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Influence of fly ash on rheological behaviour of HVFA concrete

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Abstract: High-volume fly Ash (HVFA) concrete has gained significant attention recently due to its potential for reducing environmental impact and improving long-term durability. This project investigates HVFA's influence on concrete rheology, aiming to explore its applicability in sustainable construction. HVFA concrete mixes M1 (30% fly ash), M2 (40% fly ash), and M3 (50% fly ash) were prepared, varying fly ash percentages as a partial cement replacement. Fresh concrete tests, including slump cone and flow table tests, assessed workability and flow characteristics. Hardened samples underwent compressive and split tensile strength tests to evaluate mechanical properties. Results provided insights into HVFA concrete rheology, focusing on workability, flowability, and mechanical performance. Additionally, the study explores potential environmental benefits and challenges linked to HVFA concrete. These findings aid in advancing sustainable concrete technologies, offering crucial insights for engineers, architects, and policymakers seeking innovative, eco-friendly construction materials and practices while addressing environmental challenges related to HVFA concrete.

Keywords: Fly ash, Strength, Flow, Slump, Workability, Compaction, Split tensile strength, Compressive strength, Sustainability.

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1. Introduction

Cement, a vital component of concrete and construction materials, plays a pivotal role in shaping modern infrastructure. It is the most widely used binder in the construction industry, enabling the creation of durable and sturdy structures. However, the widespread use of cement has significant environmental implications, primarily due to the high carbon dioxide (CO_2) emissions associated with its production. As the world grapples with the challenges of climate change and sustainability, finding alternative and eco-friendly solutions for cement becomes imperative.

Cement production is a highly energy-intensive process, involving the heating of limestone and other raw materials at high temperatures in kilns. This process releases substantial amounts of CO_2 as a byproduct, contributing significantly to greenhouse gas emissions. According to estimates, cement production accounts for approximately 8% of global CO_2 emissions, making it one of the largest industrial sources of greenhouse gases. Additionally, limestone quarrying for cement production can lead to habitat destruction, biodiversity loss, and landscape alteration. To address the environmental challenges posed by traditional cement, one of the most promising sustainable alternatives is the incorporation of Fly Ash in concrete. Fly Ash is a fine, powdery byproduct generated from coal-fired power plants, where it is captured from the flue gases. As a waste material, Fly Ash was once disposed of in landfills, causing environmental concerns. However, it is now being recognized as a valuable supplementary cementitious material due to its pozzolanic properties. Fly ash is a pozzolanic material added to concrete for improved properties. It's a coal combustion residue, rich in silica, alumina, and iron. Two classes, Class C and Class F, exist based on calcium content. Despite its abundance, only a small percentage is utilized in various applications [1].

A concrete mixture with a minimum 50% replacement of cement content by fly ash is termed High-Volume Fly ash Concrete [2]. Fly ash of small size and the essentially spherical form of the particles comprising fly ash usually influence the rheological properties of cementitious pastes, causing a reduction in the amount of water required for a given degree of workability [3]. Hence the use of superplasticizers becomes necessary to get workable concrete. In the revised version, IS: 10262-1982 adopts slump as the criterion for assessing workability instead of compaction factor. The use of slump as a measure of workability is considered more convenient, widely applied on construction sites, and generally more acceptable [6].

Rheological characteristics pertain to the evaluation of the flow attributes of materials in a semi-solid state. Concrete, exhibiting semi-solid properties, undergoes examination through various experiments to assess its flow behaviours. In this project, several tests including the slump cone test, flow table test, and compaction factor test were employed. These tests aimed to investigate the flow properties of M15-grade concrete. Different proportions of fly ash were incorporated while maintaining a constant water-cement ratio. The concrete mixes encompassed fly ash proportions of 30%, 40%, and 50%, coupled with both m-sand and standard sand grade 1.

