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Investigation of strength and durability properties of self-compacting concrete prepared with supplementary cementitious materials

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Abstract: Concrete is a crucial construction material, but its environmental impact is significant, as cement production releases an equivalent amount of carbon dioxide per metric ton. To mitigate this, partial replacement of cement with mineral admixtures is an effective approach. Self-compacting concrete (SCC) is a specialized type of concrete known for its superior workability, enabling it to flow and compact under its own weight without external vibration. This enhances construction efficiency by improving filling ability, passing ability, and resistance to segregation.

This study examines the performance of M40 SCC mixes incorporating fly ash as a supplementary cementitious material. The workability of SCC was evaluated through slump flow and L-box tests to determine its flow characteristics and passing ability. Mechanical properties, including compressive strength, splitting tensile strength, and flexural strength, were assessed at different curing ages. Durability performance was examined through water absorption and rapid chloride penetration tests, conducted for up to 28 days, to evaluate resistance to moisture ingress and chloride-induced deterioration. The results provide valuable insights into the effectiveness of fly ash in enhancing SCC properties, contributing to sustainable construction practices. The study also highlights areas for further research to optimize SCC performance and durability.

Keywords: Self-Compacting Concrete (SCC); Fly Ash; Workability; Mechanical Properties; Durability; Sustainable Construction.

1. INTRODUCTION

Concrete is an essential construction material, widely recognized for its high compressive strength, durability, and availability. However, conventional concrete requires mechanical vibration to ensure proper compaction, which increases labor costs and energy consumption (Okamura & Ouchi, 2003). To address these challenges, Self-Compacting Concrete (SCC) was developed as a high-performance material that can flow under its own weight and completely fill formwork without requiring external vibration (EFNARC, 2002). This innovative concrete has gained global recognition for its ability to enhance construction efficiency and improve structural durability (Khayat et al., 2021).

The development of SCC originated in Japan in the late 1980s as a solution to inadequate concrete compaction in highly reinforced structures (Okamura, 1997). Ozawa et al. (1989) introduced SCC formulations that utilized superplasticizers to achieve superior workability without segregation. Since then, extensive research has refined SCC mix designs, optimizing aggregate gradation, binder compositions, and the use of viscosity-modifying agents (Ferraris et al., 2020). The European Federation of National Associations Representing Concrete (EFNARC) proposed standard mix design guidelines in 2002, which have since been widely adopted (RILEM, 2018).

SCC is distinguished by its unique properties, including high filling ability, excellent passing ability through congested reinforcement, and resistance to segregation (Sonebi et al., 2016). These attributes contribute to enhanced construction speed, improved surface finish, and reduced labor costs (Domone, 2018). Additionally, SCC minimizes noise pollution on-site due to the elimination of mechanical vibration, making it ideal for urban construction projects (De Schutter & Audenaert, 2007). These benefits have contributed to the widespread adoption of SCC in infrastructure, high-rise buildings, and precast elements (Bouzid et al., 2019).

The composition of SCC includes cementitious materials, aggregates, superplasticizers, and viscosity-modifying agents (Khayat & Yahia, 2020). Fly ash, silica fume, and ground granulated blast-furnace slag (GGBS) are commonly used supplementary cementitious materials to enhance workability and sustainability (Su et al., 2001). The EFNARC mix design method recommends optimizing the water-to-binder ratio, aggregate gradation, and admixture dosage to achieve the desired flowability and stability (RILEM, 2018). Proper selection and proportioning of materials are crucial in ensuring SCC's fresh and hardened properties (Kuroiwa, 2019).

SCC's fresh properties are assessed using standardized tests such as the slump flow test, L-box test, V-funnel test, and J-ring test (EFNARC, 2002). The slump flow test measures the horizontal spread of SCC, ensuring adequate flowability (Skarendahl & Petersson, 2000). The L-box test evaluates passing ability through obstacles, while the V-funnel test determines viscosity and flow time (Khaleel & Al-Mahaidi, 2017). These tests ensure SCC meets construction requirements before placement (Ferraris et al., 2020).

