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Performance Evaluation of High-Performance Concrete Using Ultrafine Mineral Admixture.

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ABSTRACT -This investigation explores the utilization of Ultra-fine in the production of high-performance Concrete (HPC) with gives early age strength for concrete. The study examines the early development of compressive strength after casting, alongside assessing variations in workability and the retention thereof in mix preparation. Moreover, it investigates the compressive strain behaviour, flexural parameters, resistance to acid attack, early age shrinkage, and select durability properties of the resultant optimal concrete mixes. Microstructural modifications are evaluated using Scanning Electron Microscopy (SEM) tests. The incorporation of Ultrafine led to a reduction in fresh properties beyond certain addition percentages. Notably, substituting part of Cement with Ultrafine in HPC mixes demonstrated significant enhancements in mechanical and durability aspects. The addition of Ultrafine, when combined with fly ash at optimal quantities, notably improved the early age strength of concrete while moderately enhancing other mechanical properties. However, it was observed that the use of selected mineral admixtures under a multiple blend system increased early age shrinkage-induced stress levels and concrete brittleness. Nonetheless, an improvement in microstructure was observed, characterized by a denser hydrated matrix offering enhanced homogeneity and improved bonding with aggregates. Furthermore, an increase in strength-governing hydration phases was evidenced with the optimal addition of ultrafine. The combination of Ultrafine and Fly ash significantly enhanced durability behaviour, attributed to microstructural refinement through pore refinement.

1. Introduction

The concept of High Performance Concrete (HPC) is an evolving area of research focused on increasing concrete compressive strength more than 80 MPa, along with improving other mechanical and durability parameters. With a growing emphasis on infrastructure development, HPC is becoming more pertinent in the Indian construction scene to optimize concrete properties for optimal performance. India, ranking as the second highest global producer of Cement [1], heavily relies on Thermal Power plants for its energy needs. With approximately 196 million tons of Fly Ash (FA) produced annually in India [2], it presents a significant resource for utilization. Simply disposing of FA on land is no longer sustainable, considering its pozzolanic nature, FA holds potential for broader use in the cement concrete industry, especially in HPC where there is a demand for large quantities of cementitious components. However, some global concrete manufacturers are hesitant about using Fly ash due to its slow reactivity and lower early strength attainment when incorporated into concrete [3,4].

In the evolutionary journey of HPC, various combinations of Supplementary Cementitious Materials (SCMs) or Mineral admixtures have been explored alongside regular OPC to enhance properties. Among these mineral admixtures, Silica Fume (SF) has garnered interest from researchers due to its high reactivity compared to other SCMs. Many studies advocate for its use in HPC either alone or in combination with popular SCMs such as Ground Granulated Blast Furnace Slag (GGBS), Fly ash, Rice Husk Ash (RHA), etc. [5–13]. Despite the scarcity of SF availability in India, it is vital for the construction industry to focus on utilizing locally available Fly ash in producing HPC. However, the practical use of Fly Ash as a mineral admixture is often limited to standard grade concrete due to concerns about its slow reactivity and low early strength. With only 0.66% of the total annually produced Fly ash utilized in concrete [2], it is crucial to maximize the incorporation of Fly ash in HPC to meet the demand for early strength gain in site conditions. In addition to traditional SCMs, researchers have also explored Ultra-Fine Mineral Additives in the realm of HPC. These ultrafine consist of very fine particles with micro to nano-level sizes and high specific surface areas. It has been studied globally for their ability to enhance cement and concrete properties [10-12]. Ultrafine produced through controlled processing of GGBS, has gained popularity due to its simple production method and enhanced reactivity. Similarly, Ultra-Fine Silica, or nano Silica, has shown promise in improving concrete strength and microstructure with enhanced hydration rates and interlayer bonding. However, further investigation is needed, particularly regarding concrete strength at very early ages, to align with the current trend of fast-track construction practices.

This research aims to produce HPC using conventional mixing and curing practices to ensure economic viability and practicality for large-scale construction projects. The proposed HPC recipe includes locally available Fly ash (class F) as an SCM and Ultra-fine Mineral Additives as performance enhancers, alongside standard concrete materials. Performance attributes such as Early Compressive strength, Flexural parameters, and Microstructure modifications are considered key properties of the resulting HPC, along with ultimate compressive strength and other related mechanical parameters [14].

