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Experimental Investigation on Properties of High Strength Self Compacting Concrete

Rijul Thakur[1], Dr. Hemant Sood[2]
[1]M.E Research Scholar, Department of Civil Engineering, National Institute of Technical Teachers Training and Research, Chandigarh, India
[2]Professor and Head, Department of Civil Engineering, National Institute of Technical Teachers Training and Research, Chandigarh, India

Abstract: Self-Compacting Concrete (SCC) is an advanced concrete technology capable of flowing and consolidating under its own weight without mechanical vibration, making it suitable for heavily reinforced and complex structural elements. This study presents an experimental investigation on the fresh, hardened, and non-destructive properties of High-Strength Self-Compacting Concrete (HSSCC) of grade M60 incorporating fly ash and silica fume as supplementary cementitious materials.

Ordinary Portland Cement (OPC) 43 grade was partially replaced with fly ash at 0%, 10%, 15%, 20%, and 25%, while silica fume content was kept constant at 8%. A polycarboxylic ether-based superplasticizer was used to achieve the required workability, and mix design was carried out as per IS 10262:2019 and IS 456:2000. Fresh properties were evaluated using slump flow, V-funnel, and L-box tests, while hardened properties were assessed through compressive, split tensile, and flexural strength tests at 7 and 28 days. Ultrasonic Pulse Velocity (UPV) testing was conducted to evaluate internal quality.

Results indicated that increasing fly ash content enhanced the workability and flowability of SCC without compromising stability. The mix with 25% fly ash achieved the highest performance, with 28-day compressive strength exceeding 70 MPa and improved tensile and flexural strengths. UPV results confirmed better density and homogeneity. The study concludes that the combined use of fly ash and silica fume is effective in producing sustainable and high-strength SCC suitable for structural applications.

Keywords: High Strength Self-Compacting Concrete, Fly Ash, Silica Fume, Rheological and mechanical Properties, Ultrasonic Pulse Velocity.

I. INTRODUCTION

Concrete is one of the most extensively used construction materials worldwide, second only to water in terms of consumption. The rapid growth of infrastructure development has resulted in increased demand for concrete, leading to depletion of natural resources and heightened environmental concerns. Conventional concrete construction practices often suffer from issues related to inadequate compaction, particularly in densely reinforced sections, resulting in defects such as honeycombing and reduced durability.

Self-Compacting Concrete (SCC)was developed to address these challenges. SCC is capable of flowing and compacting under its own weight [1-8], eliminating the need for mechanical vibration. This technology not only enhances construction quality but also improves working conditions by reducing labour, noise, and energy consumption. When combined with high-strength characteristics, SCC becomes an attractive solution for modern structural applications such as high-rise buildings, bridges, and heavily reinforced members. High Strength Self-Compacting Concrete [9-10] (HSSCC) integrates the advantages of high compressive strength and superior workability. The use of supplementary cementitious materials (SCM's) such as fly ash and silica fume plays a crucial role in achieving these properties while improving sustainability. Fly ash, an industrial by-product from thermal power plants, contributes to improved workability and long-term strength through pozzolanic reactions. Silica fume, with its ultra-fine particles and high silica content, enhances the microstructure and early-age strength of concrete.

The present study aims to develop and evaluate M60 grade HSSCC incorporating fly ash and silica fume, focusing on its fresh, hardened, and non-destructive properties.

II. LITERATURE REVIEW

Extensive research has been conducted on self-compacting concrete to understand its behaviour and optimize its performance. Nan Su (2001) [11] proposed a simplified mix design method emphasizing aggregate packing and paste volume, highlighting the importance of sand content in achieving self-compactability. EFNARC guidelines (2002) [12] provided standardized criteria for assessing SCC properties, including flowability, passing ability, and segregation resistance.

Several studies have explored the use of fly ash in SCC. Cengiz (2005) [13] reported that high-volume fly ash SCC could achieve satisfactory workability and strength when combined with appropriate superplasticizers. Khatib (2008) [14] observed that replacing up to 40% cement with fly ash resulted in compressive strengths exceeding 65 MPa at later ages. Siddique (2011, 2012) [15-16] demonstrated that fly ash [17-18] improves durability characteristics such as resistance to chloride penetration and carbonation.
Silica fume has been widely recognized for enhancing the strength and durability of high-performance concrete. Heba A. Mohamed (2011) [19] reported that SCC mixes containing 15% silica fume achieved higher compressive strength compared to fly ash mixes. The combined use of fly ash and silica fume has been shown to balance early-age strength and long-term performance.
Despite significant progress, further experimental studies are required to optimize mix proportions for high-strength SCC using locally available materials and to evaluate both fresh and hardened properties in detail. This research addresses these gaps by experimentally investigating M60 grade HSSCC incorporating fly ash and silica fume.