“The setting time for the concrete is longer than the traditional concrete due to the low content of cement and water” [4]. It has low bleeding and heat of hydration and has better mechanical and durability properties that are required for structural applications. “The amount of fly ash to be added in the concrete is given by BIS codal provision of IS 3812: 2003” [5]. Mixtures with 25% to 55% are acceptable depending upon the applications. The age of strength acceptance may need to be extended based on the amount of fly ash used.

2. Methodology

2.1 Slump cone test

Slump cone test is used for measuring the consistency of concrete which cannot be used for very wet or dry concrete. It is used as a control test and indicates the uniformity of the concrete. While the test doesn't directly determine all aspects of concrete's rheology (flow and deformation behaviour), it provides practical information about its behaviour during construction.
The metallic frustum cone has the following dimensions,

i. Bottom diameter = 20cm
ii. Top diameter = 10cm
iii. Height = 30cm

The prepared sample concrete is poured into the metallic frustum cone in 3 layers with each layer tamped 25 times with a standard tamping rod of diameter 16mm. The cone is then lifted allowing the concrete to slide down. There are 3 types of slumps namely,

i) True slump
ii) Shear slump
iii) Collapse slump

2.2 Flow table test

The flow table test indicates the quality of concrete with respect to consistency, cohesion, and affinity towards segregation. A larger spread indicates better flow properties, while a smaller one suggests stiffness. This test offers insights into concrete's ability to flow and deform, helping with construction decisions. However, it's a basic method and should be supplemented with more comprehensive tests and models for a complete understanding of concrete behaviour.
Similar to the slump cone test this test also consists of a small frustum cone with the following dimensions,

i. Bottom diameter = 25cm
ii. Top diameter = 17cm
iii. Height = 12cm

The prepared sample concrete is poured into the metallic frustum cone in 3 layers with each layer tamped 25 times with a standard tamping rod of diameter 16mm. The apparatus is plugged in and switched on. The flow table is allowed to rise and drop 15 times. The diameter of the flow of concrete is measured along 3 directions and the average of it gives the flow of concrete.

2.3 Compaction factor test

The compaction factor test is most efficient in measuring the workability of concrete. It works on the principle of degree of compaction achieved with a standard amount of work done by allowing the concrete to fall from a standard height. A concrete mix with a high compaction factor flows well and can be easily compacted, indicating a more fluid and deformable material. This is consistent with positive rheological behaviour, where the concrete can flow and adapt to different shapes.

The test apparatus consists of 2 hoppers at standard height and a cylinder placed at the base. The concrete is loaded into the first hopper and is allowed to fall freely onto the second hopper and then to the cylinder. Then the cylinder is weighed. The same amount of concrete is taken and compacted manually in the cylinder in 3 layers with each layer tamped 25 times with a standard tamping rod. The cylinder is then weighed. The percentage ratio of the weight of the partially (free fall) compacted sample to the weight of the fully (manually) compacted sample gives the compaction factor for the concrete sample.