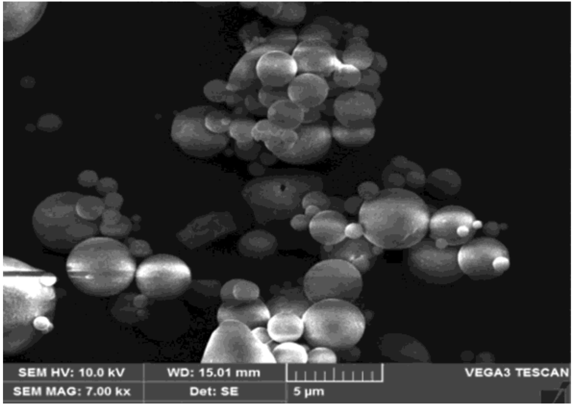
2. Materials

2.1. Fly Ash -Fly ash used in this experimental work was obtained from TATA Thermal Power Plant, fly ash referred as ASTM Class F fly ash or low calcium fly ash. The colour of fly ash can be brown, depending upon the chemical and mineral constituents Mean particle size ranges from less than 1 µm to no more than 150 µm. It consists of finesse test result is 29 % by wet sieving method as per IS:3812. The specific gravity, fineness modulus & specific surface area and density of fly ash are 2.2, 1.320, 300 m 2 /kg and 1.4 kg/m 3 respectively. The fig 2.1. SEM fly ash.

2.2. Ultrafine - Ultrafine is a controlled particle size and shape, ensuring high reactivity and optimal particle packing within concrete and cement paste matrices, thereby enhancing concrete strength and durability. The primary hydration reaction is attributed to the presence of inbuilt Cao. Ultrafine operates in three key ways: firstly, its average particle size of less than 6 microns and uniform particle distribution ensure a densely packed matrix. Secondly, it facilitates a pozzolanic reaction that transforms unreacted Calcium Hydroxide into a C-S-H crystal structure. Physical properties of Ultrafine is as per IS 16715:2018 standards, specific gravity is 2.3, Fineness (BET Method), Minimum m2/kg 1500 2730, Particle size range 3.59 µm to 8.79 µm. The fig 2.2 is SEM ultrafine.

2.3. Aggregate - Locally available Manufacturing sand having fineness modulus 3.10, specific gravity 2.72 and conforming to grading zone-II as per I.S: 383 - 1970. Coarse aggregate is of angular shaped crushed granite with different sizes of 20mm and 10 mm were used. Its fineness modulus and specific gravity are 7.38 and 2.825 respectively. Potable water with pH value 7.0 was used for the concrete.

2.4. Admixture - Super plasticizer in the form of liquid as pe IS 9103 and ASTM C 642 as a high range water reducing admixture (TP Builtech 350) was used in percentage of cementitious material.



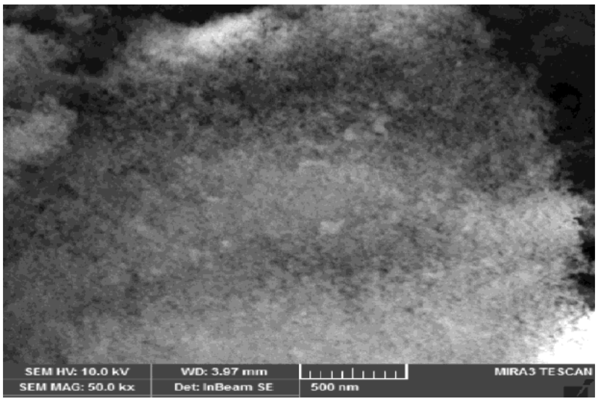
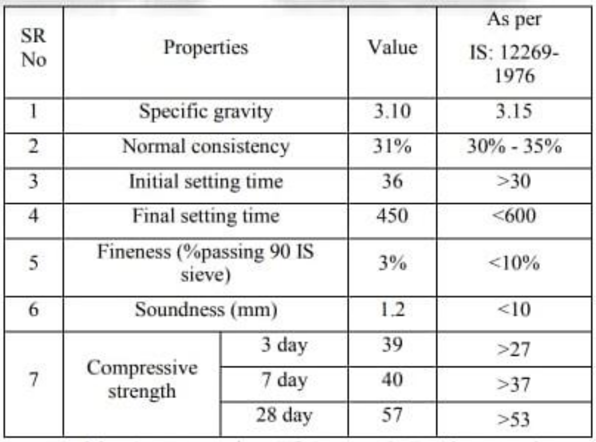


Fig. 2.1. SEM of Fly ash. Fig. 2.2. SEM of Ultrafine

2.5. Cement - Ordinary Portland cement-53 grade (UltraTech Cement) available in local market was used in investigation. The cement was tested according to IS 4031: 1988. It confirmed to IS 12269: 1987. Its Properties is given in Table . SR No Properties Value As per IS: 12269- 1976. The Fig 2.3 is SEM of cement.