III. MATERIALS AND EXPERIMENTAL METHODOLOGY

A. Materials

Ordinary Portland Cement (OPC) of 43 grade conforming to IS 8112:2013 was used as the primary binder, with a specific gravity of 3.15. Fine aggregate consisted of locally available river sand conforming to Zone II as per IS 383:2016, having a fineness modulus of 3.13. Crushed stone with a maximum size of 12.5 mm was used as coarse aggregate. Fly ash sourced from a thermal power plant in Punjab, with a specific gravity of 2.2, was used as a partial cement replacement. Silica fume containing approximately 93% silica was incorporated at a constant dosage of 8% of the total cementitious material. A polycarboxylate ether–based superplasticizer (MasterGlenium Sky 8866) was employed to achieve the desired flowability, and potable water conforming to IS 456:2000 was used for mixing and curing.

B. Mix Design

The mix design for M60 grade SCC was carried out in accordance with IS 10262:2019. The target mean strength was calculated as 68.25 MPa. A water-to-binder ratio of 0.26 was adopted. Fly ash was used as partial replacement of cement at levels of 0%, 10%, 15%, 20%, and 25%, while silica fume content was maintained constant. The final optimized mix consisted of 442.75 kg/m^3 of cement, 165.25 kg/m^3 of fly ash, 53 kg/m^3 of silica fume, 170 litres of water, 615.27 kg/m^3 of fine aggregate, and 921.77 kg/m^3 of coarse aggregate.

C. Testing Program

The experimental program was designed to evaluate the fresh and hardened properties of self-compacting concrete incorporating varying proportions of fly ash as a partial replacement of cement. A series of SCC trial mixes were prepared with fly ash replacement levels of 0%, 10%, 15%, 20%, and 25%, while the dosage of silica fume and superplasticizer was kept constant to maintain consistency in mix performance. All concrete mixes were prepared in a laboratory mixer, ensuring uniform mixing of dry constituents prior to the addition of water and chemical admixture.
The fresh properties of SCC were assessed immediately after mixing using slump flow, T_{50} flow time, V-funnel, and L-box tests in accordance with relevant standards. These tests were conducted to evaluate flowability, filling ability, passing ability, and resistance to segregation of the concrete mixes.
For hardened property evaluation, standard cube, cylinder, and prism specimens were cast and cured under controlled conditions. Compressive strength tests were conducted on cube specimens at 7 and 28 days of curing. Split tensile strength and flexural strength tests were carried out on cylindrical and prismatic specimens, respectively, at the same curing ages. Ultrasonic Pulse Velocity (UPV) measurements were performed on cube specimens prior to compressive strength testing to assess internal quality and homogeneity. The testing program enabled a comprehensive assessment of the influence of fly ash on the performance characteristics of self-compacting concrete.

IV. RESULTS AND DISCUSSION

A. Fresh Properties

The fresh state behaviour of self-compacting concrete incorporating varying proportions of fly ash was evaluated using slump flow, T_{50} flow time, V-funnel, and L-box tests, and the results are discussed collectively based on the observed graphical trends. The slump flow values increased progressively from 720 mm for the reference mix to 785 mm for the mix containing 25% fly ash, demonstrating a clear improvement in flowability with increasing fly ash content.

This enhancement in flow behaviour can be attributed to the increased fines content and the spherical morphology of fly ash particles, which improve particle packing and reduce internal friction within the mix. The corresponding reduction in T_{50} flow time from 4.8 s to 3.8 s further confirms the increased flow rate and reduced viscosity of the SCC mixes with higher fly ash replacement levels.

The V-funnel results show a systematic decrease in flow time from 10 s to 6.6 s as the fly ash content increases, indicating improved flowability and ease of passage through restricted sections. The T_5-minute flow times also exhibited a decreasing trend, suggesting enhanced stability and resistance to segregation even after rest periods. This behaviour reflects the ability of fly ash to improve cohesiveness and maintain uniform distribution of constituents within the SCC matrix. Additionally, the L-box test results reveal a consistent increase in the blocking ratio (H_2/H_1) from 0.82 to 0.91 with increasing fly ash content, indicating improved passing ability through congested reinforcement. All fresh property parameters remained within the prescribed limits for SCC, confirming that the combined use of fly ash and silica fume results in a highly workable, stable, and self-flowing concrete suitable for practical structural applications.