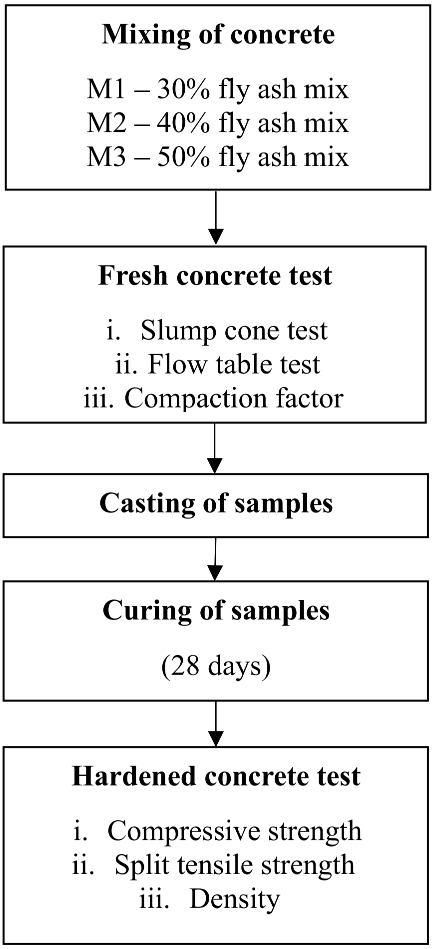

Figure 1. Working Methodology

3. Mix ratio

The experimental mix design adheres to the specifications outlined in the latest IS - 10262:2019 code for mix design. This standard provides the guidelines for proportioning concrete mixes as per the requirements using the concrete-making materials including other supplementary materials identified for this [7]. By following the protocols laid out in IS - 10262:2019, the mix design is worked out and the following quantities of materials are arrived for Msand and Standard Sand in Table 1 and Table 2 respectively.

3.1 Msand

Table 1. Mix Ratio for Mix using Msand

Mix	W/C ratio	Cement (kg)	Fly ash (kg)	Coarse aggregate (kg)	Fine aggregate (kg)	Water (ml)	Admixture (ml)
M1	0.45	1.9	0.82	7.54	4.28	1210	8
M2	0.45	1.64	1.08	7.48	4.26	1279	8.2
M3	0.45	1.36	1.36	7.41	4.2	1275	8.13

3.2 Standard Sand

Table 2. Mix Ratio for Mix using Standard Sand

Mix	W/C ratio	Cement (kg)	Fly ash (kg)	Coarse aggregate (kg)	Fine aggregate (kg)	Water (ml)	Admixture (ml)
M1	0.45	1.87	0.82	7.54	4.27	1273	8.12
M2	0.45	1.64	1.08	7.47	4.24	1279	8.2
M3	0.45	1.36	1.36	7.41	4.21	1278	8.16

4. Result

Below are the test results for M15 concrete mixes with different percentages of fly ash (30%, 40%, and 50%) using both Msand and Standard Sand. The results include fresh concrete tests (slump cone, flow table, and compaction factor) and tests on hardened concrete (compressive strength, split tensile strength, and density).

4.1 Fresh Concrete test results

4.1.1 Msand

Table 3. Fresh concrete test results for Msand.

Mix	Slump value (mm)	Inference	Flow (cm)	Compaction factor (%)
M1	147.5	Highly workable	41.585	92.68
M2	147.5	Highly workable	41.195	93.61
M3	135	Highly workable	40.45	87.55

It was observed that 30% and 40% mix showed a reasonable flowability when compared to 50% mix but on the other hand 50% mix showed high compaction leading to denser concrete mix as in Figure 2 and Figure 3. This suggests that higher amounts of fly ash led to reduced workability, potentially requiring additional efforts during concrete placement and compaction. The decrease in slump value aligns with conventional expectations, as fly ash particles tend to fill in the gaps between particles and thus reduce the overall lubricating effect that enhances workability. This observation correlates with the reduction in slump values and further underscores the potential trade-off between incorporating more fly ash for environmental benefits and maintaining desired concrete workability and flow characteristics. The compaction factor, a critical parameter reflecting the workability of concrete, was systematically assessed. Notably, M2, containing 40% fly ash, exhibited the highest compaction factor at 93.61%, indicating superior workability compared to the other mixes as in Table 3. The study delves into the specific impact of fly ash on the compaction process, attributing the observed trends to the ball-bearing effects of fly ash particles. The spherical morphology of fly ash particles contributes to enhanced lubrication within the concrete matrix, facilitating optimal particle arrangement during compaction.

