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EFFECT OF FLY ASH AND SILICA FUME AS PARTIAL REPLACEMENTS OF CEMENT ON THE MECHANICAL PROPERTIES OF SELF-COMPACTING CONCRETE

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ABSTRACT: Self-compacting concrete (SCC) is a type of concrete that can flow and fill molds without the need for mechanical compaction, thereby improving the overall efficiency of concrete construction projects. The use of fly ash and silica fume in SCC can improve its mechanical properties. Therefore, this study investigates the effect of partial cement replacement using 15% fly ash and 10% silica fume on the fresh and hardened properties of SCC. A total of 48 cylindrical specimens were prepared, consisting of 24 specimens for compressive strength testing and 24 specimens for tensile strength testing. Fresh concrete properties were evaluated using slump flow and V-funnel tests in accordance with ACI 237R-07, while compressive and tensile strengths were tested at curing ages of 7 and 28 days. The results showed that the addition of 15% fly ash increased the slump flow, while 10% silica fume reduced the slump flow due to higher water demand. In terms of mechanical properties, SCC mixtures containing fly ash and silica fume exhibited slightly lower compressive strength at 7 days. However, at 28 days, significant strength improvements were observed. The compressive strength increased by up to 17.75% in the mixture containing 10% silica fume, while the tensile strength showed a maximum increase of 7.50%. These findings indicate that silica fume, in particular, is highly effective in enhancing the long-term mechanical performance of SCC.

Keywords: SCC, Fly ash, Silica fume, Slump flow, Mechanical properties

1. INTRODUCTION

Self-compacting concrete (SCC) is a high-performance concrete that is capable of flowing and filling formwork under its own weight without the need for mechanical vibration (Fig.1). This type of concrete was first developed in Japan in the early 1990s to overcome problems related to inadequate compaction, labor limitations, and durability issues in conventional concrete construction [1–4]. Since then, SCC has been increasingly applied in modern construction due to its excellent workability, homogeneity, and ability to ensure consistent concrete quality.

Compared to conventional vibrated concrete, SCC exhibits high flowability while maintaining sufficient viscosity and resistance to segregation. These characteristics allow SCC to pass through densely reinforced sections and complex formwork geometries, making it particularly suitable for tunnels, bridge piers, high-rise buildings, and precast concrete elements (Fig.2) [5–6]. By eliminating the need for vibration and ensuring uniform material distribution, SCC offers a reliable solution to these challenges and contributes to improved structural safety and long-term performance.

Poor compaction and segregation in conventional concrete can significantly reduce structural performance and durability. Inadequately compacted concrete often leads to reduced strength and increased permeability, which may compromise structural safety, especially under seismic loading conditions [7–10]. SCC offers an effective solution by ensuring uniform material distribution and proper encapsulation of reinforcement, thereby improving the reliability and long-term performance of concrete structures.

Despite its advantages, SCC generally requires a higher content of cement and fine materials to achieve the desired rheological properties. This increased cement usage may lead to higher costs and greater environmental impacts, particularly due to carbon dioxide (CO_2) emissions associated with cement production. Consequently, the use of supplementary cementitious materials (SCMs) as partial replacements for cement has become an important strategy in the development of sustainable SCC mixtures.

Fly ash and silica fume are among the most commonly used SCMs in concrete technology. Fly ash, a by-product of coal combustion, possesses fine and spherical particles that can improve concrete workability, reduce water demand, and enhance long-term strength through pozzolanic reactions. In SCC, fly ash is especially beneficial for improving flowability and reducing the risk of segregation [11-12]. Silica fume, on the other hand, is an ultrafine material rich in amorphous silicon dioxide with very high pozzolanic activity [13]. Its incorporation can significantly enhance mechanical strength and densify the concrete microstructure, although it may reduce workability due to increased water demand.

