

THE ROLE OF ADMIXTURES IN ENHANCING CONCRETE WORKABILITY AND STRENGTH AND MICROSTRUCTURAL ANALYSIS

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Abstract

This study investigates the use of fly ash, *Calotropis gigantea*, and superplasticizers to develop sustainable, high-performance concrete. The scope includes partially replacing cement with fly ash (5-25%) and enhancing mix properties using 3% *Calotropis gigantea* milk and 2% superplasticizer. The inclusion of *Calotropis gigantea* milk, a natural admixture, and superplasticizers further improved the concrete's workability, flowability, and compressive strength. Tests, including slump, L-box, J-ring, V-funnel, and U-box, evaluated fresh concrete properties, while compressive strength was assessed at 7, 14, and 28 days. The results identified optimal performance with a mix containing 15% fly ash, 3% *Calotropis gigantea* milk, and 2% superplasticizers. This combination achieved superior workability, enhanced flow characteristics, and a maximum compressive strength of 39.35 MPa at 28 days. The microstructural analysis shows the less pores in T12 mix compared to T1 and T9 mix. These findings highlight the potential of incorporating industrial byproducts and natural admixtures to reduce cement consumption, lower environmental impact, and improve concrete performance.

Keywords: Calotropis Gigantea Milk; Fly Ash; Self-Compacting Concrete; Workability

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Introduction

Chemical admixtures play a vital role in enhancing the workability and strength of self-compacting concrete (SCC). These admixtures, often used in combination with mineral admixtures, help achieve the desired fluidity and mechanical properties without the need for vibration during placement.

The integration of mineral admixtures, such as fly ash (FA), ground granulated blast furnace slag (GGBS), and silica fume, further augments the performance of SCC. (Kadhar *et al.*, 2021) These materials influence the particle size distribution, leading to improved packing density and a reduction in the demand for superplasticizers. (Kumar *et al.*, 2024) Substituting 20-30% of cement with fly ash can lower the required superplasticizer dosage by up to 15%, depending on the mix design, while also improving workability and reducing segregation. (Sobuz *et al.*, 2024) Silica fume, used at 5-10% of cement content, improves the viscosity and strength of SCC, ensuring durable and defect-free finishes. (Yaqin *et al.*, 2024) Superplasticizers are critical in enhancing the flow properties of self-consolidating concrete (SCC), enabling it to flow freely and fill intricate formworks under its own weight without mechanical vibration. (Bernal *et al.*, 2018) Typically, the addition of superplasticizers reduces the water-to-cement (w/c) ratio to below 0.40, significantly improving both the fluidity and the compressive strength of SCC. (Altalabani *et al.*, 2020) The optimal dosage, generally ranging from 0.5% to 3% of the cement weight depending on the product type and mix design, enhances the flowability and filling ability, ensuring complete compaction and reducing labour-intensive vibration processes. (Özcan and Halil Kaymak, 2018)

The materials improve the particle packing density, leading to a denser microstructure that increases strength. For instance, replacing 20-40% of Portland cement with FA or GGBS can result in compressive strengths exceeding 78 MPa at 28 days, depending on the mix design and curing conditions. (Gurusamy *et al.*, 2024; Rajamallu *et al.*, 2024) This strength improvement makes SCC ideal for high-performance applications. (Kanamarlupudi *et al.*, 2020) In addition to mechanical strength, mineral admixtures enhance SCC's durability. FA and GGBS improve resistance to sulphate attacks by reducing the permeability of the concrete matrix, thus mitigating expansion and cracking caused by aggressive sulphate environments. (Ho *et al.*, 2003) They significantly reduce chloride ion permeability, a key factor in preventing corrosion of embedded steel reinforcement. Chloride permeability reductions of up to 50% have been observed when

GGBS is used at replacement levels of 40-50%. (Tangadagi *et al.*, 2021) These improvements result in longer service life and reduced maintenance costs for structures exposed to harsh environmental conditions. By incorporating these mineral admixtures, SCC becomes a more sustainable, durable, and high-performing material. (Zhao *et al.*, 2024)

Fly ash plays a vital role in enhancing the workability and flowability of concrete, particularly in self-consolidating concrete (SCC). Its spherical particle shape acts as a lubricant within the mix, improving its handling and placement characteristics. (Carvalho *et al.*, 2020) However, one potential drawback of FA is its tendency to increase bleeding, where excess water rises to the surface during placement. (Chen and Liu, 2008) The issue can be mitigated by combining FA with ground granulated blast furnace slag (GGBS) or silica fume, which improve cohesion and reduce water migration. (Sabet *et al.*, 2013) Replacing a portion of Portland cement with mineral admixtures like FA and GGBS not only enhances concrete performance but also reduces the overall cement content. (Arasu *et al.*, 2023) This reduction is economically beneficial, as it lowers material costs, and environmentally advantageous, as it decreases carbon dioxide emissions associated with cement production. (Wu, 2019) Cement replacement levels of 20-50% with FA or GGBS can reduce CO₂ emissions by approximately 20-40% while maintaining or enhancing concrete properties. (Jin and Li, 2003) Additionally, these replacements lead to lower hydration heat, which minimizes the risk of thermal cracking in large structural elements. By integrating FA and GGBS into mix designs, the industry achieves a more sustainable, cost-effective, and high-performing material. (Vakhshouri and Nejadi, 2016)