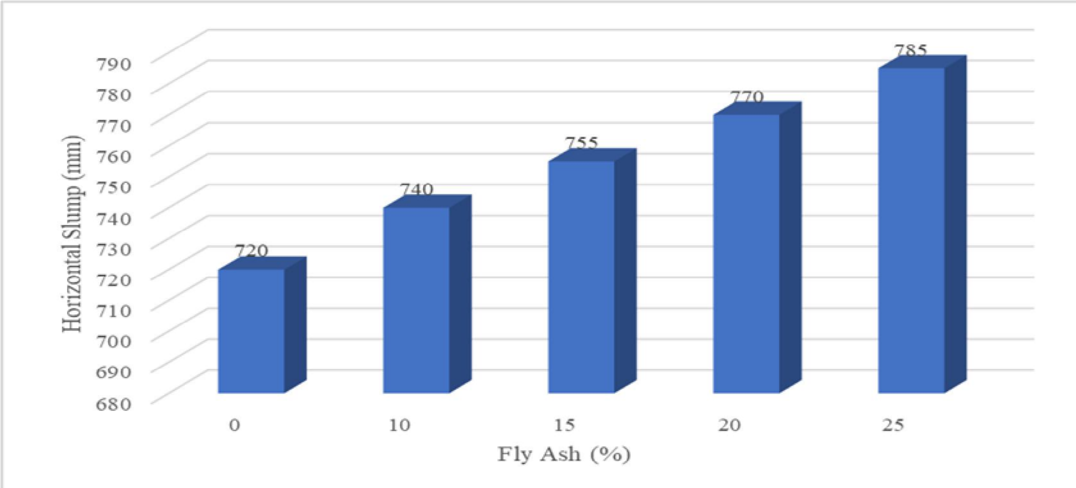

Figure-1: Slump value for different fly ash percentages

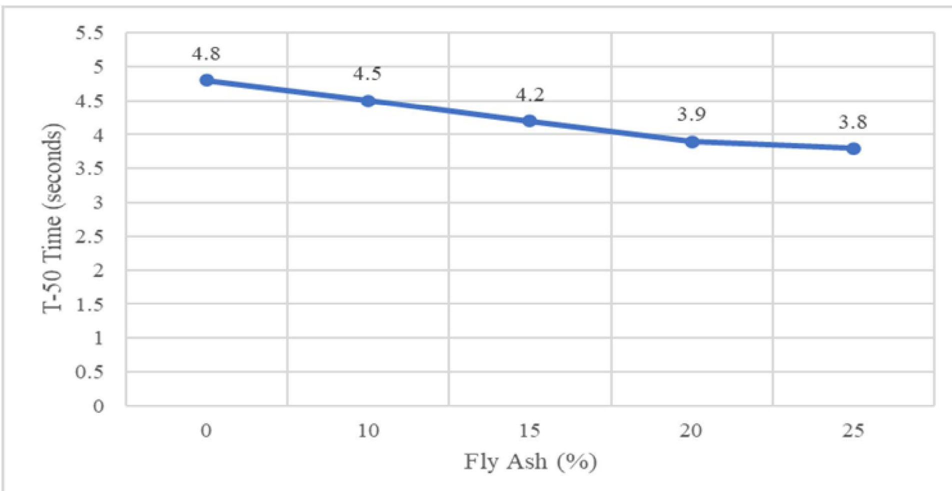

Figure-2: T-50 time for different fly ash percentage

The T50 time, illustrated in Figure 2, was found to decrease with higher content of fly ash, indicating a slight increase in flow speed due to the increased fineness and cohesiveness of the mix.

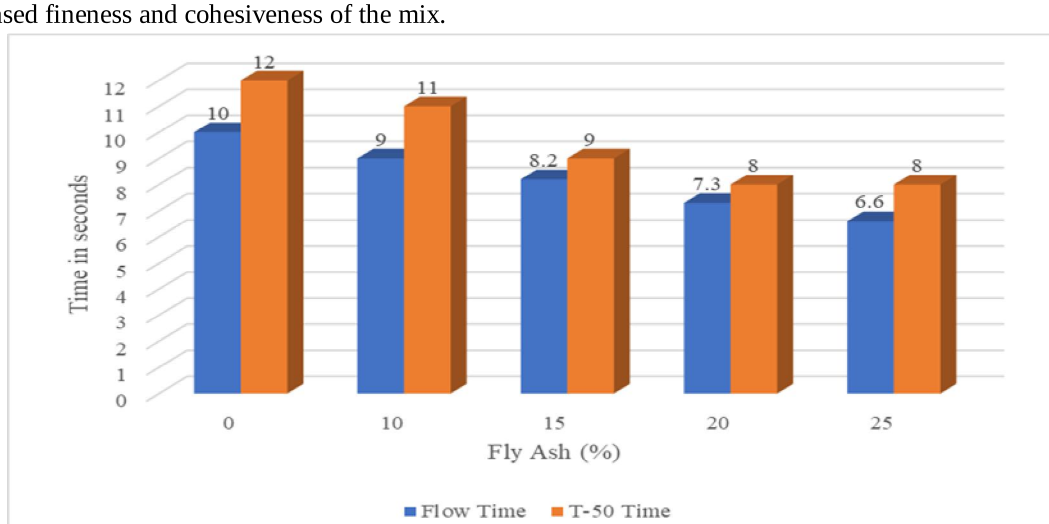

Figure-3: Flow time and $T_{5\ min}$ time comparison

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Figure 3 illustrates the comparison between flow time and T5-minute time for mixes containing different fly ash percentages. This comparison helps in understanding how varying fly ash content influences the flowability and stability characteristics of self-compacting concrete.