SCC exhibits excellent mechanical properties, including high compressive strength, enhanced tensile resistance, and superior flexural performance (Khayat & Guizani, 1997). The elimination of vibration reduces void formation, leading to improved bond strength and durability (Persson, 2001). SCC also demonstrates high resistance to water absorption, chloride penetration, freeze-thaw cycles, and sulfate attack, making it suitable for aggressive environments (Ganesan et al., 2021). The improved durability characteristics contribute to the extended service life of SCC structures (Deeb et al., 2012).

The versatility of SCC has led to its widespread use in various construction projects. It is extensively employed in precast elements, high-rise buildings, bridges, tunnels, and nuclear power plants (Bapat et al., 2021). SCC is particularly advantageous in highly reinforced structural elements where traditional vibration techniques are impractical (Collepardi, 2019). The material's ability to self-level and fill intricate spaces ensures superior performance in complex architectural designs and infrastructure projects (Sonebi et al., 2016).

Despite its advantages, SCC faces challenges related to high material costs, sensitivity to mix variations, and the need for specialized expertise (Yahia & Khayat, 2021). Future research aims to enhance SCC sustainability by incorporating recycled aggregates, nanomaterials, and bio-based admixtures (Bouzid et al., 2019). Advances in digital modeling and artificial intelligence are also being explored to optimize SCC mix designs and placement techniques (RILEM, 2023). Addressing these challenges will further improve the efficiency and sustainability of SCC in construction.

Self-Compacting Concrete represents a significant advancement in concrete technology, offering unparalleled workability, durability, and structural efficiency. Its widespread adoption has revolutionized modern construction practices, reducing labor requirements and enhancing sustainability. Ongoing research and technological innovations continue to refine SCC properties, paving the way for its increased utilization in high-performance infrastructure and sustainable construction projects.

2. SIGNIFICANCE OF THE PAPER

The primary aim of this study is to investigate the effectiveness of incorporating fly ash as a supplementary cementitious material in Self-Compacting Concrete (SCC) and to evaluate its influence on workability, mechanical strength, and durability. Given the environmental concerns associated with cement production, this research aims to contribute to sustainable construction by promoting partial cement replacement with fly ash, thereby reducing the carbon footprint.

- Assessing the workability of M40 SCC incorporating fly ash through slump flow and L-box tests to determine flowability and passing ability.
- Evaluating the mechanical performance of SCC by measuring compressive strength, splitting

tensile strength, and flexural strength at different curing ages.

- Investigating the durability properties of SCC through water absorption and rapid chloride penetration tests over a 28-day period to assess resistance to moisture ingress and chloride-induced deterioration.
- Understanding the role of fly ash in enhancing the microstructural properties of SCC and its contribution to improving long-term durability and mechanical performance.
- Identifying potential areas for further research to optimize SCC mix designs, ensuring improved sustainability and structural efficiency.

By systematically analyzing these aspects, this study provides valuable insights into the practical applications of SCC in modern construction and supports the development of eco-friendly concrete solutions that align with sustainable construction practices.

3. MATERIALS USED IN THE PAPER

The materials used in this study were carefully selected to ensure the successful development and performance evaluation of Self-Compacting Concrete (SCC). The selection was based on workability, strength, and durability considerations. Each material plays a crucial role in achieving the desired properties of SCC, from flowability and passing ability to long-term strength and resistance to environmental factors.

Portland cement serves as the primary binding agent in SCC due to its well-established properties, including high strength, durability, and hydration characteristics. However, because cement production is associated with significant carbon dioxide emissions, partial replacement with supplementary cementitious materials (SCMs) is a sustainable and effective approach.

Fly ash, a byproduct of coal combustion in thermal power plants, was incorporated into the SCC mix to improve its workability, reduce the heat of hydration, and enhance long-term mechanical properties. Fly ash is a pozzolanic material, meaning it reacts with calcium hydroxide released during cement hydration to form additional calcium silicate hydrate (C-S-H) gel. This secondary C-S-H gel strengthens the microstructure, reducing permeability and improving durability. The use of fly ash also contributes to the sustainable use of industrial byproducts, minimizing waste and promoting environmentally friendly construction practices.

Both fine and coarse aggregates are essential components of SCC, influencing its flow characteristics and mechanical strength. Fine aggregate, in the form of well-graded river sand, was used to enhance flowability and minimize the risk of segregation. Proper gradation of fine aggregates ensures that SCC maintains homogeneity while preventing excessive bleeding.