Using mineral admixtures, which are often industrial by-products, can reduce the cost of SCC and lower the environmental impact by decreasing the amount of Portland cement required. (Devi *et al.*, 2020; Łażniewska-Piekarczyk, 2013) The interaction between cement and chemical admixtures can affect the rheological properties of SCC. Polycarboxylate superplasticizers, for example, are generally compatible with various cements, although their effectiveness can be influenced by the cement's alkaline sulphate content. (Krishnadas *et al.*, 2024) Chemical admixtures, particularly superplasticizers, are essential for achieving the desired workability and strength in self-compacting concrete. (Kapoor *et al.*,

2016) When used in conjunction with mineral admixtures, they not only enhance the mechanical properties and durability of SCC but also offer cost and environmental benefits. (Gesoglu *et al.*, 2009) The careful selection and combination of admixtures are pivotal in optimizing the performance of self-consolidating concrete (SCC). The strategic use of chemical and mineral admixtures significantly enhances the durability of SCC by reducing porosity and creating a denser microstructure. (Liang *et al.*, 2023) This improvement minimizes the ingress of harmful substances, such as water, chloride ions, and carbon dioxide, which are primary contributors to concrete degradation. (Amare *et al.*, 2023) These admixtures combat carbonation, a process where carbon dioxide penetrates and reacts with concrete, potentially weakening its alkalinity and compromising steel protection. The dense matrix achieved with SCC containing mineral admixtures slows down carbonation rates, extending the structure's service life. (Manickaraj *et al.*, 2025) These durability enhancements make SCC a superior choice for aggressive environments, such as coastal areas, wastewater treatment plants, and industrial facilities, ensuring reliable and long-lasting performance.

The use of bio-admixtures derived from plant-based materials as internal curing agents in fly ash-based concrete. Their results demonstrated that bio-admixtures enhanced hydration, improved compressive strength, and reduced water absorption, particularly in mixes with higher fly ash content. (Appaji and Chethan, 2023) Explored the durability of bio-self-cured fly ash concrete in aggressive environments, showing increased resistance to acid and sulfate attacks. These findings support the potential of natural admixtures for internal curing and performance enhancement in blended cement systems. (Malathy *et al.*, 2020) The influence of magnetic water on concrete properties, noting improved workability, reduced water demand, and higher strength when water was magnetized for optimal durations. (Malathy, 2017) The effectiveness of magnetic water in high-strength concrete applications, where magnetic treatment acted as a water-reducing agent, enhancing compressive strength and microstructural integrity. This investigation to prestressed concrete beams, concluding that magnetic water significantly enhanced flexural performance and load-bearing capacity. (Ramalingam *et al.*, 2022a)

The role of recycled aggregates in developing environmentally responsible concrete. Their study showed that recycled aggregates, when properly treated, can partially or fully replace natural aggregates without significantly compromising

strength. This promotes circular economy practices in construction and supports sustainability goals. (Malathy *et al.*, 2022) The integration of nanomaterials such as nanosilica has received considerable attention for enhancing concrete at the microstructural level. (Ramalingam *et al.*, 2022b) Explored high-strength concrete infused with nanomaterials, reporting improved packing density, reduced porosity, and superior mechanical performance. (Annamalai *et al.*, 2025) Fibre-reinforced concrete with nanosilica, observing increased compressive and flexural strength along with enhanced durability under aggressive conditions. (Anbarasu *et al.*, 2025) The partial cement replacement with silica fume improved concrete strength and reduced permeability, confirming its effectiveness as a supplementary cementitious material. (Anbarasu *et al.*, 2024)

This study uniquely combines fly ash, *Calotropis gigantea* milk, and superplasticizers to enhance concrete performance. The novel use of natural latex improves workability and strength at 28 days. Microstructural analysis confirms reduced porosity, promoting sustainable, high-performance concrete with lower cement content and environmental impact.

Materials

Ordinary Portland Cement (OPC) grade 53, adhering to IS 12269 (1987) standards, is chosen for its high early strength and durability, ensuring reliable results in concrete experimentation. With a specific gravity of 3.14 and a surface area of 2250 cm²/gm, OPC 53 exhibits excellent binding properties. Its particle size, under 90 microns, enhances reactivity, while its 3 mm volume expansion indicates stability. (Shankar *et al.* 2024) These characteristics make OPC 53 ideal for high-performance concrete applications. Ordinary Portland Cement (OPC) 53 Grade is characterized by its high lime (CaO) content, typically ranging 62.98%, which contributes to its rapid strength development. The silica (SiO₂) content ranges 19.65%, while alumina (Al₂O₃) and iron oxide (Fe₂O₃) are present in smaller amounts. Magnesia (MgO) is usually below 6%, ensuring soundness, and sulphur trioxide (SO₃) remains under 3.5%. Loss on ignition (LOI) is kept below 4%, indicating minimal pre-hydration. (Akshana *et al.*, 2020) The alkali content is controlled to reduce alkali-aggregate reactivity. These chemical characteristics make OPC 53 Grade ideal for high-strength applications, ensuring early setting, durability, and long-term structural performance. Figure 1 shows the particle distribution of cement.