SR No	Properties		Value	As per IS: 12269-1976
1	Specific gravity		3.10	3.15
2	Normal consistency		31%	30% - 35%
3	Initial setting time		36	>30
4	Final setting time		450	<600
5	Fineness (%passing 90 IS sieve)		3%	<10%
6	Soundness (mm)		1.2	<10
7	Compressive strength	3 day	39	>27
		7 day	40	>37
		28 day	57	>53

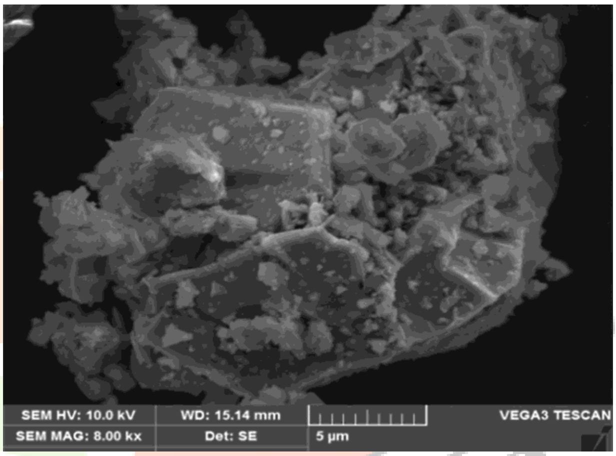


Fig.

2.3. SEM of cement.

3. METHODOLOGY

3.1. Mix proportion and concrete preparation

3.1.1 Mix design- The fractions of aggregate, both coarse (10 mm & 20 mm) and fine Aggregate Zone II (4.75 mm downsize) as per IS:383, are initially proportioned to achieve the minimum void percentage, following IS 2386 guidelines. Based on the void percentage variation for different aggregate combinations, a ratio of 55:45 for coarse to fine aggregate is selected to ensure maximum packing density. Once the aggregate proportions are determined, concrete mixes are optimized by increasing the paste volume in conventional sample utilizing only OPC and FA as cementitious components. It's ensured that the OPC content doesn't exceed 450 kg/m3, aligning with IS 456:2000 guidelines. After evaluating the compressive strength performance of conventional mixes, one mix is chosen as a reference for ordinary mixes, which incorporate a ternary blend with the addition of UFS in powder form at incremental percentages by weight of OPC. The best-performing ordinary mix chosen for next performance evaluation and testing. Detailed mix proportions, along with designations, are provided in Table 3.1, including recorded flow parameters for each concrete variant. A consistent water-to-cement ratio of 0.3 is maintained for all mixes, and the superplasticizer content is varying as per mix requirement by weight of cementitious material throughout the study. Conventional pan mixers are employed for preparing concrete mixes, involving 2 to 3 minutes of dry mixing followed by 5 minutes of further mixing after water addition. No external compaction is applied to the fresh concrete mixes after casting into moulds, allowing compaction solely through their own weight.

3.1.2 Mixing and casting - The required mass of coarse aggregate, fine aggregate, ultrafine, fly ash are weighed prior to mixing. The solids constituents of the fly ash- ultrafine based concrete, i.e. the aggregate sand the fly ash, ultrafine were dry mixed in the trial mixture in laboratory. The added water (Potable), and the super plasticiser (Mid PC) and mixes around 10 min up to well mixture of material of concrete. The wet mixing usually continued for another four minutes. The mixtures were usually cohesive. The workability of the fresh concrete was measured by Flow cone test apparatus.

3.2. Concrete test parameters

3.2.1. Fresh property/flow behaviour – The mixing of all ingredients checked the mix is cohesive and workable after mixing the flow is taken each and every 30 min of all mixes and it recorded up to 3 hr consistency of concrete. The flow value of concrete rises with increasing Ultrafine percentage up to 10 % replacement. However, increased percentages of fly ash (15% to 30%) as per IS 3812, result in stickiness observed in the concrete. Conversely, with an increase in ultrafine percentages from 4% to 10%, stickiness in the concrete is also noted.