Coarse aggregates with a maximum size of 12.5 mm were chosen for their ability to facilitate better passing ability through congested reinforcement. A smaller aggregate size ensures that SCC can flow easily without blockages while maintaining its structural integrity. The aggregates were carefully graded and selected to provide consistent performance in the SCC mix. The quality and cleanliness of the aggregates were also considered to prevent impurities from negatively affecting the concrete properties.

To achieve the self-compacting properties of SCC, admixtures play a crucial role. Superplasticizers (SP) are high-range water reducers that improve the fluidity of SCC without increasing the water-to-binder ratio. A polycarboxylate ether (PCE)-based superplasticizer was used in this study due to its superior dispersion capabilities, which enhance workability, maintain cohesion and reduce the need for additional water. Additionally, a viscosity-modifying agent (VMA) was incorporated to prevent segregation and bleeding. VMAs improve the cohesiveness of SCC, ensuring that fine and coarse particles remain uniformly distributed throughout the mix. This stability is particularly important when dealing with complex formwork or highly reinforced structural elements, where maintaining homogeneity is critical.

Water is an essential component in SCC, influencing both hydration and workability. The water-to-binder (w/b) ratio was carefully optimized to achieve the required flowability while maintaining the strength and durability of the concrete. An excessive water content could lead to segregation and bleeding, whereas insufficient water could hinder workability. Potable water, free from impurities and contaminants, was used in the mixing process to ensure consistency and reliability in the final SCC mix. The controlled use of water ensures that the cementitious reactions occur optimally, leading to a well-hydrated and structurally sound SCC mix.

3.1 Mix proportions

The mix proportions table presents five different Self-Compacting Concrete (SCC) mixes with varying levels of fly ash replacement (0% to 40%) as a partial substitute for cement. As the fly ash content increases, the cement content decreases proportionally to maintain the total binder content. The water content is slightly increased in higher fly ash mixes to ensure adequate workability and flowability. Superplasticizer dosage is progressively increased to enhance the self-compacting ability of SCC, as fly ash tends to reduce early-age strength and increase setting time. Fine aggregate content is adjusted upwards to maintain cohesion, while coarse aggregate content is reduced to improve flow and passing ability. Viscosity Modifying Admixture (VMA) is also increased slightly to prevent segregation and ensure uniformity. These adjustments help maintain the essential properties of SCC, ensuring smooth placement without the need for vibration. Table 1 presents the mix proportions of the self-compacting concrete prepared with fly ash.

Table 1: Mix proportions of self-compacting concrete in kg/m^3

Mix id	Cement	Fly Ash	Water	Fine Aggregate	Coarse Aggregate	Superplasticizer (% of binder)	VMA
M1	400	0	175	900	750	0.8	1.5
M2	360	40	175	920	730	0.9	1.6
M3	320	80	180	940	710	1.0	1.7
M4	280	120	185	960	690	1.1	1.8
M5	240	160	190	980	670	1.2	1.9

3.2 Preparation of samples

The preparation of SCC with fly ash begins with the careful selection and weighing of materials according to the mix proportions. Cement and fly ash are measured to maintain the desired replacement percentage, while fine and coarse aggregates are selected based on proper grading and moisture conditions. The required water, superplasticizer, and viscosity-modifying admixture (VMA) are also precisely measured to achieve self-compacting properties.

The mixing process starts with dry mixing of cement, fly ash, and aggregates in a pan or drum mixer for uniform blending. After this, water and half of the superplasticizer are added, followed by mixing for 2-3 minutes to begin hydration. The remaining superplasticizer and VMA are then added gradually to enhance flowability, viscosity, and stability, and the mixing continues for another 3-5 minutes until a homogeneous and workable SCC mix is obtained.

Before casting, the fresh SCC mix is tested for workability and self-compacting ability using several tests. The Slump Flow Test ensures adequate flowability, while the V-Funnel Test assesses viscosity. The L-Box and U-Box Tests are conducted to evaluate passing and filling abilities, ensuring that SCC can flow freely around reinforcement without segregation or blocking. If the mix meets the required performance criteria, it proceeds to the casting stage.