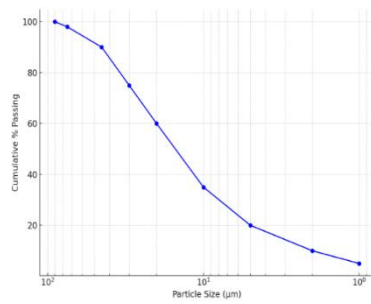


Figure 1. Particle size distribution curve of cement

Fly ash from Mettur Thermal Power Station, rich in pozzolanic materials like silica (67.44%), alumina (21.66%), and iron oxide (6.19%), replaces cement in concrete, enhancing workability, durability, and sustainability. Minor constituents include calcium oxide (1.25%), magnesium oxide (0.81%), and trace sulfur trioxide. (Sajeev *et al.*, 2025) This eco-friendly approach conserves resources, reduces cement use, mitigates fly ash disposal's environmental impact, and promotes greener construction practices and efficient industrial waste management.

River sand was selected as the fine aggregate for its local availability, cost-effectiveness, and environmental benefits. The sand conformed to IS Grade Zone-II specifications (IS 383:1970), ensuring proper particle size distribution and quality. Thorough cleaning eliminated contaminants like silt and clay, which could affect performance. Passing through a 4.75 mm sieve, the sand met all criteria for high-quality concrete production, aligning with sustainability goals and supporting the creation of durable, consistent mixtures. The natural coarse aggregate used in this study has a size of 12.5 mm with an angular shape. Key properties include a specific gravity of 2.65, water absorption of 1.74%, and a crushing value of 17.54%. The impact strength is 14.69%, bulk density is 1620 kg/m³, moisture content is 0.8%, and the fineness modulus is 6.8%.

Calotropis gigantea milk, a natural byproduct, has notable physical properties that make it suitable for use in concrete. It has a specific gravity of 1.1 and a solid content of $3.5 \pm 0.1\%$, which contributes to its effectiveness as a self-curing agent. The pH of the milk ranges from 7.19 to 8.21, indicating neutrality. Its white liquid form enables easy incorporation into concrete mixtures, enhancing hydration and reducing early-age cracking, ultimately improving concrete's durability and performance.

Superplasticizers, also known as high-range water-reducing admixtures (HRWRA), play a crucial role in the formulation of High-Performance Concrete (HPC) by enhancing workability and

performance. Conplast SP430, an effective plasticizer, is used at a dosage of 2% by weight of cement to reduce water content while maintaining workability. This superplasticizer can reduce water content by up to 30%, which lowers the water-to-binder (w/b) ratio, improving concrete strength and durability. Conforming to ASTM C494 and IS: 9103-1998, Conplast SP430 ensures reliable. Conplast SP430 is a high-performance superplasticizer based on sulphonated naphthalene formaldehyde (SNF), designed to improve the workability and strength of concrete. It appears as a dark brown liquid with a specific gravity of 1.20 ± 0.02 and is chloride-free, making it safe for reinforced concrete. This admixture allows significant water reduction of up to 25%, enabling high-slump, pumpable, and dense concrete with enhanced durability. Conplast SP430 is compatible with all types of Portland cement and supplementary cementitious materials like fly ash and GGBS. It is particularly effective in precast, high-performance, and high-strength concrete applications, improving both early and ultimate strength. Figure 2 shows the SEM image of flyash.

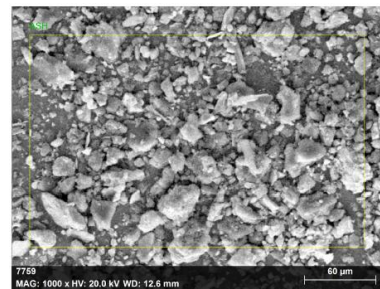


Figure 2. SEM of Flyash

Experimental Investigation

Self-Compacting Concrete's (SCC) flowability and filling capacity were evaluated using the slump flow test. Six liters of SCC mix were placed on a 500 mm diameter foundation plate within a slump cone that measured 300 mm in height and 200 mm in base diameter. The concrete was able to spread once the cone was raised. Important information on the SCC's flowability and self-leveling characteristics was revealed by timing how long it took for a 500 mm diameter circle to develop. (Pahsha *et al.*, 2025)

The L-box test was used to evaluate the passage capacity of Self-Compacting Concrete (SCC), assessing its ability to flow through confined spaces and dense reinforcement. The test involves an L-shaped rectangular section with reinforcing bars and a movable gate dividing the horizontal and vertical parts. About 14 liters of SCC were placed

into the vertical section without compaction and allowed to settle for one minute. (Benaicha *et al.*, 2025) The blocking ratio, calculated by comparing the heights of the horizontal (H2) and vertical (H1) sections, indicates the concrete's ability to pass through obstacles.