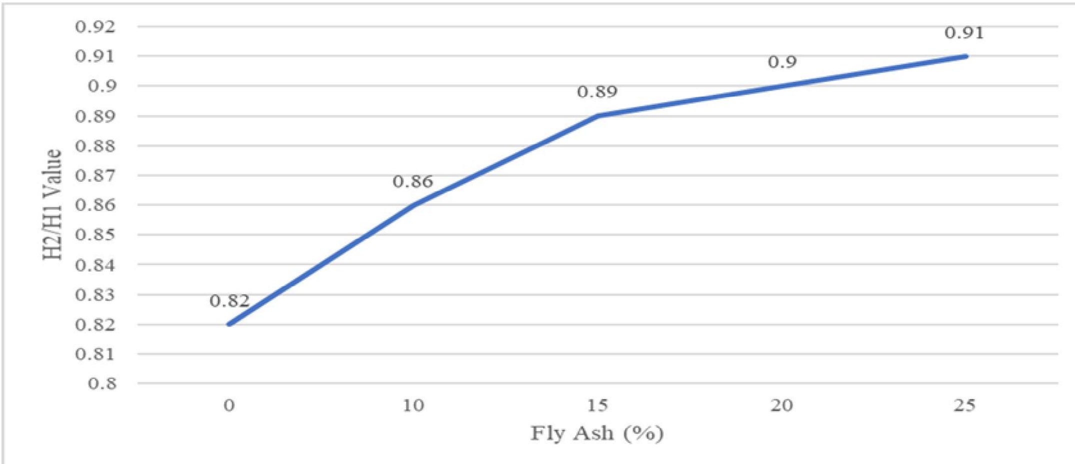

Figure-4: L-box value with different fly ash percentage

Figure 4 presents the trend of H_2/H_1 values increasing as the fly ash content increases, illustrating the effect of fly ash on the passing ability of the self-compacting concrete.

B. Hardened Properties

The hardened performance of SCC mixes was evaluated through compressive strength, split tensile strength, flexural strength, and ultrasonic pulse velocity (UPV) tests, and the combined results indicate a consistent enhancement in mechanical and structural quality with increasing fly ash content as shown in figure. The compressive strength results show a steady increase at both 7 and 28 days of curing, with 28-day strength improving from approximately 62.5 MPa for the reference mix to about 70.6 MPa for SCC containing 25% fly ash. This improvement is attributed to the pozzolanic reaction between fly ash and calcium hydroxide, resulting in the formation of additional C-S-H gel and a denser cementitious matrix. The percentage increase in compressive strength observed from the graphical analysis further confirms the beneficial role of fly ash in strength development, particularly at later ages. A similar increasing trend was observed in split tensile and flexural strengths with increasing fly ash content as shown in figure. The split tensile strength increased from approximately 4.3 MPa to 5.0 MPa at 7 days and from 5.0 MPa to 5.9 MPa at 28 days, indicating improved tensile resistance and enhanced crack-bridging capability of the SCC matrix. Flexural strength also exhibited gradual improvement, reaching up to 6.0 MPa at 28 days for the highest fly ash replacement level. These improvements reflect enhanced bond strength at the aggregate-paste interface and reduced micro-cracking due to improved microstructural refinement.

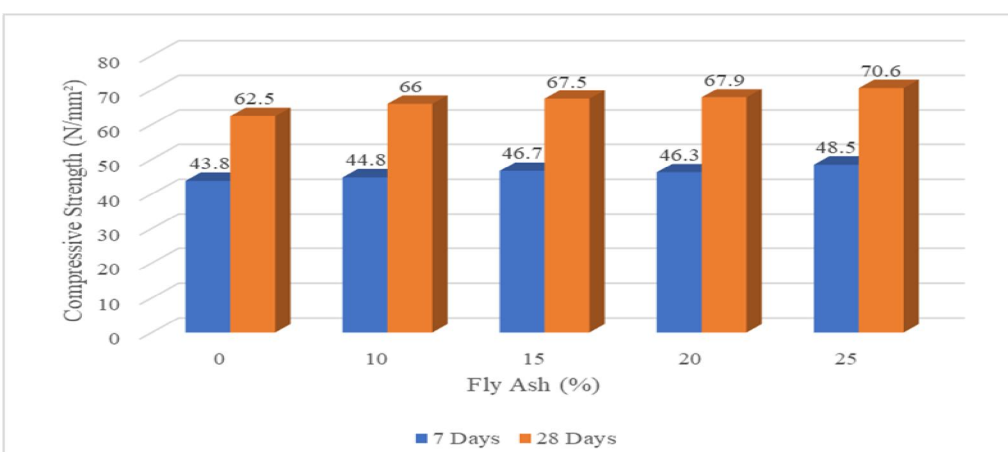

Figure-5: 7th and 28th day comparison of compressive strength with different percentage of fly ash