Fig. 1 Self-compacted concrete [1]

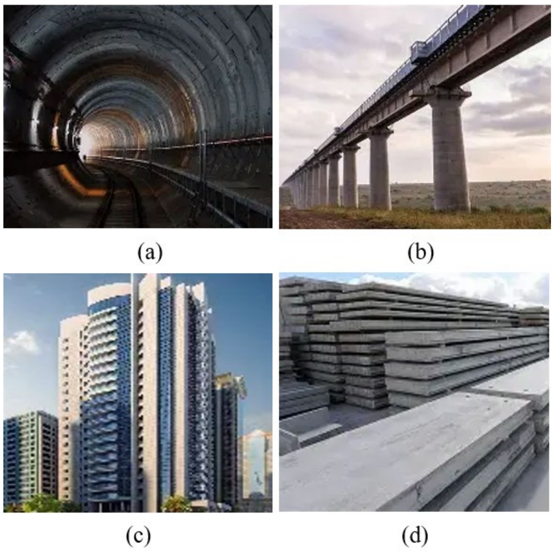

Fig. 2 Application of SCC concrete: a) tunnels, b) bridge pillars, c) high-rise building, d) precast concrete

Previous studies have demonstrated that fly ash and silica fume can improve the fresh and hardened properties of SCC; however, their effects vary depending on replacement levels and curing age [11-13]. In particular, the combined influence of fly ash and silica fume on both early-age and later-age mechanical properties of SCC remains limited and requires further experimental investigation

Therefore, this study aims to evaluate the effect of partial replacement of cement with fly ash and silica fume on the fresh and hardened properties of self-compacting concrete. SCC mixtures incorporating 15% fly ash and 10% silica fume, both individually and in combination, are investigated. Fresh concrete performance is assessed through slump flow and V-funnel tests, while hardened concrete properties are evaluated in terms of compressive and tensile strength at curing ages of 7 and 28 days. The results of this study are expected to contribute to the development of efficient, high-performance, and environmentally friendly SCC mixtures.

2. RESEARCH SIGNIFICANCE

This study aims to determine the effect of the addition of fly ash and silica fume as a substitute for some cement to SCC concrete in increasing its mechanical strength, especially its compressive and tensile strength. This study examined the fresh and hardened properties of self-compacting concrete with fly ash and silica fumes, taking into account the impact of waste by reducing fly ash waste. The results of this research can be used as a new invention in the world of concrete technology that has the advantages of workability, durability, and high strength, so that it can be applied well to high-rise buildings and precast concrete structures around the world.

3. MATERIAL AND MIX DESIGN

3.1 Material

3.1.1 Cement

The binding material used in this study is Portland cement of the Portland Composite Cement (PCC) type, with the brand name Semen Tiga Roda, produced by PT Indocement Tunggal Prakarsa Tbk. as shown in Fig. 3. This cement was chosen because it has met the SNI 7064:2014 qualification and has stable quality consistency, so it is expected to provide representative test results for the characteristics of concrete.

Fig.3 Ordinary Portland Cement

3.1.2 Coarse aggregate

Fig.4 Coarse aggregate

Coarse aggregates are obtained from locally available aggregates with a maximum size of 12.5 mm in accordance with ASTM C33/C33M [14], which is produced by the PT. Statika Mitrasarana, used in this study, as shown in Fig.4. The properties of coarse aggregates are shown in Table 1.

Table 1. Properties of coarse aggregate

Property	Value
Specific Gravity	2.64
Absorption	2.09 %
Fine Modulus (FM)	6.06
Water Content	0.86 %

3.1.3 Fine aggregate

Locally available fine aggregates were used in this study, as shown in Fig. 5, with a maximum size of 4.76 mm [15]. Table 2 shows the properties of fine aggregates.

Fig.5 Fine aggregate

Table 2. Properties of fine aggregate

Property	Value
Specific Gravity	2.38
Absorption	0.4 %
Fine Modulus (FM)	2.5
Water Content	1.21 %

3.1.4 Water

Potable water that meets the requirements (SNI 7974-2013) of concrete mixing water that is free from oil, acids, or organic substances will be used for mixing and processing concrete in this study [16].