The V-Funnel test is vital for evaluating the flow dynamics and traversing ability of Self-Compacting Concrete (SCC). The test involves filling a V-shaped funnel with SCC and releasing the outlet's obstruction to initiate flow, while a stopwatch measures the time taken for the concrete to exit the funnel. Short flow times indicate good flowability and maneuverability, while longer times suggest higher viscosity or reduced workability, which may hinder self-leveling. (Moghaddam *et al.*, 2025)

The capacity of Self-Compacting Concrete (SCC) to flow uniformly and preserve structural integrity during casting, avoiding segregation, is assessed using the J-ring test. SCC is poured into a J-shaped mold with a horizontal lower section and an upper funnel as part of the test. After removing the funnel, the concrete flows through the horizontal portion, and its spread at the widest point is measured to assess its ability to pass through

confined spaces without segregation. (Mukherjee *et al.*, 2025)

An essential technique for assessing Self-Compacting Concrete's (SCC) segregation resistance and passing capacity during casting is the U-Box test. The test uses a U-shaped mold with two top arms and a connected base section. SCC is poured into the mold and allowed to flow through the arms, simulating real-world placement. The test assesses the concrete's ability to resist segregation and maintain homogeneity, ensuring uniform material distribution and structural integrity.

The compression strength test is essential for determining the load-bearing capacity and structural integrity of concrete. Concrete specimens, typically in cylindrical or cubic form, are subjected to an axial load under controlled conditions until failure occurs. The process involves preparing the samples, curing them, and positioning them in a compression testing machine. The applied load induces stress, and the resulting deformation is measured. Figure 3 shows the experimental setup.

This study examines the microstructural and phase composition of cementitious mixes (T1, T9, and T12) using X-ray Diffraction (XRD) and Scanning Electron Microscopy (SEM). XRD

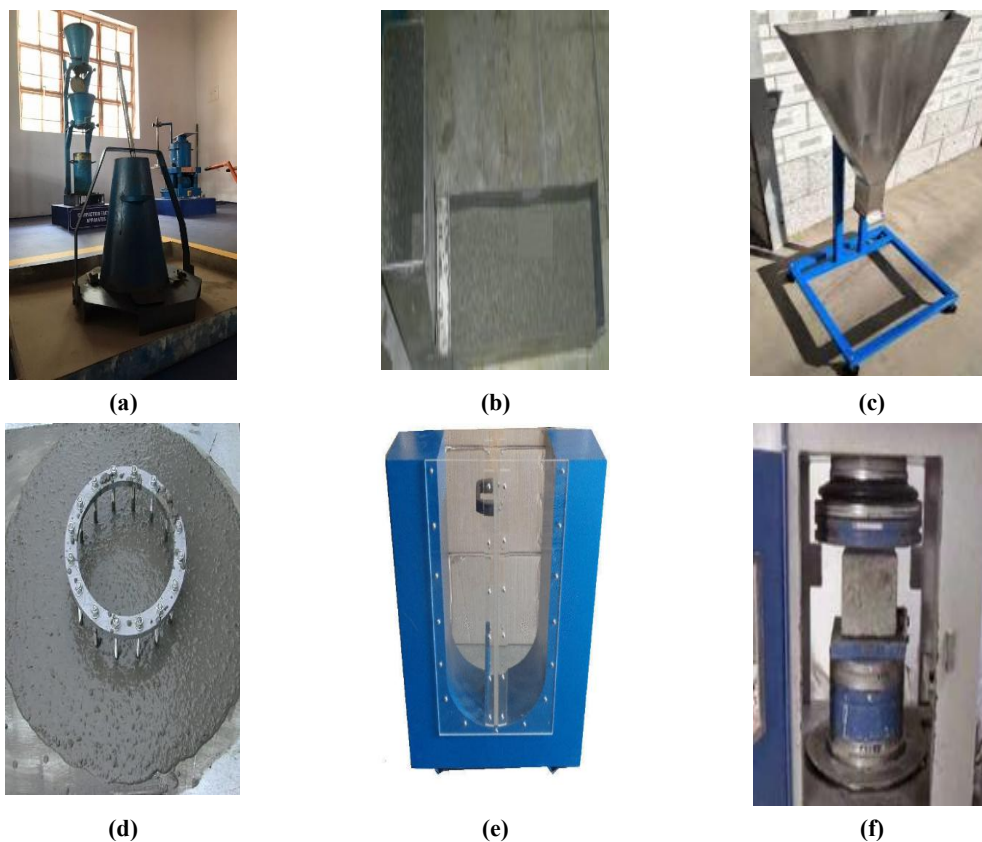


Figure 3. Experimental Setup

analysis identifies key hydration products such as C-S-H, Ca(OH)_2 , and CaCO_3 , while SEM reveals microstructural changes. The investigation assesses hydration progress, particle distribution, and porosity. The results highlight the enhanced densification and reduced unreacted phases in T12, indicating improved mechanical properties and durability compared to T1 and T9.

Mix Proposition

Table 1 shows the mix proposition of various mix.