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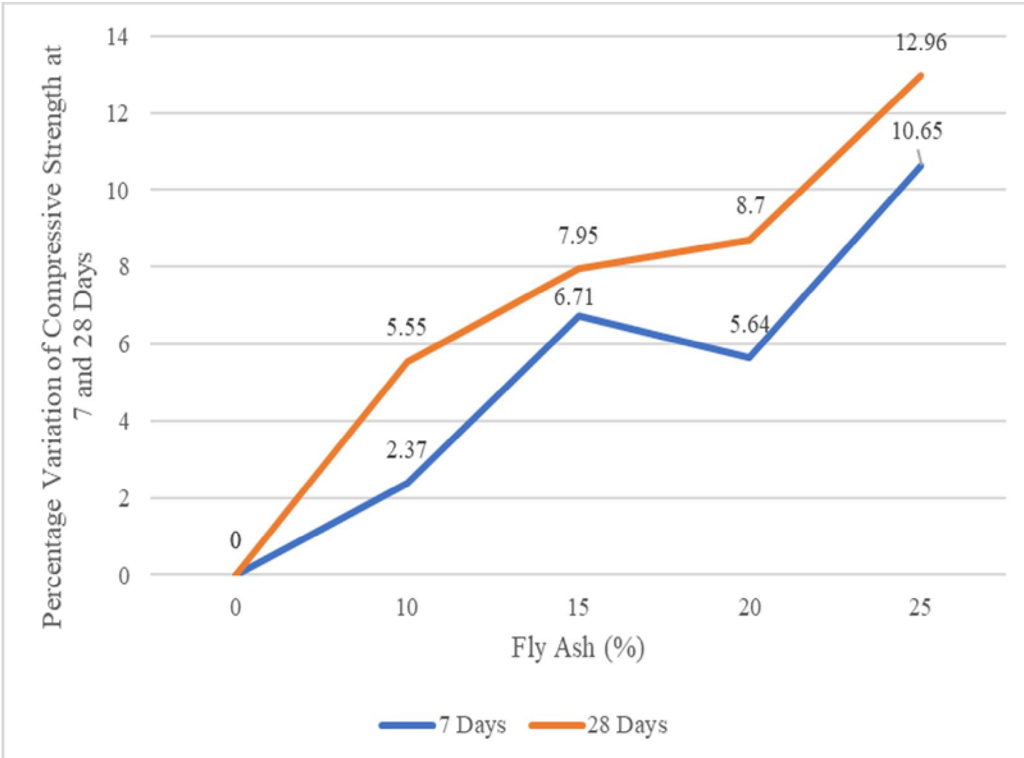

Figure-6: Increase in percentage of compressive strength with increase in fly ash content

From Figure 6, it is seen that the compressive strength of concrete increased with the rise in fly ash content. At 7 days of curing, the percentage increments in compressive strength were 2.37%, 6.71%, 5.64% and 10.65% for 10%, 15%, 20% and 25% content of fly ash, respectively. Similarly, at 28 days, the corresponding increments were 5.55%, 7.95%, 8.70%, and 12.96%. Hence, the inclusion of fly ash in the designed SCC mix enhances the compressive strength, indicating its beneficial influence on concrete performance.

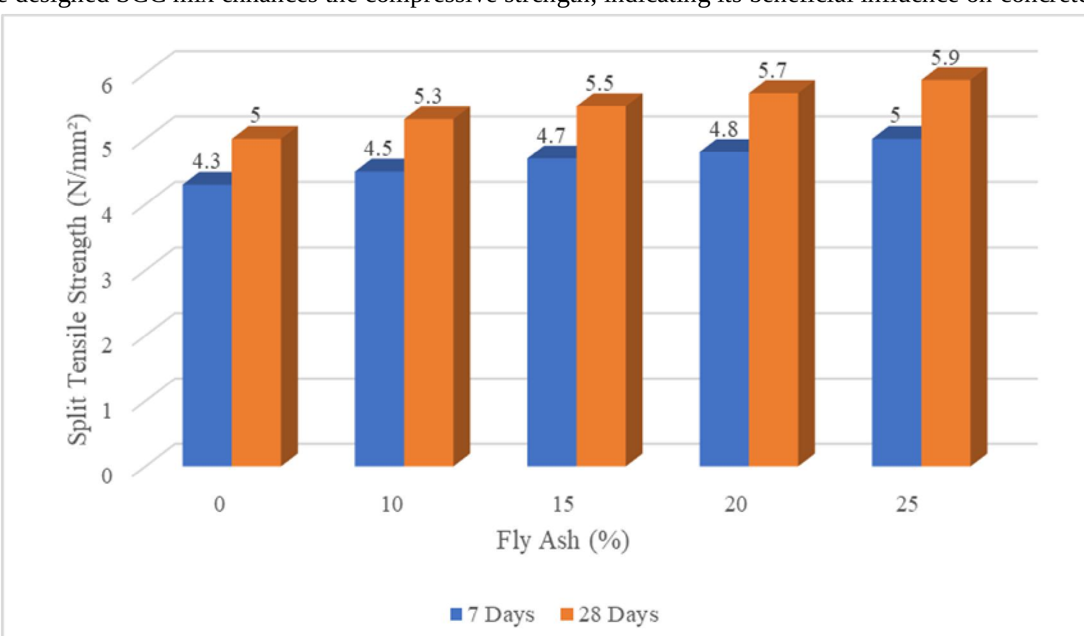

Figure-7: 7th and 28th day comparison of split tensile strength with different percentage of fly ash