3.1.5 Admixture

SCC concrete is a concrete that flows easily, so it requires superplasticizer materials such as high-range water reducing admixture (HRWRA). In this study, as shown in Fig. 6, ViscoCrete-3115, a third-generation superplasticizer for concrete and mortar produced by Sika, was used. It is particularly developed to produce high-flow concrete with exceptional flow retention properties.

Fig.6 Sika viscocrete 3115N

3.1.6 Fly ash

Fly Ash is waste from burning coal in power plants, which is used in place of some cement to improve the durability of concrete. The effect of fly ash in concrete is the smooth pozzolan property that makes concrete denser, so that it can reduce pores in concrete, and with the right amount of fly ash, can also increase the strength of concrete.

In this study, Fly ash class C (Fig.7) was used, which, according to ACI, contains pozzolan and hydrolysis properties, has a high CaO content that can harden itself when reacting with water, such as cement, and has the benefit of increasing the compressive strength of concrete. The Fly Ash classification conforms to ASTM C 618–05, shown in Table 3 [17].

Fig.7 Fly ash class C

Table 3. Classification of fly ash

Fly Ash	Class
	C
SiO2 + A12O3 + Fe2O3,min,%	50.0
SO3,max, %	5.0
Moisture Content, max, %	3.0
Loss on ignition, max, %	6.0

3.1.7 Silica fume

Silica Fume is a microscopic material used to improve the strength and resistance of concrete to corrosion and chemical reactions. According to the American Concrete Institute (ACI), silica fume is a very fine concrete additive that has a particle size of about 1/100th the size of a cement particle, as shown in Fig.8. Silica fume is rich in high silicon dioxide (SiO2), more than 85%, and behaves as a reactive pozzolan material (ASTM C168-03) [18]. Physical properties of Silica Fume can be seen in Table 4.

Fig.8 Silica fume

Table 4. Physical properties of silica fume

Physical properties	Value
Particle Size	< 1μm
Color	Dark gray
Bulk Density (kg/m^3)	200 - 300
Specific Gravity	2.2
Smoothness (kg/m^2)	15.000 – 30.000

3.2 Mix Design Proportions

The design of SCC concrete mixtures with a target compressive strength of 62.1 MPa (9000 psi) is calculated based on ACI 211.4R-08 [19]. The water/cement ratio was maintained constant on all mixtures with a value of 0.3. The percentage of fly ash is 15% and silica fume is 10% of the total weight of cement. The control mixture is regulated as 0% fly ash and silica fume. Details of the proportions of concrete mixtures are listed in Table 5

Table 5. Mix proportions of SCC-fly ash-silica fume

Material	FA+SF 0%	FA 15%	SF 10%	FA 15% +SF 10%
Cement (kg/m^3)	628.9	534.6	566.0	471.7
Fine Aggregate (kg/m^3)	698.6	679.0	673.6	654.0
Coarse Agg (kg/m^3)	800.0	800.0	800.0	800.0
Water (kg/m^3)	185.7	185.7	185.7	185.7
FA+SF (kg/m^3)	0.0	94.3	62.9	157.2
Viscocrete-3115 (L/m^3)	1.24	1.24	1.24	1.24

All research activities are carried out systematically and are divided into two tests, namely fresh concrete testing and hardened concrete testing. Fresh concrete testing consists of two tests, namely the flow ability test through the slump flow test and viscosity measurement through the v-funnel test.

Hard concrete testing, as many as 48 cylindrical test pieces were prepared, consisting of 24 cylinders for compressive strength testing, and 24 cylinders for tensile strength testing.

The properties of concrete are measured by the diameter of the deterioration flow using the slump tool (Fig.9) and the separation resistance using the v-funnel (Fig.10) according to ACI237R-07 [20].

The targeted slump diameter range is 650-750 mm, which allows the concrete to flow through tight reinforcement without the need for compaction. Concrete made using cylindrical molds has a diameter of 150 mm and a height of 300 mm (Fig.11). The properties of Self-Compacting Concrete (SCC) were tested using cylindrical test pieces on days 7 and 28 (Fig.12-13), hard concrete tests including compressive strength tests [21], and tensile strength [22], which aims to evaluate the development of the strength and mechanical performance of concrete after the hardening process.