Table 1. Mix proportions

Sl. No.	Mix	Description
1	T1	Conventional Concrete
2	T2	95% Cement + 5% Flyash
3	T3	90% Cement + 10% Flyash
4	T4	85% Cement + 15% Flyash
5	T5	80% Cement + 20% Flyash
6	T6	75% Cement + 25% Flyash
7	T7	85% Cement + 15% Flyash + 1% Calotropis gigantea milk
8	T8	85% Cement + 15% Flyash + 2% Calotropis gigantea milk
9	T9	85% Cement + 15% Flyash + 3% Calotropis gigantea milk
10	T10	85% Cement + 15% Flyash + 4% Calotropis gigantea milk
11	T11	85% Cement + 15% Flyash + 3% Calotropis gigantea milk + 1% Superplasticizers
12	T12	85% Cement + 15% Flyash + 3% Calotropis gigantea milk + 2% Superplasticizers
13	T13	85% Cement + 15% Flyash + 3% Calotropis gigantea milk + 3% Superplasticizers

Results and Discussion

Slump Cone Test

The slump test results demonstrate the impact of incorporating fly ash, Calotropis gigantea milk, and superplasticizers on the workability of concrete. Conventional concrete (T1) exhibited a slump value of 704 mm. Replacing cement with fly ash increased slump values, with T2 (5% fly ash) reaching 707 mm, and T4 (15% fly ash) achieving a peak of 720 mm, reflecting improved workability. However, further replacement of cement with fly ash (T5-T6) led to a slight decline, suggesting an optimal replacement percentage near 15%.

Introducing Calotropis gigantea milk (T7-T10) alongside 15% fly ash slightly improved

workability, peaking at 719 mm with 3% milk (T9). Beyond this percentage, the slump value slightly decreased, indicating diminishing returns on workability. The addition of superplasticizers (T11-T13) significantly enhanced the slump values, reaching 730 mm with 3% superplasticizers (T13). The combination of 15% fly ash, 3% Calotropis gigantea milk, and superplasticizers achieved the highest workability, optimizing the mix for enhanced flow and placement.

These results indicate that integrating fly ash, Calotropis gigantea milk, and superplasticizers effectively improves concrete workability, with optimal proportions enhancing mix performance for sustainable construction. Figure 4 shows the slump cone test.

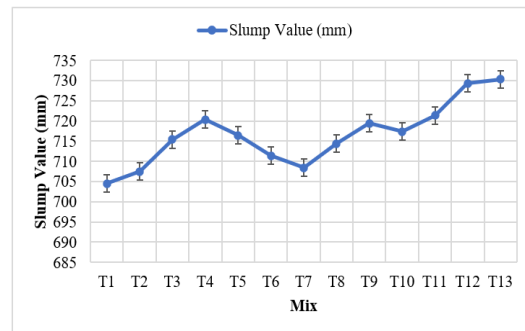


Figure 4. Slump cone test

L-Box Test

The L-box test results reveal the passing ability and flow behavior of concrete mixes with varying proportions of fly ash, Calotropis gigantea milk, and superplasticizers. Conventional concrete (T1) showed a ratio of 0.840. Incorporating fly ash improved the flow, with T2 (5% fly ash) achieving 0.844 and T4 (15% fly ash) peaking at 0.859. Beyond 15% fly ash (T5-T6), the ratio slightly declined, suggesting an optimal replacement level for enhanced flowability.

Adding Calotropis gigantea milk (T7-T10) further improved the L-box ratio. The mix with 3% milk (T9) reached a peak of 0.858, indicating improved passing ability without segregation. However, at 4% milk (T10), the ratio slightly decreased, implying an optimal milk content of 3%. Superplasticizers (T11-T13) significantly enhanced the passing ability, achieving a maximum ratio of 0.871 with 3% superplasticizers (T13). This mix, containing 15% fly ash, 3% Calotropis gigantea milk, and 3% superplasticizers, demonstrated the best flow characteristics. Figure 5 shows the L-Box test results.

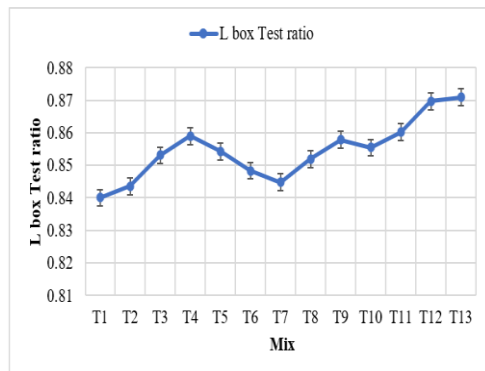


Figure 5. L-Box test

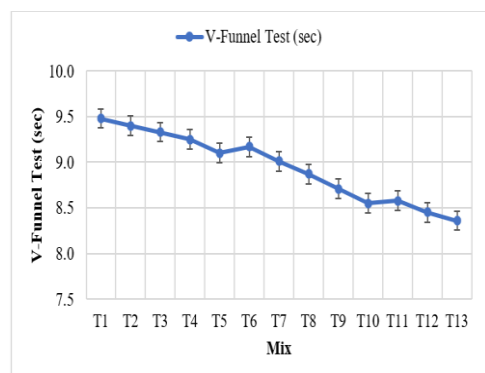


Figure 6. V-Funnel test

V-Funnel Test

The V-funnel test results provide insights into the flow time and viscosity of various concrete mixes. Conventional concrete (T1) recorded a flow time of 9.48 seconds. Replacing cement with fly ash reduced flow time, indicating improved fluidity, with 15% fly ash (T4) achieving 9.25 seconds and 20% fly ash (T5) further lowering it to 9.10 seconds. Beyond this, the fluidity slightly decreased, as seen in T6 (55% fly ash). The inclusion of *Calotropis gigantea* milk (T7-T10) progressively enhanced flow time. The best performance was achieved with 4% milk (T10) at 8.55 seconds, indicating its potential as a natural admixture to improve viscosity and flow.