During casting, the molds (such as cylinders, cubes, or beams) are cleaned and lightly oiled to prevent the SCC from sticking. Unlike conventional concrete, SCC does not require mechanical vibration; instead, it is poured directly into the molds and allowed to flow and settle under its self-weight. The top surface is gently leveled with a trowel to ensure a smooth and uniform finish.

After casting, the samples are covered with plastic sheets or wet burlap to prevent moisture loss and ensure proper hydration. The specimens remain in the molds for about 24 hours, after which they are demolded carefully and transferred to a water curing tank at 23 ± 2°C. Proper curing is essential to develop the desired strength and durability of SCC, as it ensures complete hydration of cement and fly ash particles. This systematic preparation and casting process ensures that SCC samples exhibit excellent workability, uniformity, and durability, making them suitable for laboratory strength and durability tests.

4. TEST METHODS

This study evaluates the workability, mechanical properties, and durability of M40 SCC incorporating fly ash as a supplementary cementitious material. Various standardized test methods were employed to assess the performance characteristics of SCC, ensuring its effectiveness in sustainable construction applications.

4.1 Workability Tests

Since SCC is designed to flow and compact under its own weight without the need for mechanical vibration, its workability was assessed using two key tests: the Slump Flow Test and the L-Box Test. The Slump Flow Test is a fundamental method used to determine the flowability of SCC. In this test, a standard Abrams cone is filled with fresh SCC and lifted vertically, allowing the concrete to spread freely. The diameter of the spread (in mm) is measured to evaluate the flowability, while the T50 time (in seconds)—the time taken for the concrete to reach a 500 mm spread—indicates the viscosity of the mix. A higher slump flow value signifies better flowability, which is critical for ensuring uniform placement in highly reinforced structures.

The L-Box Test, on the other hand, assesses the passing ability of SCC through narrow gaps, simulating the presence of dense reinforcement. This test involves filling the vertical section of an L-shaped box with SCC and allowing it to flow into the horizontal section through a set of closely spaced bars. The ratio of the final heights of the concrete at the two ends of the box (H_2/H_1) is recorded as the blocking ratio, which indicates whether the mix can pass through tight spaces without segregation or blockage. A higher blocking ratio signifies better passing ability, which is essential for SCC used in heavily reinforced sections.

4.2 Mechanical Properties Tests

The strength characteristics of SCC were evaluated using compressive strength, splitting tensile strength, and flexural strength tests at different curing ages. The Compressive Strength Test was conducted using standard cube specimens (150 mm × 150 mm × 150 mm) subjected to axial loading in a compression testing machine. This test determines SCC's ability to withstand compressive loads, which is crucial for structural applications. The compressive strength was measured at 7, 14, and 28 days to track the strength development over time. The incorporation of fly ash, known for its pozzolanic activity, can enhance long-term strength due to continued secondary hydration reactions.

The Splitting Tensile Strength Test was performed using cylindrical specimens, where a compressive load was applied along the diameter until the specimen split. This indirect tensile strength test is essential for understanding SCC's resistance to tensile stresses, which influence cracking behavior under service loads. Additionally, the Flexural Strength Test was conducted on beam specimens subjected to third-point loading to assess SCC's ability to resist bending stresses. Flexural strength is particularly important for concrete elements such as slabs, beams, and pavements, where tensile forces play a significant role.

4.3 Durability Tests

To ensure the long-term performance of SCC and its resistance to environmental deterioration, durability tests such as Water Absorption Test and Rapid Chloride Penetration Test (RCPT) were carried out. The Water Absorption Test measures the ability of SCC to absorb moisture, which is an indicator of its permeability and porosity. Lower water absorption values signify a denser and more durable concrete mix, reducing the risk of water-induced deterioration such as freeze-thaw damage and chemical attack.

The Rapid Chloride Penetration Test (RCPT) is a widely used method to assess SCC's resistance to chloride ion ingress, a key factor in preventing steel reinforcement corrosion. In this test, a voltage is applied across concrete specimens, and the total charge passed (in Coulombs) is measured over a 28-day curing period. A lower charge value indicates better resistance to chloride penetration, enhancing the durability of SCC in marine or chloride-exposed environments. Since fly ash helps refine the pore structure of concrete, it can significantly improve resistance to chloride-induced deterioration.