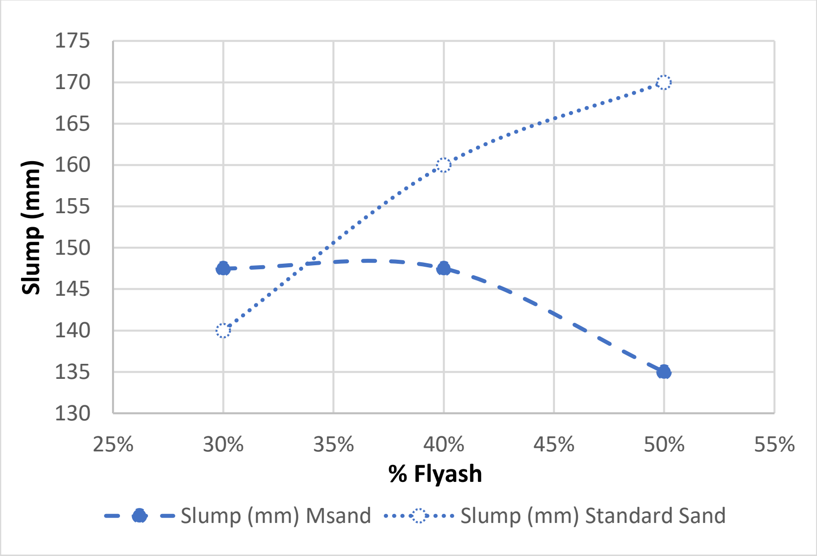

Figure 2. Comparison of Slump Value for Msand and Standard Sand with Fly Ash Content

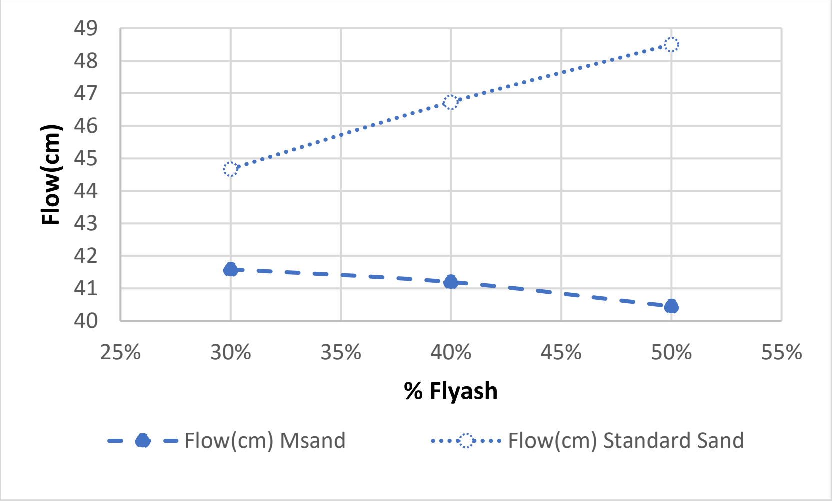

Figure 3. Comparison of Flow Value for Msand and Standard Sand with Fly Ash Content

4.1.2 Standard sand

Table 4: Fresh concrete test results for standard sand

Mix	Slump value (mm)	Inference	Flow (cm)	Compaction factor (%)
M1	140	Highly workable	44.67	81.97
M2	160	Highly workable	46.73	95.36
M3	170	Highly workable	48.5	97.45

In contradiction to Msand, it was observed that standard sand has an increase in flowability with an increase in the percentage of fly ash due to the particle size of grade 1 standard sand (1mm to 2mm) which is relatively coarser when compared to Msand. As the particle size increases the flowability of concrete gradually increases which is inferred from Figure 2 and Figure 3. The fine particles in the sand, coupled with the reactive characteristics of fly ash, likely contribute to improved particle packing and lubrication within the mixture. This combination enhances the flowability and workability of the concrete.

The fine particles in the grade 1 standard sand may interact with the fly ash, resulting in better dispersion and bonding, which could explain the increase in slump and flow values. The increasing trend in slump value also aligns with the notion that fly ash, as a fine and pozzolanic material, could lead to improved particle packing and lubrication within the mixture, promoting better workability. The rising flow values imply that higher amounts of fly ash could potentially enhance the fluidity and self-levelling properties of the concrete, making it more suitable for applications requiring intricate Mold-filling or complex formwork.