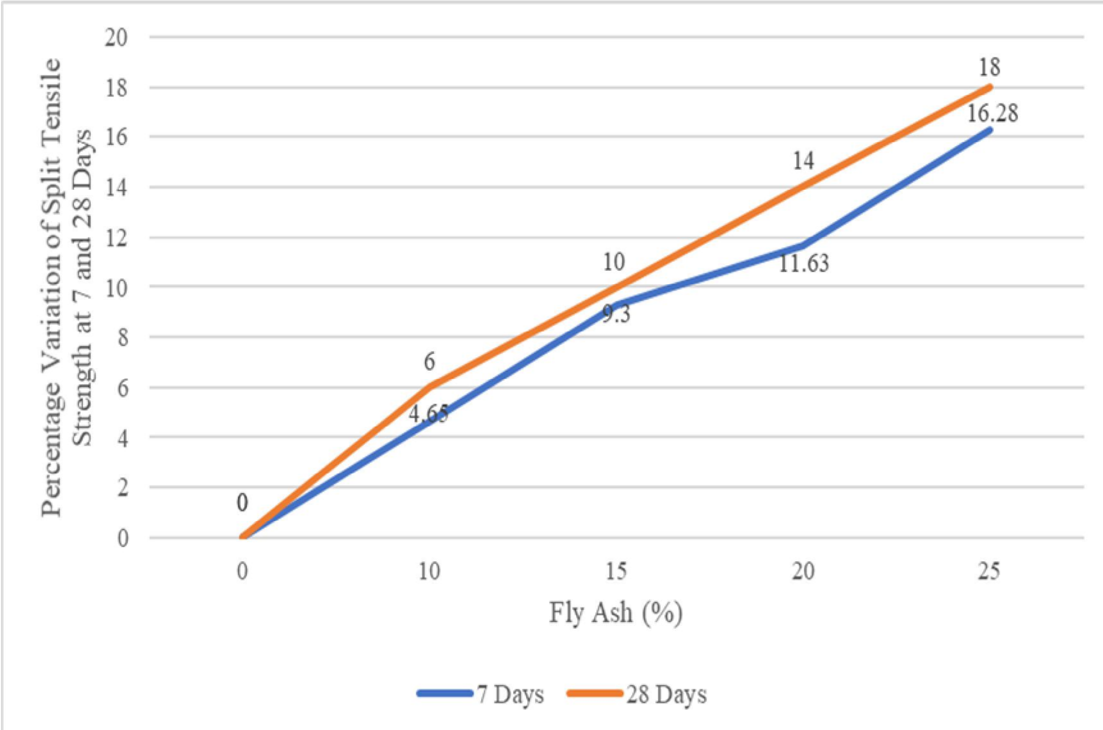

Figure-8: Increase in percentage of split tensile strength with increase in fly ash content

From Figure 8, it is seen that the split tensile strength of SCC increases with higher fly ash content. At 7 days, the percentage improvements in strength were 4.65%, 9.3%, 11.63% and 16.28% for 10%, 15%, 20%, and 25% fly ash, respectively. Similarly, at 28 days, the corresponding increases were 6%, 10%, 14% and 18%. Hence, incorporating fly ash in the SCC mix enhances the split tensile strength, demonstrating its beneficial influence on the mechanical performance of concrete.