The combination of these test methods provided a comprehensive evaluation of the workability, strength, and durability of SCC-containing fly ash. The results helped determine the effectiveness of fly ash in improving SCC performance while promoting sustainable construction practices by reducing cement consumption and minimizing environmental impact. These tests also highlighted the potential of SCC for use in high-performance applications, where ease of placement, durability, and strength are critical. Further research can focus on optimizing fly ash content and investigating its long-term performance in various environmental conditions to enhance SCC's suitability for modern construction needs.

5. RESULTS AND DISCUSSIONS

5.1 Workability

Table 2 presents the workability characteristics of self-compacting concrete (SCC) incorporating fly ash at different replacement levels. The workability of SCC is assessed through three key parameters: slump flow diameter, T50 slump flow time, and L-Box blocking ratio (H_2/H_1). These parameters help evaluate the flowability, viscosity, and passing ability of SCC, ensuring that it meets the required performance standards for placement in reinforced structures without the need for external vibration.

1. Slump Flow Diameter (mm) – Flowability of SCC

The slump flow diameter is a critical indicator of the fluidity and self-compacting ability of SCC. The values in the table range from 690 mm (M1) to 740 mm (M5), showing an increase in flowability with higher fly ash content. Mix M1 (0% fly ash) has the lowest slump flow (690 mm), indicating a relatively lower fluidity, whereas M5 (40% fly ash) exhibits the highest flow (740 mm), demonstrating superior flowability. Fly ash plays a crucial role in enhancing the workability of SCC by acting as a lubricating agent, reducing internal friction between aggregates, and improving the pore structure of the mix. As fly ash content increases, the mix becomes more cohesive and spreads more easily under its own weight, thus requiring minimal effort for placement. However, excessive flowability beyond recommended limits could lead to segregation, which needs to be controlled.

2. T50 Slump Flow Time (sec) – Viscosity of SCC

The T50 slump flow time represents the viscosity of the mix, i.e., how quickly the concrete flows. A lower T50 time indicates a more fluid mix, while a higher time suggests increased viscosity. In the table, the T50 values range from 2.5 seconds (M1) to 3.5 seconds (M5). As fly ash content increases, the mix becomes slightly more viscous, as indicated by the gradual rise in T50 time from 2.5 to 3.5 seconds. This increase is due to the fine particle size of fly ash, which enhances cohesion and reduces the likelihood of segregation and bleeding. However, despite the increase in viscosity, all values remain within the acceptable range of 2–5 seconds for SCC, ensuring that the concrete maintains its self-compacting properties without excessive stiffness.

3. L-Box Blocking Ratio (H_2/H_1) – Passing Ability of SCC

The L-Box test is used to assess the passing ability of SCC through reinforcement without blockage. The blocking ratio (H_2/H_1) increases from 0.92 (M1) to 0.98 (M5), indicating that SCC with higher fly ash content experiences less resistance when passing through obstructions. A higher blocking ratio (closer to 1.0) signifies better passing ability, meaning the mix can flow through narrow gaps without segregation or blockages. The improvement in passing ability is attributed to the enhanced lubrication effect of fly ash, which reduces inter-particle friction and allows the mix to move freely. This is particularly important for SCC used in densely reinforced structures, where poor passing ability could lead to voids and incomplete filling. The results confirm that replacing cement with fly ash contributes to better rheological properties, ensuring uniform placement and consolidation.

Table 2: Workability values of self-compacting concrete

Mix Id	Slump Flow Diameter (mm)	T50 Slump Flow Time (sec)	L-Box Blocking Ratio (H_2/H_1)
M1 (0% FA)	690	2.5	0.92
M2 (10% FA)	715	2.7	0.94
M3 (20% FA)	720	3.0	0.96
M4 (30% FA)	730	3.2	0.97

M5 (40% FA)	740	3.5	0.98

5.2 Mechanical properties

The mechanical properties of self-compacting concrete (SCC) incorporating fly ash were assessed through compressive strength, splitting tensile strength, and flexural strength at different curing ages (7 and 28 days). These properties are crucial indicators of the concrete's structural performance, durability, and suitability for various applications. The results, as shown in the table, highlight the influence of fly ash as a partial cement replacement on the strength development of SCC.