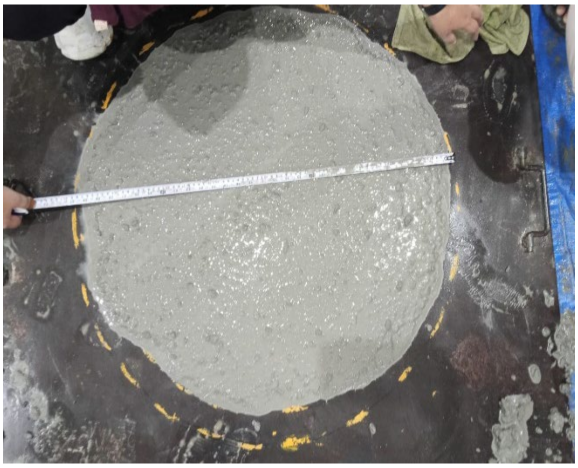

Fig. 9 Slump test

Fig. 10 V funnel test

Fig. 11 Concrete molding process

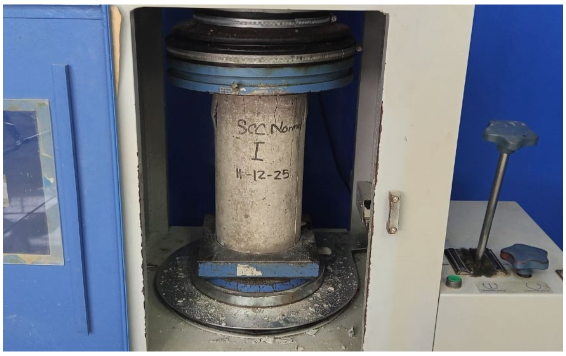

Fig.12 Compression test on cylindrical specimens

Fig.13 Tensile test on cylindrical specimen

4. RESULT AND DISCUSSION

4.1 Properties of Fresh Concrete

The results of fresh concrete testing conducted using the slump flow test and the V-funnel test show that the addition of fly ash and silica fume significantly affects the flowability and viscosity of SCC mixtures. The presence of fly ash increases the slump flow due to its fine and spherical particles, which are able to fill the voids between cement particles and reduce internal friction, allowing the concrete to flow more easily. After the addition of 15% fly ash, the slump flow value increased, indicating that the concrete became more workable and exhibited faster flow characteristics compared to the control mixture, as shown in Fig. 14.

Meanwhile, the addition of 10% silica fume resulted in a decrease in the slump flow value. This behavior occurs because silica fume has extremely fine particles with a very large specific surface area, which increases water demand and causes the concrete mixture to become more viscous. As a consequence, the flowability of the SCC decreased, and the flow became slower compared to the control concrete. This result is reflected in the increased T500 flow time, as presented in Fig. 15, indicating higher viscosity and reduced initial flow rate.