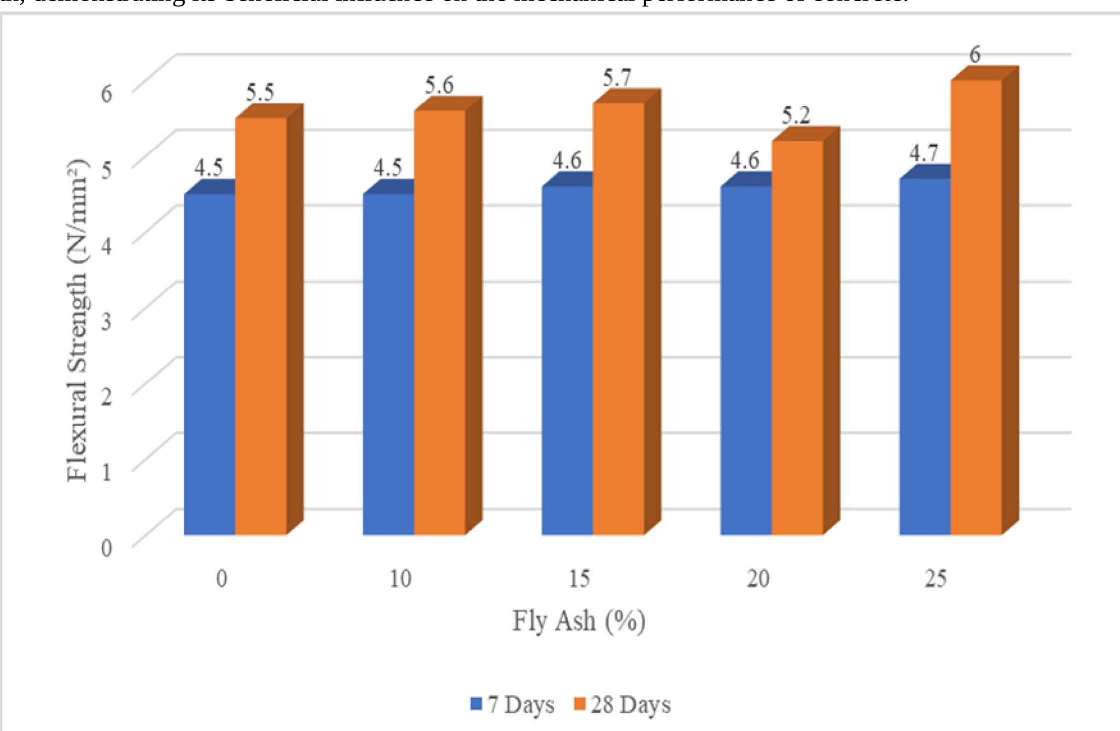

Figure-9: 7^{th} and 28^{th} comparison of flexural strength with different percentage of fly ash

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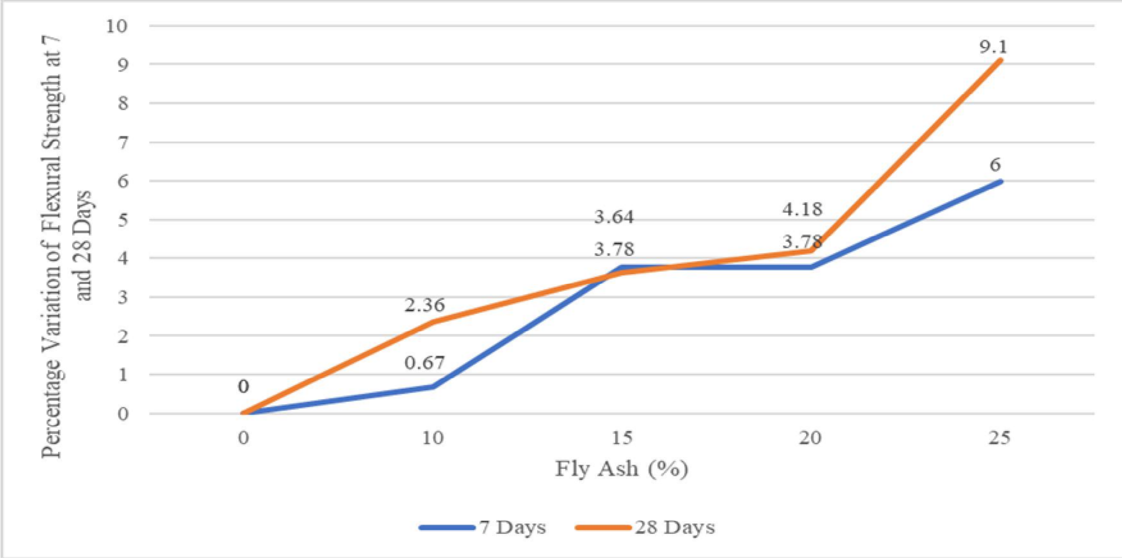

Figure-10: Increase in percentage of flexural strength with increase in fly ash content

From Figure 10, it is evident that the flexural strength of SCC increases progressively with higher content of fly ash. At 7 days, the percentage gains were 0.67%, 3.78%, 3.78% and 6% for 10%, 15%, 20% and 25% fly ash respectively. Similarly, at 28 days the corresponding improvements were 2.36%, 3.64%, 4.18% and 9.1%. Hence, the inclusion of fly ash in the SCC mix enhances its flexural strength, indicating a beneficial influence on the overall performance of the concrete.

C. Ultrasonic Pulse Velocity

The UPV results further support the observed improvements in hardened properties, as pulse velocity values increased consistently with fly ash content at both curing ages as shown in figure 12. The UPV values ranged from approximately 4375 m/s to 4695 m/s at 7 days and from 4465 m/s to 4783 m/s at 28 days, indicating improved homogeneity, reduced voids, and a denser internal structure. The higher UPV values recorded for fly ash-based SCC compared to the reference mix confirm the formation of a compact and well-integrated microstructure. Overall, the combined mechanical and UPV results demonstrate that the incorporation of fly ash significantly enhances the strength, durability, and internal quality of self-compacting concrete.

