longevity. To mitigate the increase in viscosity linked to GO, it is advisable to employ high-range water-reducing admixtures (PCE-based superplasticizers) to sustain flowability while ensuring structural integrity.

Future investigations should concentrate on enhancing GO dispersion methods, as agglomeration continues to pose a significant challenge impacting the consistency of SCC. It is essential to examine hybrid binder systems that incorporate additional supplementary cementitious materials (SCMs), including silica fume and ground granulated blast furnace slag (GGBFS), to improve the mechanical properties and durability of SCC. Furthermore, conducting long-term durability studies and implementing large-scale field applications are crucial for evaluating the practical use of FA-GO-enhanced SCC in actual construction environments. Future efforts must assess GO’s influence on SCC concerning dynamic loading, shrinkage behavior, and sustainability factors, confirming its appropriateness for high-performance and sustainable construction applications.

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Conflicts of Interest

All authors do not have a conflict of interest

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