Adding superplasticizers (T11-T13) further improved flow time, with T13 (3% superplasticizers) achieving the shortest time of 8.36 seconds. This mix, incorporating 15% fly ash, 3% *Calotropis gigantea* milk, and 3% superplasticizers, demonstrated optimal performance for achieving high fluidity and workability. These results suggest that fly ash, *Calotropis gigantea* milk, and superplasticizers synergistically enhance the viscosity and flow of concrete, supporting better placement and compaction. Figure 6 shows the V-Funnel test results.

J-Ring Test

The J-ring test results illustrate the passing ability and resistance to segregation of various concrete mixes. Conventional concrete (T1) recorded a value of 6.19 mm. Replacing cement with fly ash progressively improved the results, with the highest performance at 20% fly ash (T5) at 6.33 mm, before slightly decreasing at 55% fly ash (T6). This trend suggests an optimal fly ash replacement level of 15-20% for improved segregation resistance. Incorporating *Calotropis gigantea* milk (T7-T10) further enhanced the J-ring value, with T10 (4% milk) achieving 6.59 mm, demonstrating its potential to improve mix stability. However, the incremental improvement diminishes as milk concentration increases, indicating a saturation point for its effectiveness.

The addition of superplasticizers (T11-T13) further boosted the J-ring values. T13, containing 15% fly ash, 3% *Calotropis gigantea* milk, and 3% superplasticizers, achieved the highest value of 6.73 mm. This combination demonstrates optimal passing ability and cohesion, minimizing segregation. These findings highlight the synergistic effects of fly ash, *Calotropis gigantea* milk, and superplasticizers in enhancing concrete's stability and flow, supporting sustainable and efficient construction practices with improved performance characteristics. Figure 7 shows the J-Ring test results.

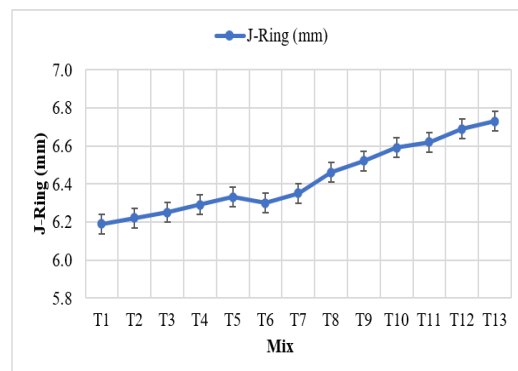


Figure 7. J-Ring test

U-Box Test

The U-box test results highlight the filling ability of various concrete mixes. Conventional concrete (T1) recorded a filling height difference of 26 mm. Replacing cement with fly ash progressively improved filling ability, with T4 (15% fly ash) reaching 30 mm and T5 (20% fly ash) achieving 31 mm, indicating enhanced flowability and reduced blockage. Beyond 20% fly ash (T6), the values plateaued, suggesting an optimal replacement range

of 15-20%. The inclusion of *Calotropis gigantea* milk (T7-T10) significantly increased the U-box height. The mix with 4% milk (T10) attained 37 mm, demonstrating improved filling and flow characteristics due to the milk's lubricating effect. However, the rate of improvement lessened with higher milk concentrations.

Superplasticizers (T11-T13) further enhanced filling ability, with the maximum U-box value of 41 mm achieved in T13 (15% fly ash, 3% *Calotropis gigantea* milk, and 3% superplasticizers). This mix demonstrated superior flow and filling characteristics, optimizing concrete performance. These results show that combining fly ash, *Calotropis gigantea* milk, and superplasticizers significantly improves concrete's filling ability, supporting efficient and sustainable construction practices by utilizing industrial by-products and natural additives while enhancing mix workability and flow. Figure 8 shows the U-Box test results.

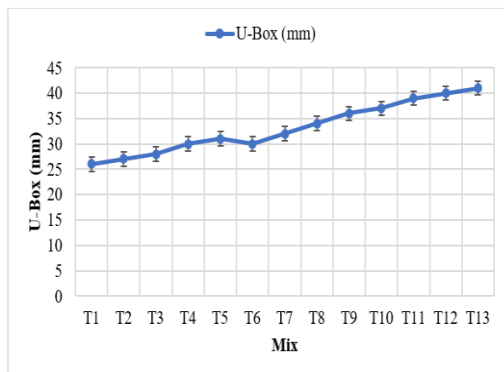


Figure 8. U-Box test

Compression Strength Test

The compressive strength results illustrate the effect of fly ash, *Calotropis gigantea* milk, and superplasticizers on concrete strength over 7, 14, and 28 days. Conventional concrete (T1) achieved 32.68 MPa at 28 days. Replacing cement with fly ash gradually increased compressive strength, peaking at 35.72 MPa with 20% fly ash (T5). Beyond this (T6), strength slightly declined, indicating an optimal replacement level near 15-20%. Incorporating *Calotropis gigantea* milk (T7-T10) enhanced strength further. The mix with 3% milk (T9) achieved the highest strength among these mixes, reaching 37.48 MPa at 28 days. Strength plateaued or slightly declined with higher milk concentrations, indicating 3% milk as the optimal dosage.