3.2.2. Hardened properties- The compressive strength of the cube is determined by averaging the results of testing at three 150 mm cube specimens for each mix trial, following the required curing period from concrete casting. Testing is conducted according to the guidelines of IS 516:2018, employing a Compression Testing Machine with Automated loading control panel. For the evaluation of flexural behaviour after 28 days of curing, concrete beams measuring 150 mm on each side and 700 mm in length are utilized. Flexural parameters are assessed by testing the beams using a Flexure Testing Machine under point loading conditions. A minimum of three beams are tested to determine the average flexural strength. The load versus midspan deflection during flexural loading is plotted to determine the Area under Curve (AUC) as the toughness parameter. Although standard codal guidelines for flexural toughness assessment are limited to steel fibre reinforced concrete, the testing method is adapted from such codes, considering AUC as the determining parameter of flexural toughness for the test specimens. Split tensile strength is determined according to IS 5816, using concrete cylinders measuring 100 mm in diameter and 200 mm in length. The average tensile strength value is obtained by testing three such cylinders for each trial. For shear strength assessment, customized moulds are inserted into standard 150 mm cube moulds before casting concrete to produce test specimens. The peak load during shear failure is utilized to calculate the shear strength of concrete along the failure zone of 75 mm and 100 mm sides. An average of three such values is recorded as the shear strength of concrete. The DIN-1048(Part 5) Permeability test is conducted on a minimum of three test specimens to determine the limits for water penetration into concrete. The results of the water permeability test can serve as a preliminary indication of the degree of concrete compactness and the reduction in capillary/macro pores in the concrete specimen. Scanning Electron Microscope (SEM) analysis is employed to assess the microstructural variations in the concrete mixes and understand the benefits of using ultra-fine additives in terms of hydrated phases. Samples for SEM studies are obtained from selected mixes after 28 days of curing.

Table 3.1
Mix proportion details and flow recordings of concrete under investigation.

Mix series	Mix ID	Water kg/m^3	OPC kg/m^3	Fly Ash kg/m^3	Ultrafine kg/m^3	Crush sand kg/m^3	20 mm kg/m^3	10 mm kg/m^3	Admixt. kg/m^3	Flow mm
Conventional mix	**CM1**	199	450	99	0	584	633	516	3.84	550
Ordinary mix	**M1**	202	450	105	24	780	513	419	4.053	520
	M2	202	450	107	36	772	508	414	4.151	530
	M3	202	450	110	49	763	502	409	4.872	530
	M4	202	450	113	63	753	496	404	5.654	520

4. Results and discussion

4.1. Flow variation of mix -The fresh concrete mixes all exhibit flow values greater than 500 mm, as outlined in Table 4.1. Fly ash, characterized by its spherical particles (refer to Fig. 2.2), enhances the flow parameter for Series 1 mixes up to an optimal dosage. However, it's worth noting that with a constant amount of water and SP dosage, the flow parameter gradually decreases with the addition of ultrafine, as observed in Series 2 and 3 mixes. Due to their high specific surface area and particle shapes (see Figs. 2.3 and 2.4), ultrafine contribute to increases flow in fresh concrete, even at minimal dosage levels. Increased water demand due to their ultra-fine particle size and shape [11], ultimately affecting flow behaviour, particularly beyond an optimal dosage, employing different methods of ultrafine addition, exhibit similar trends in recorded flow values, direct powder state addition of ultrafine.

4.2. Compressive strength - The average compressive strength results of various mixes examined in the study are presented in Table 4.1, with values rounded off to the nearest whole number. The analysis of compressive strength results indicates a positive improvement with each addition of ultra-fine admixtures. Conventional mixes comprising only OPC and fly ash have demonstrated successful performance in meeting high ultimate strength criteria with the adopted mix design and material optimization. For the best-performing combination, the strength reached 96 MPa on the 28th day and 104 MPa on the 56th day of curing. This improvement can be attributed to the reactive calcium and silica phases of ultrafine, along with its higher fineness, resulting in more hydrated products at an early age. The increase in compressive strength with ultrafine addition has been sustained even at 28 and 56 days, recording values of 99 MPa and 108 MPa, respectively. Ultra-fine silica has further enhanced the characteristic strength in direct powder form. The highly reactive silica phases from ultrafine may have resulted in enhanced early strength by interacting with calcium phases from OPC and ultrafine. Additionally, the greater specific surface area offered by ultrafine might have led to the formation of more hydrated phases in the initial period. The trend of strength increment after ultrafine addition is observed to be positive with successive curing periods, recording a maximum of 99 MPa and 108 MPa after 28 and 56 days of curing (mix M4). Overall, the results of compressive strength suggest that the addition of ultrafine up to an optimal dosage has induced an accelerating effect on the hydration of the cement paste.