Compressive strength is the most fundamental property of concrete, reflecting its ability to withstand axial loads. The test results indicate that early-age strength (7 days) decreases as the fly ash content increases. The compressive strength of SCC with 0% fly ash (M1) at 7 days is 35.2 MPa, whereas for SCC with 40% fly ash (M5), it is reduced to 29.5 MPa. This reduction is expected because fly ash is a pozzolanic material, which does not hydrate immediately like cement. The initial strength development relies primarily on cement hydration, and with higher cement replacement levels, the available clinker content is lower, resulting in slower early strength gain.

However, at 28 days, the compressive strength increases significantly across all mixes. The long-term strength gain is higher in fly ash-based SCC, with M5 reaching 54.0 MPa, compared to 50.5 MPa in M1. This suggests that the pozzolanic reaction of fly ash contributes to strength enhancement over time. The presence of fly ash refines the microstructure, filling voids and improving the interfacial transition zone (ITZ) between the paste and aggregates, leading to denser and stronger concrete. The increased strength at later ages demonstrates the latent hydraulic properties of fly ash, making it a beneficial component for sustainable and durable SCC.

Splitting tensile strength is a measure of the concrete's ability to resist tensile forces, which is crucial for crack resistance and durability. The results indicate that at 7 days, the tensile strength decreases with increasing fly ash content, following a pattern similar to compressive strength. For instance, M1 has a splitting tensile strength of 3.1 MPa, while M5 records 2.7 MPa.

At 28 days, however, tensile strength improves, with M5 achieving the highest value of 4.7 MPa, compared to 4.2 MPa in M1. The improvement can be attributed to the secondary hydration reaction of fly ash, which strengthens the matrix and enhances bonding within the mix. The refined microstructure also contributes to better stress distribution and crack resistance. This suggests that although SCC with fly ash may exhibit lower early-age tensile strength, it compensates with better long-term performance, making it a reliable option for applications requiring higher durability and crack resistance.

Flexural strength represents the ability of concrete to resist bending and shear stresses, making it an important parameter for structures like pavements, bridges, and beams. The table shows that at 7 days, the flexural strength decreases with higher fly ash content, with M1 exhibiting 5.5 MPa and M5 reaching 4.8 MPa. This trend aligns with the delayed strength gain seen in compressive and tensile strength due to the slower reaction of fly ash.

At 28 days, the flexural strength improves across all mixes, with M5 reaching the highest value of 7.5 MPa, compared to 6.8 MPa in M1. The improved flexural strength is due to enhanced cohesion within the paste and better aggregate-paste bonding, resulting from the fine pozzolanic reaction of fly ash. The reduction in porosity and improved particle packing contribute to increased flexural capacity, which is advantageous for applications requiring high bending resistance and load-bearing capacity.

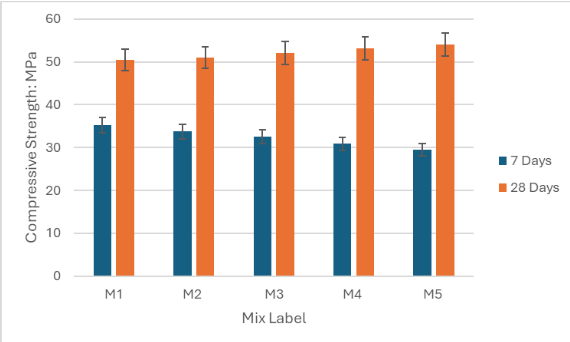

Figure 1: Compressive strength of SCC with the replacement of cement with fly ash

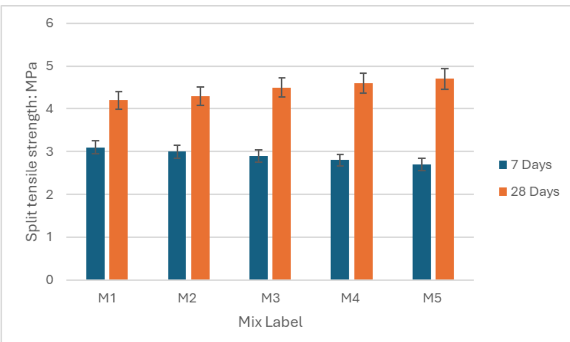

Figure 2: Split tensile strength of SCC with the replacement of cement with fly ash