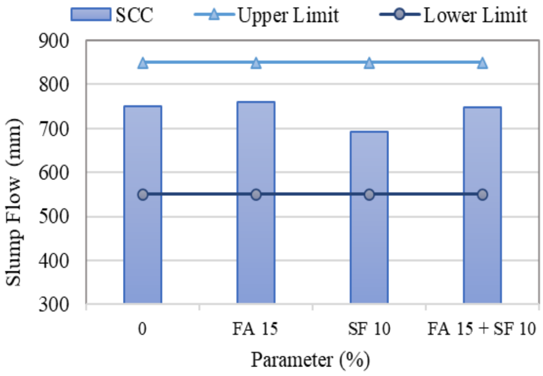

Fig.14 Slump flow result

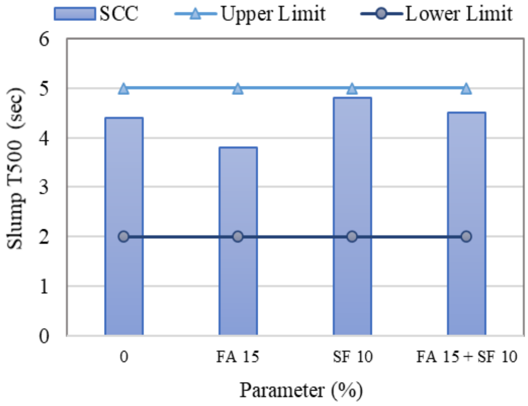

Fig.15 Result of slump T500

The test results of SCC mixtures incorporating both fly ash and silica fume show a combined effect on fresh concrete properties. Fly ash contributes to improving flowability, while silica fume tends to reduce it due to increased water absorption. As a result, the interaction between these two materials produces a balanced SCC mixture. The time required for the concrete to reach a diameter of 500 mm (T500) during the slump flow test represents the viscosity and stability of the concrete mixture. Based on the test results, the T500 values ranged between approximately 4.0 and 5.0 seconds, while the slump flow diameters were in the range of about 650–750 mm, indicating that all mixtures satisfied the SCC workability requirements.

Furthermore, the V-funnel test results for all mixtures demonstrate that the SCC mixtures achieved flow times within the recommended limits, as shown in Fig. 16, indicating adequate viscosity and good resistance to segregation. Overall, all SCC mixtures met the criteria for self-compacting concrete in terms of flowability, viscosity, and stability.

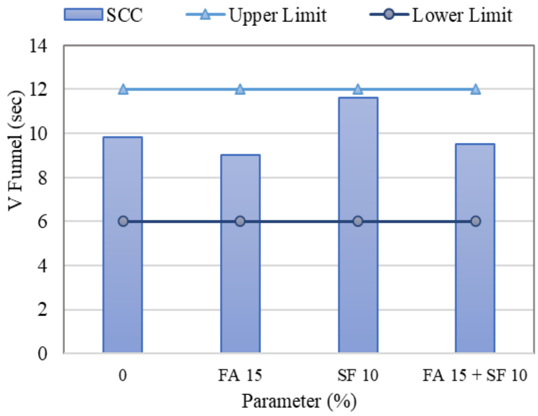

Fig.16 Result of V funnel

4.2 Properties of Hard Concrete

4.2.1 Compressive strength test

The compressive strength of all SCC mixtures was evaluated at curing ages of 7 and 28 days. The test results indicate that the addition of fly ash and silica fume influences the strength development of SCC at both early and later ages, as shown in Fig. 17 and Table 6.

At 7 days, all SCC mixtures containing fly ash and/or silica fume exhibited lower compressive strength than the control mixture. The mixture with 15% fly ash showed a strength reduction of 31.11%, while the mixture with 10% silica fume experienced a reduction of 24.13%. The combined mixture containing 15% fly ash and 10% silica fume exhibited the greatest reduction, reaching 35.24%. This behavior is attributed to the reduced cement content and the slower early-age pozzolanic reaction of fly ash and silica fume, which delays the formation of hydration products responsible for early strength development.

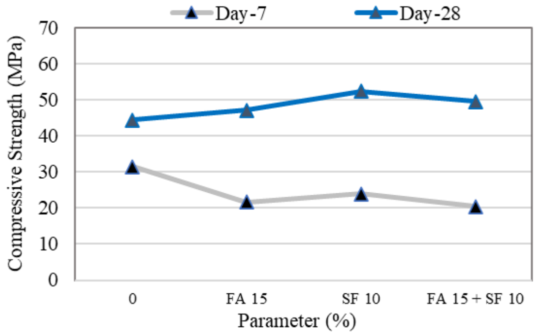

Fig.17 Compressive test results

Table 6. Percentage of increase in compressive strength

No	Parameter SCC (%)	Day-7	Day-28
		Percentage of Increase (%)	Percentage of Increase (%)
1	0.0	-	-
2	FA 15	-31.11	6.07
3	SF 10	-24.13	17.75
4	FA 15 + SF 10	-35.24	11.46

At 28 days, different strength development trends were observed. The SCC mixture containing 15% fly ash showed a modest compressive strength increase of 6.07% compared to the control mixture. A significant improvement was observed in the mixture incorporating 10% silica fume, which achieved the highest compressive strength increase of 17.75%. Meanwhile, the combined mixture of 15% fly ash and 10% silica fume showed an increase of 11.46%.