The addition of superplasticizers (T11-T13) resulted in the highest compressive strengths, with T12 (15% fly ash, 3% milk, 2% superplasticizers) achieving a peak strength of 39.35 MPa at 28 days.

T13 showed a slight reduction, suggesting 2% superplasticizers as the optimal dosage for maximum compressive strength. These findings highlight that combining fly ash, *Calotropis gigantea* milk, and superplasticizers significantly enhances the compressive strength of concrete, promoting sustainable construction practices while achieving superior performance through optimal material proportions. Figure 9 shows the compressive strength test results.

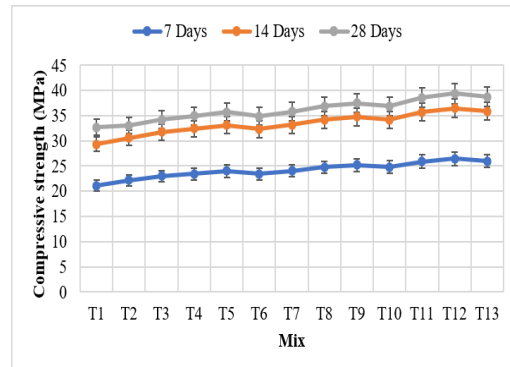


Figure 9. Compressive strength

SEM Analysis

Figures 10, 11, and 12 display the Scanning Electron Microscopy (SEM) images of the T1, T9, and T12 mixes, respectively. The microstructural analysis provides insights into the morphological differences among the mixes, highlighting the formation of hydration products, porosity, and particle distribution. In Figure 10 (T1 mix), a rough and porous microstructure is observed with a significant presence of needle-like ettringite formations and loosely packed hydration products. The presence of unreacted particles and a relatively porous structure suggests incomplete hydration, which may affect the mechanical properties and durability of the mix.

In Figure 11 (T9 mix), a denser microstructure is evident compared to T1. The hydration products appear more compact, and the quantity of unreacted particles is reduced. The presence of C-S-H gel is more prominent, indicating improved hydration. However, some microcracks and voids are still visible, which could influence strength development. In Figure 12 (T12 mix), the most compact and well-developed microstructure is observed. The particles appear more interconnected, with minimal voids and a high degree of C-S-H formation. The reduction in porosity and improved bonding among the hydration products suggest enhanced mechanical performance and durability. The absence of large unreacted particles indicates a more complete hydration process. During cement

hydration, calcium silicate hydrate (C-S-H) forms as the primary binding phase, contributing significantly to the strength and durability of concrete. Calcium hydroxide (CH), a secondary product, does not enhance strength and can make the matrix more susceptible to chemical attacks, though it supports pozzolanic reactions when present. Overall, the SEM analysis reveals progressive densification from T1 to T12, correlating with increased hydration and reduced porosity, which are essential for improving mechanical strength and durability in cementitious materials.

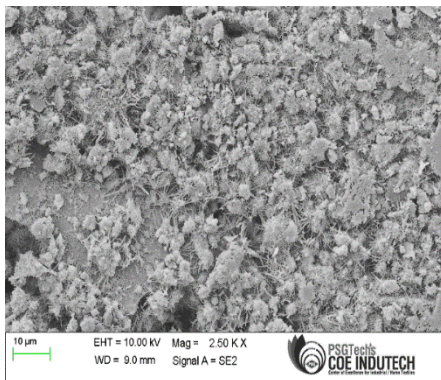


Figure 10. SEM of T1 mix

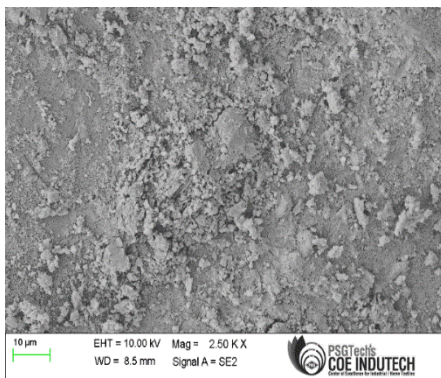


Figure 11. SEM of T9 mix



Figure 12. SEM of T12 mix

XRD

Figures 13, 14, and 15 present the X-ray diffraction (XRD) patterns of the T1, T9, and T12 mixes, respectively. The analysis reveals the presence of major crystalline phases, including calcium hydroxide (Ca(OH)_2), calcium carbonate (CaCO_3), calcium silicate hydrate (C-S-H), silicon dioxide (SiO_2), and ettringite. In Figure 13 (T1 mix), a significant peak for Ca(OH)_2 is observed at lower angles, indicating the presence of unreacted portlandite. C-S-H, the primary hydration product responsible for strength development, is also identified with an intense peak around 30° . The presence of CaCO_3 suggests carbonation of some hydration products. Additionally, peaks for SiO_2 and ettringite are visible, indicating the formation of secondary hydration phases.