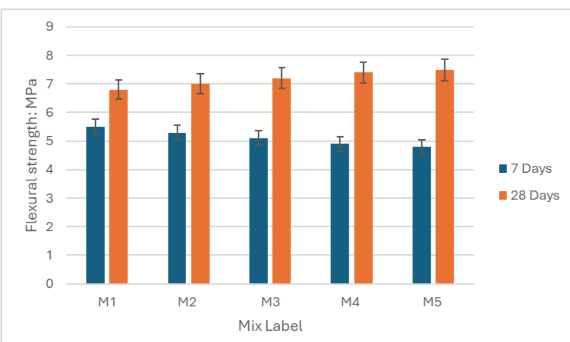

Figure 3: Flexural strength of SCC with the replacement of cement with fly ash

5.3 Durability properties

Durability is a critical property of concrete that determines its long-term performance and resistance to environmental degradation. In this study, water absorption and rapid chloride penetration test (RCPT) results were analyzed to evaluate the durability characteristics of SCC with varying percentages of fly ash (0% to 40%) as a partial cement replacement. The findings indicate that incorporating higher fly ash content enhances the durability of SCC by reducing permeability and improving resistance to chloride penetration.

Water absorption in concrete is a key indicator of its porosity and permeability, both of which influence the material's resistance to moisture ingress and potential deterioration due to freeze-thaw cycles and sulfate attack. The test results show that water absorption decreases as fly ash content increases. The control mix (M1) with 0% fly ash recorded the highest water absorption at 3.1%, while the M5 mix (40% fly ash) exhibited the lowest absorption at 2.3%. This trend can be attributed to the pozzolanic reaction of fly ash, which refines the pore structure by consuming calcium hydroxide (CH) and forming additional calcium silicate hydrate (C-S-H) gel, leading to a denser and more compact microstructure (Thomas, 2013).

The reduction in water absorption enhances the resistance of SCC to aggressive environments, as lower permeability limits the ingress of harmful ions such as chlorides and sulfates, which are responsible for reinforcement corrosion and sulfate attack (Mehta & Monteiro, 2014). The improved pore structure also mitigates the risk of alkali-silica reaction (ASR) and freeze-thaw damage, making fly ash-based SCC more suitable for marine structures, bridges, and infrastructure exposed to water ingress (Neville, 2011). Figure 4 illustrates the water absorption of SCC.

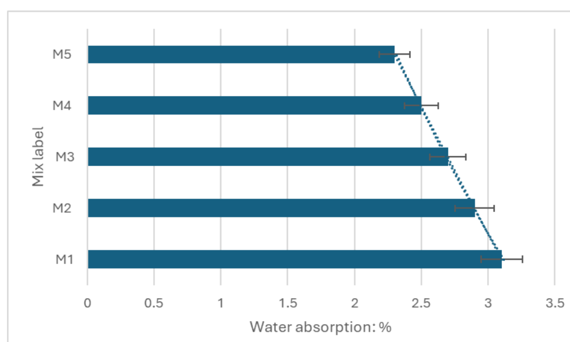

Figure 4: Water absorption of SCC with the replacement of cement with fly ash

Chloride penetration is one of the most significant durability concerns in reinforced concrete structures, as chloride ions accelerate the corrosion of steel reinforcement, leading to structural deterioration and reduced service life. The RCPT results indicate a significant improvement in chloride penetration resistance with increasing fly ash content. The control mix (M1) recorded the highest charge passed (3200 Coulombs), categorized as moderate chloride penetration, whereas M5 (40% fly ash) exhibited the lowest charge passed (1800 Coulombs), classified as very low chloride penetration. This trend suggests that fly ash contributes to a denser matrix, reducing the transport of chloride ions through the concrete (Gebler & Klieger, 1986).

The improvement in chloride resistance can be explained by the refinement of the pore structure and reduction in capillary porosity due to secondary hydration reactions facilitated by fly ash. The pozzolanic reaction consumes calcium hydroxide, replacing it with C-S-H gel, which enhances impermeability and chemical resistance (Shetty, 2005). Additionally, higher fly ash content reduces the alkalinity of pore water, which slows down the rate of chloride diffusion and mitigates the risk of steel corrosion (ACI Committee 232, 2003). The M5 mix (40% fly ash) demonstrated superior chloride resistance, making it ideal for marine applications, coastal structures, and chloride-exposed environments such as highways and industrial zones.