These results indicate that while fly ash and silica fume reduce early-age compressive strength, silica fume is particularly effective in enhancing the long-term compressive strength of SCC.

4.2.2 Tensile strength test

The tensile strength of SCC mixtures was tested at curing ages of 7 and 28 days, and the results are presented in Fig. 18 and Table 7.

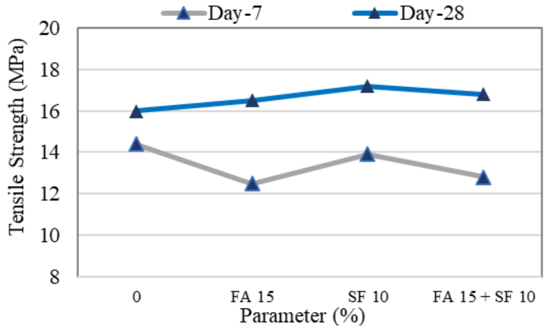

Fig.18 Tensile strength test results

Table 7. Percentage of increase in tensile strength

No	Parameter SCC (%)	Day-7	Day-28
		Percentage of Increase (%)	Percentage of Increase (%)
1	0.0	-	-
2	FA 15	-13.19	3.13
3	SF 10	-3.47	7.50
4	FA 15 + SF 10	-11.11	5.00

At 7 days, all SCC mixtures containing fly ash and silica fume showed lower tensile strength than the control mixture. The mixture with 15% fly ash exhibited a reduction of 13.19%, while the mixture with 10% silica fume showed a smaller reduction of 3.47%. The combined mixture experienced a reduction of 11.11%. This reduction is associated with delayed hydration and weaker early-age bonding between the cement paste and aggregates due to partial cement replacement.

At 28 days, an improvement in tensile strength was observed for all modified SCC mixtures. The mixture containing 15% fly ash showed a tensile strength increase of 3.13%, while the combined mixture of 15% fly ash and 10% silica fume exhibited an increase of 5.00%. The highest tensile strength improvement was achieved by the SCC mixture containing 10% silica fume, with an increase of 7.50% compared to the control mixture. This enhancement is attributed to the micro-filling ability and high pozzolanic activity of silica fume, which improves the interfacial transition zone and reduces microcrack propagation.

Overall, the tensile strength results confirm that silica fume provides the most significant contribution to improving the tensile performance of SCC at later curing ages.

5. CONCLUSION

Based on experimental findings examining the properties of SCC with added fly ash and silica fume, the following conclusions were drawn:

1. The addition of 15% fly ash increased the slump flow due to its fine particle size and filler effect, which enhanced the flowability of SCC. In contrast, the incorporation of 10% silica fume reduced the slump flow as a result of its higher water demand and increased viscosity. The combined use of fly ash and silica fume produced a balanced SCC mixture that satisfied the slump flow, T500, and V-funnel requirements.
2. The compressive strength of SCC at 7 days showed a slight reduction when fly ash and silica fume were used, indicating delayed early hydration. However, at 28 days, all modified SCC mixtures demonstrated higher compressive strength than the control SCC. The greatest improvement was achieved by the mixture containing 10% silica fume, with a compressive strength increase of up to 17.75%, attributed to enhanced pozzolanic reactions and matrix densification.
3. The tensile strength of SCC increased with curing age for all mixtures. At 28 days, SCC incorporating 10% silica fume showed the highest tensile strength improvement, reaching 7.50% compared to the control mixture. This enhancement is associated with improved interfacial bonding and reduced microcrack development resulting from the micro-filling and pozzolanic effects of silica fume.
4. Overall, the partial replacement of cement with fly ash and silica fume effectively improved the fresh and hardened properties of SCC while reducing cement consumption. This approach enhances the mechanical performance and durability of SCC, making it a promising and sustainable construction material.

6. ACKNOWLEDGMENTS

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