In addressing the challenge of lower compaction factors associated with uniformly graded aggregates, this study explores the potential of mitigating this limitation through the incorporation of fly ash in concrete mixtures. Utilizing the results from M1, characterized by a comparatively lower compaction factor, we consider the impact of increased fly ash percentages. Given the proven benefits of fly ash, such as its pozzolanic properties and ball-bearing effects, an augmentation in fly ash content is examined to enhance lubrication during compaction. The findings from M2 and M3, which exhibit higher compaction factors as in Table 4, support the notion that an elevated fly ash percentage can contribute positively to compaction characteristics. This suggests optimizing uniformly graded aggregates in concrete mixes, demonstrating the technical feasibility of adjusting fly ash proportions to overcome challenges associated with compaction and improve overall workability. Careful consideration of the balance between fly ash content and other mix constituents is crucial to achieving optimal concrete performance.

5. Hardened Concrete test

5.1 Compressive strength and split tensile strength

Table 5. Hardened concrete test results for M sand.

Mix	Compressive strength (N/mm^2)		Split tensile strength (N/mm^2)	
	Msand	Standard sand	Msand	Standard sand
M1	16.67	18.5	2.1	2.26
M2	17.97	16.35	1.66	2.89
M3	17.13	17.93	1.84	2.41

It was observed that there was a gradual increase in compressive strength with its peak at 40% of fly ash for the Msand mix as in Figure 4. Inferring from the graph Figure 4, an optimum replacement level was found in a 40% fly ash mix. Further increase in fly ash content increases the porosity in the concrete leading to a decrease in compressive strength of the concrete. The compressibility trends as seen in Table 5, suggest that different fine aggregates respond uniquely to varying levels of fly ash content, potentially due to particle size distribution, shape, and interaction effects. There is a consistent decrease in split tensile strength for Msand as the mix percentage increases [1] as in Figure 6. Interestingly, Standard sand exhibits a more erratic trend, with a significant drop at 40% mix as seen in Figure 5. These findings shed light on the nuanced influence of sand proportions on concrete's split tensile strength, providing valuable insights for mix design considerations in construction practices.