The combined effects of lower water absorption and improved chloride penetration resistance indicate that fly ash enhances the long-term durability of SCC. The results align with previous research findings that demonstrate fly ash's ability to improve concrete durability by refining the microstructure, reducing permeability, and increasing resistance to aggressive agents (Bilodeau & Malhotra, 2000). The optimal fly ash replacement level appears to be between 30-40%, where SCC achieves superior durability while maintaining adequate strength. In connection, the use of fly ash in SCC enhances durability performance, making it an environmentally sustainable and cost-effective solution for long-lasting infrastructure. By incorporating fly ash, the carbon footprint of cement production is reduced, and the service life of concrete structures is extended, leading to lower maintenance costs and increased sustainability. Further studies should explore the long-term durability performance beyond 28 days, including resistance to sulfate attack, carbonation, and freeze-thaw cycles, to provide more comprehensive durability data for practical applications. Table 3 presents the TCPT test results of SCC.

Table 3: RCPT analysis of SCC

Mix ID	RCPT Charge Passed (Coulombs)	Chloride Penetration Category
M1	3200	Moderate
M2	2900	Moderate
M3	2500	Low
M4	2100	Low
M5	1800	Very Low

CONCLUSIONS

Based on the evaluation of workability, mechanical properties, and durability performance of self-compacting concrete (SCC) with varying levels of fly ash replacement (0% to 40%), several key conclusions can be drawn:

1. The inclusion of fly ash significantly improves the workability of SCC, as indicated by increased slump flow diameter, T50 slump flow time, and L-box blocking ratio. The slump flow diameter increased from 690 mm (M1) to 740 mm (M5), demonstrating improved flowability. Similarly, the L-box blocking ratio increased from 0.92 (M1) to 0.98 (M5), showing better passing ability. These results confirm that fly ash enhances the self-compacting properties of SCC, making it more suitable for applications with complex formwork and congested reinforcement.

2. The compressive strength of SCC initially increases with fly ash replacement up to 20-30% but shows a slight reduction at 40% fly ash. The M3 (20% fly ash) and M4 (30% fly ash) mixes exhibit the highest compressive strengths, suggesting that an optimal fly ash replacement level exists for achieving both strength and workability benefits. The minor decrease in strength at 40% fly ash is likely due to slower pozzolanic reactions, which may require longer curing periods to achieve strength equivalence with lower replacement levels.

3. The splitting tensile and flexural strength values followed a similar trend to compressive strength. SCC mixes with 20-30% fly ash (M3 and M4) exhibited the best performance, indicating that fly

ash contributes positively to microstructural refinement and load-bearing capacity. However, at 40% replacement, there was a minor decrease in tensile and flexural strength, reinforcing the need for optimization in high-volume fly ash SCC.

4. The durability properties of SCC improved with increasing fly ash content, as demonstrated by lower water absorption and enhanced resistance to chloride penetration. Water absorption decreased from 3.1% (M1) to 2.3% (M5), indicating a denser microstructure with reduced permeability. Similarly, RCPT results showed a significant reduction in charge passed, from 3200 Coulombs (M1) to 1800 Coulombs (M5), confirming enhanced resistance to chloride ion ingress. These findings suggest that fly ash enhances the long-term durability of SCC by reducing permeability, refining pore structure, and mitigating chloride-induced deterioration.

5. The partial replacement of cement with fly ash in SCC reduces cement consumption, thereby lowering the carbon footprint of concrete production. This aligns with sustainable construction practices by promoting the use of industrial by-products while maintaining structural integrity and durability. Fly ash-based SCC is particularly suitable for marine structures, bridges, and high-performance concrete applications where both workability and durability are critical.

The study demonstrates that SCC incorporating fly ash up to 30% replacement offers optimal performance in terms of workability, mechanical strength, and durability. Higher fly ash content (40%) further enhances workability and durability but results in a slight reduction in strength. Therefore, an optimal fly ash replacement level of 20-30% is recommended for achieving a balance between strength, durability, and sustainability. Future research can focus on long-term durability performance, extended curing effects, and alternative pozzolanic materials to further optimize SCC properties for various construction applications.

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