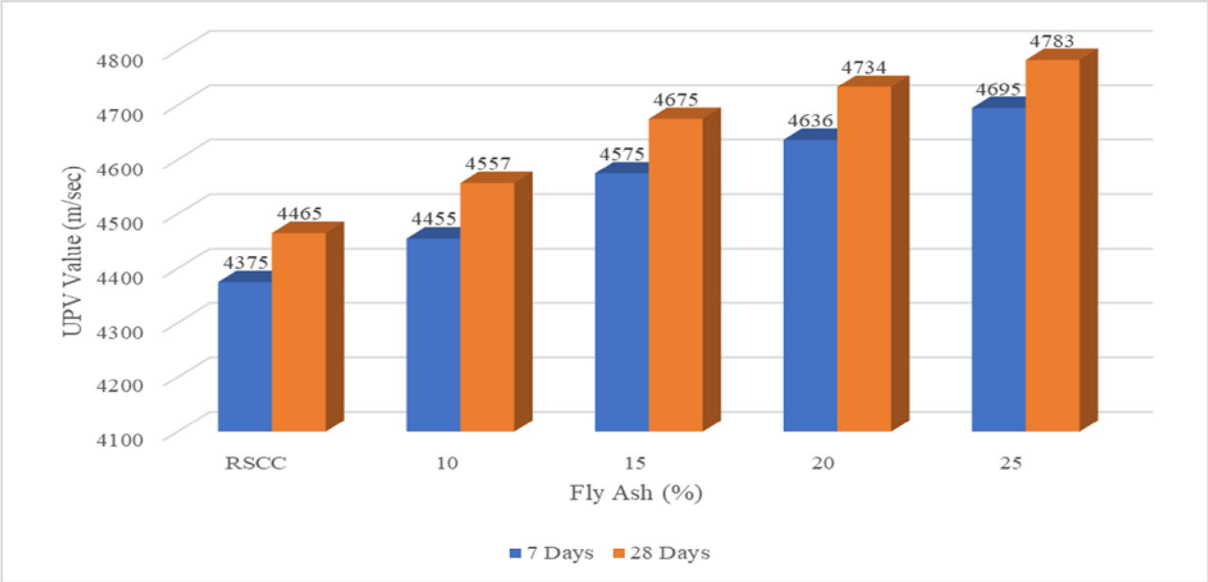

Figure-11: 7th and 28th day comparison of the UPV values of concrete samples

From figure 11, the UPV values for the designed SCC at 0%, 10%, 15%, 20%, and 25% fly ash content were recorded as 4375, 4455, 4575, 4636, and 4695 m/s at 7 days, and 4465, 4557, 4675, 4734, and 4783 m/s at 28 days, respectively. The results show a consistent increase in UPV values with higher fly ash content, suggesting improved homogeneity and a denser internal pore structure.

For the Reference Self-Compacting Concrete (RSCC), the Ultrasonic Pulse Velocity (UPV) values at 7 days and 28 days fell within the typical range of 4200–4700 m/s reported for good quality SCC. At 7 days, UPV value corresponded to the early development of a dense and cohesive internal matrix, indicating satisfactory initial compaction and bonding. By 28 days, the UPV value showed a noticeable increase, reflecting continued hydration and further refinement of the microstructure. Overall, the RSCC exhibited homogeneity and internal quality consistent with standard SCC performance criteria. The reference SCC (RSCC, 0% fly ash), UPV readings were 4373, 4384 and 4368 m/s at 7 days (optimum 4375 m/s), and 4464, 4472 and 4458 m/s at 28 days (optimum 4465 m/s). These values are lower than the corresponding fly ash mixes, indicating improvement in homogeneity and density with fly ash addition.

V. CONCLUSIONS

Based on the experimental investigation, the following conclusions are drawn:

1) The experimental results demonstrate that the incorporation of fly ash in self-compacting concrete significantly enhances both fresh and hardened properties while maintaining all performance parameters within the recommended limits for SCC.
2) The fresh state characteristics improved progressively with increasing fly ash content, as evidenced by increased slump flow, reduced T_{50} and V-funnel flow times, and higher L-box blocking ratios, indicating improved flowability, passing ability, and segregation resistance.
3) The compressive strength of SCC increased consistently at both 7 and 28 days with higher fly ash replacement levels, with the maximum strength achieved at 25% fly ash, confirming its positive contribution to strength development.
4) Split tensile and flexural strengths exhibited a gradual improvement with increasing fly ash content, reflecting enhanced tensile resistance, improved crack control, and better interfacial bonding within the concrete matrix.
5) Ultrasonic Pulse Velocity results showed a steady increase with fly ash incorporation, indicating improved internal homogeneity, reduced voids, and a denser microstructure compared to the reference SCC mix.
6) Based on the overall evaluation of rheological behaviour, mechanical performance, and UPV characteristics, fly ash replacement of up to 25% is found to be optimal for producing high-performance and sustainable self-compacting concrete.

VI. FUTURE SCOPE

Future research may focus on the long-term durability performance of fly ash–based self-compacting concrete through tests such as water absorption, chloride penetration, sulphate resistance, and carbonation. Microstructural studies using SEM, XRD, and TGA may be conducted to correlate mechanical performance with internal pore refinement. Further investigations on higher fly ash replacement levels and SCC behaviour under aggressive environmental and elevated temperature conditions would help extend its application in sustainable construction.

VII. LIMITATIONS OF THE PRESENT STUDY

The present study is limited to the evaluation of fresh and mechanical properties of self-compacting concrete with fly ash replacement levels up to 25% under controlled laboratory conditions. Long-term durability aspects, field performance, and exposure to aggressive environmental conditions were not investigated. Additionally, microstructural analysis was not included, which could provide deeper insight into the mechanisms governing strength development and internal densification of the SCC matrix.

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