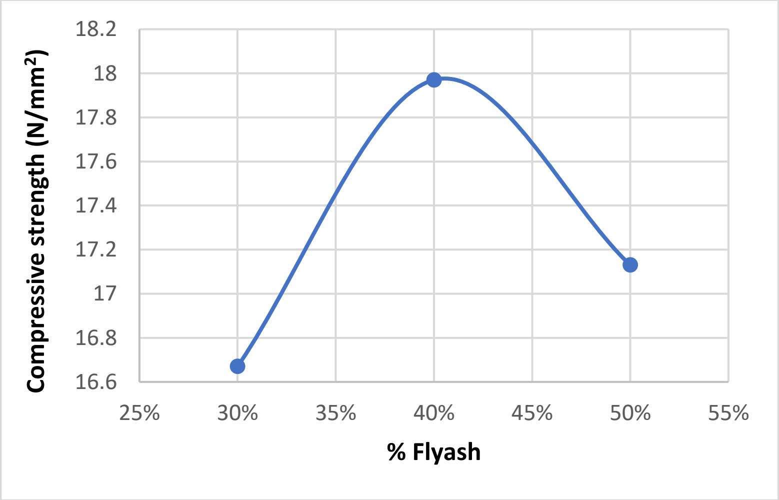

Figure 4. Relation Between Fly Ash Content with Compressibility Using Msand

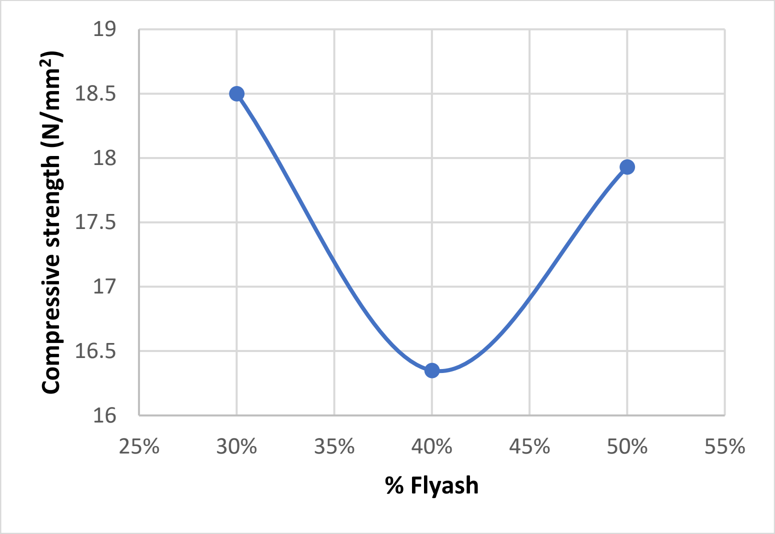

Figure 5. Relation Between Fly Ash Content with Compressibility Using Standard Sand

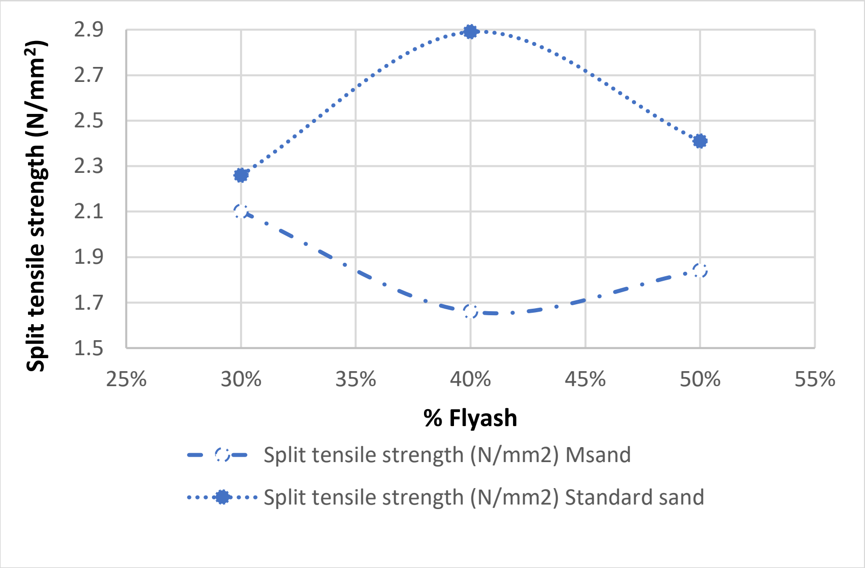

Figure 6. Relation Between Fly Ash Content with Split Tensile Strength for Msand and Standard Sand

6. Density

Table 6. Hardened Concrete Test Results for Standard Sand

Mix	Density (kg/m³)	
	Standard sand	Msand
M1	2573	2516
M2	2647	2596
M3	2530	2590

At 30% fly ash, the highest density of 2573 kg/m³ as in Table 6 and Figure 7 could indicate an optimal balance between the finer fly ash particles and the standard sand particles. However, a slight decrease in density at 50% fly ash (2530 kg/m³) might be attributed to the dominance of the lighter fly ash particles, impacting the overall mixture density. Higher density in standard sand can lead to a higher overall weight of the concrete mix, potentially making it more suitable for specific applications where greater mass is desirable.

In contrast, m-sand mixtures show a different trend. The density is lowest at 30% fly ash (2516 kg/m³) as in Figure 7, possibly due to interactions between m-sand and fly ash particles resulting in a less compact arrangement. As the fly ash content increases to 40%, the density rises (2596 kg/m³), indicating that the addition of fly ash is starting to improve particle packing within the m-sand mixture. At 50% fly ash, the density remains relatively stable (2590 kg/m³), suggesting a balance between the effects of increased fly ash content and the inherent characteristics of m-sand. M sand's lower density might be advantageous in terms of reducing the overall weight of the concrete mix, which can be beneficial in situations where lighter structures are desired, or when constructing elements like precast panels.