Figure 14 (T9 mix) exhibits a similar phase composition, with notable differences in peak intensities. The C-S-H peak remains dominant, reflecting ongoing hydration. The intensity of Ca(OH)_2 is slightly reduced compared to T1, suggesting increased reaction with supplementary materials. The presence of multiple CaCO_3 peaks implies further carbonation. In Figure 15 (T12 mix), the most significant feature is the pronounced intensity of C-S-H peaks, suggesting enhanced hydration. Ca(OH)_2 intensity is notably lower than in T1 and T9, indicating a more complete reaction. SiO_2 and ettringite peaks remain visible, contributing to microstructural stability. Overall, the results demonstrate progressive hydration across the mixes, with T12 showing the highest degree of reaction and reduced Ca(OH)_2 content, which may lead to improved mechanical performance and durability.

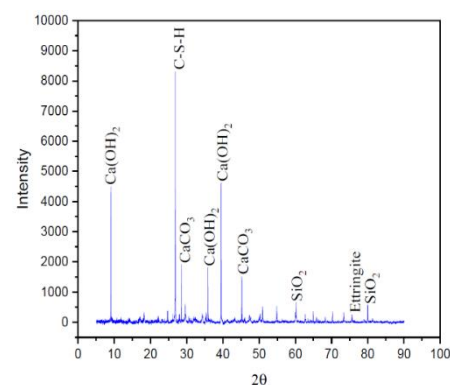


Figure 13. XRD of T1 mix

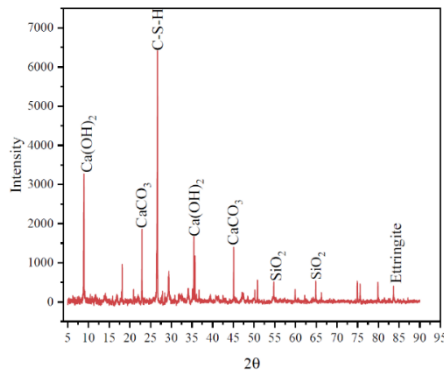


Figure 14. XRD of T9 mix

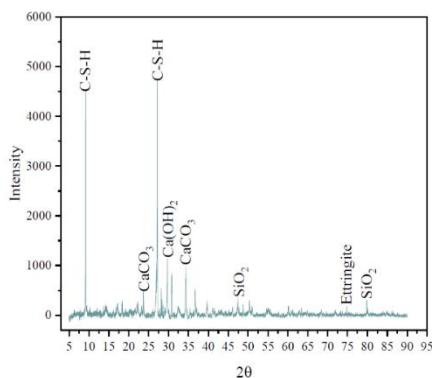


Figure 15. XRD of T12 mix

Conclusion

This study investigated the impact of replacing cement with fly ash, incorporating *Calotropis gigantea* milk, and adding superplasticizers on the properties of concrete. The results demonstrate the effectiveness of these materials in improving workability, flowability, and compressive strength, while also contributing to sustainability and efficient resource utilization.

Fly ash, a byproduct of coal combustion, served as a partial replacement for cement. At an optimal replacement level of 15-20%, fly ash significantly enhanced the workability (slump test), passing ability (L-box and J-ring tests), and flow time (V-funnel test) without compromising performance. Fly ash not only improved concrete's fresh properties but also increased compressive strength, achieving a peak of 35.72 MPa at 28 days with 20% replacement. This demonstrates the material's pozzolanic properties and its potential to reduce cement usage, conserving natural resources and mitigating environmental impact.

The addition of *Calotropis gigantea* milk further enhanced the concrete's properties. Acting as a natural admixture, it improved workability and flow characteristics, as evidenced by increased slump, reduced V-funnel time, and enhanced J-ring and U-box values. The optimal dosage was 3%, resulting in superior performance across all tests and achieving a compressive strength of 37.48 MPa at 28 days.

Superplasticizers played a vital role in further optimizing the mix. Their inclusion significantly enhanced flowability and workability while achieving the highest compressive strength of 39.35 MPa at 28 days. The optimal combination of 15% fly ash, 3% *Calotropis gigantea* milk, and 2% superplasticizers yielded the best overall performance, striking a balance between fresh and hardened properties.

The XRD and SEM analyses reveal progressive hydration and densification from T1 to T12, with T12 exhibiting the most compact microstructure and highest C-S-H formation. Reduced Ca(OH)_2 content and porosity indicate improved mechanical strength and durability, making T12 the most optimized mix for enhanced performance in cementitious materials.

Using 15% fly ash in concrete reduces cement consumption, significantly lowering CO_2 emissions and environmental impact. It promotes recycling of industrial waste, conserves natural resources, and decreases the heat of hydration. Additionally, it enhances concrete durability, extending service life and reducing maintenance needs, contributing to more sustainable construction practices.

Overall, the study confirms the viability of using fly ash, *Calotropis gigantea* milk, and superplasticizers to produce high-performance concrete. This approach not only improves concrete properties but also promotes sustainable construction by reducing reliance on traditional cement and effectively managing industrial and natural waste. The synergistic effects of these materials create a concrete mix that is environmentally friendly, cost-effective, and capable of meeting modern construction demands.

Future studies could explore long-term durability, environmental benefits, and scaling this approach for industrial applications. Implementing these findings could pave the way for greener construction practices, addressing environmental concerns while achieving superior concrete performance.

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