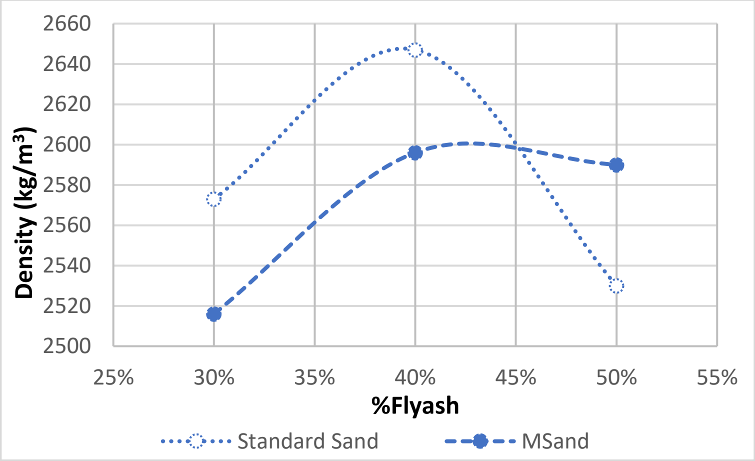

Figure 7. Comparison of Concrete Density for Msand and Standard Sand with Fly Ash Content

7. Conclusion

The 40% fly ash mix in both Msand and standard sand shows favourable results in terms of workability and strength. The 50% fly ash mix also exhibits good workability, but its compressive strength is lower than the 40% mix. The use of standard sand results in slightly higher compressive strength values compared to Msand for the same fly ash percentage (e.g., 40% fly ash mix). For 1m^3 concreting around 700kg of fine aggregate is required which costs about Rs 81,900 for standard sand and Rs 44,100 for Msand which is half the amount required by standard sand. Hence the use of Msand in construction can considerably be cost effective.

The 30% fly ash mix generally shows high workability but lower density, which may be suitable for certain applications. When we replace 30% of cement with fly ash, it's considered a moderate replacement. This mix maintains good early strength and can be suitable for various applications, including structural elements like beams and columns aligning with previous findings [2]. Using a lower percentage of fly ash 30% is common in pile foundations to ensure the necessary strength is achieved. This helps maintain early and long-term strength. The 40% fly ash mix demonstrates a good balance between workability, and density and retains its flowability for a maximum of 30 minutes giving additional time to work with the concrete. This percentage is often chosen for slabs where a balance between sustainability and workability is essential. Concrete with 40% fly ash replacement can still maintain good workability and flowability while reaping the environmental benefits of fly ash and, it's often preferred for non-structural elements like pavements and sidewalks due to its improved durability [1]. The 50% fly ash mix provides high workability but has lower density and compressive strength. This mix may have slightly reduced early strength but can still be used for structural elements with proper design considerations and can also be used in slabs with finishing and for some foundations like drilled piers [2]. However, it's often used in applications where long-term strength and sustainability are more critical than immediate strength.

The compatibility of superplasticizer with HVFA concrete emphasizes the impact of binder content on the dosage of high-range water-reducing admixture (HRWR). Adequate curing is crucial for optimal HVFA concrete performance. The relationship between total binder content and properties like strength development and pore size distribution is a shared focus, indicating that increasing the total binder content may not significantly benefit certain aspects of concrete performance [3].

Based on the comprehensive test results and graphical comparisons, the 40% fly ash mix with Msand emerges as a recommended choice. This composition presents a well-balanced compromise between workability and compressive strength [3]. The test outcomes and graphical analyses indicate that this blend offers promising characteristics that meet both the criteria of ease of handling during construction and structural strength. As a result, it stands out as an optimal option for applications where a balance between these two crucial factors is essential in concrete formulation.

8. References

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