This effect is more pronounced after the addition of ultrafine. The ultra-fine reactive particles may act as centres of nucleation of hydration products and rapidly react with calcium hydroxide phases, thereby inducing rapid strength gain. Furthermore, the improved particle packing of the cementitious matrix by the physical filling effect of ultrafine may result in enhancement of the bond at the aggregate-cement Interfacial Transition Zone (ITZ). Such ITZ improvement, along with dense hydrated products at the early age, is expected to improve the concrete homogeneity and thereby the long-term mechanical performance. Enhanced long-term compressive strength may be linked to the continuous hydration process contributed by the slow reactive silica phases from fly ash to balance with the later available calcium compounds offered from OPC and ultrafine. Based on the compressive strength results, Mix, and M3 are selected for further testing of relevant mechanical parameters after 28 days of curing. The relative increment in compressive strength of selected mixes with reference to mix is presented in Table 4.1. The graph plotted for comparison of compressive strength of preferred mixes is provided in Fig. 4.1.

Table 4.1

Relative increment in Compressive strength with respect .

Mix series	**Mix ID**	**Compressive Strength, MPa at different time period**				
		24 hr	**3 days**	**7 days**	**28 days**	**56 days**
Conventional Mix	**CM1**	11	20	34	56	58
Ordinary mix	**M1**	20	36	55	79	86
	M2	22	45	63	88	94
	M3	28	51	68	96	104
	M4	28	54	70	99	108

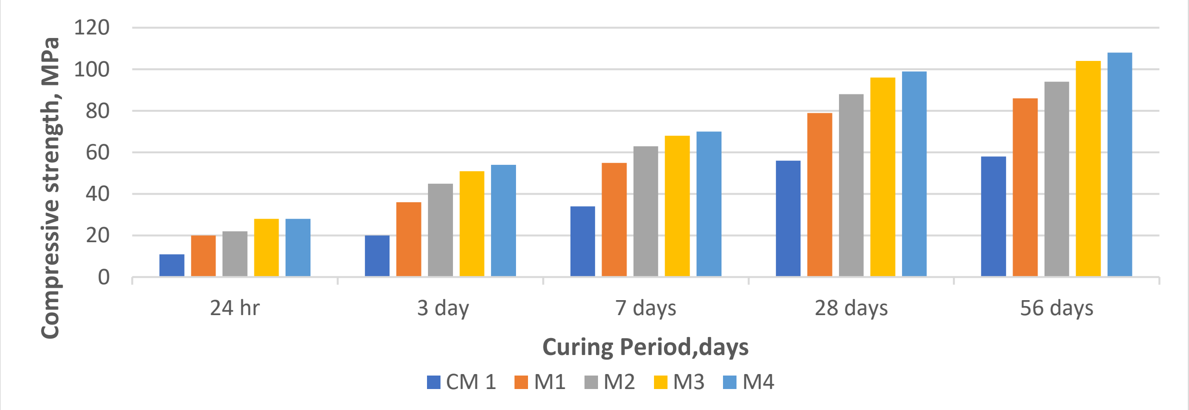


Fig. 4.1. Compressive strength variations for selected mixes.

4.3. Flexural performance -The flexural performance data obtained from testing concrete beams is presented in Table 4.3. The table also includes the expected standard flexural strength, fcr, calculated using the IS 456:2000 formulation: [fcr = 0.7(fck)0.5], where fck represents the 28-day compressive strength of the respective concrete mixes. Based on the recorded actual flexural strength, the performance has improved by 18–26% compared to conventional concrete mix with the addition of ultrafine admixtures. The relative variation of recorded fcr concerning mix is provided in Table 4.2. The addition of Ultrafine has ensured the achievement of the standard estimated flexural strength without any significant deviation, as observed in mixes ordinary concrete. Additionally, it is noted that the Flexural Toughness of concrete, calculated in terms of the Area enclosed under the Load vs. Deflection curve under bending stresses, has significantly improved with the addition of Ultrafine. The fig 4.1 is flexural testing machine.

Table 4.2

Flexural performance parameters.

Mix series	**Mix ID**	Flexural Strength, MPa at different time period				
		24 hr	3 days	7 days	28 days	56 days
Conventional Mix	**CM1**	1.4	1.9	3.7	6.5	7.2
Ordinary mix	**M1**	2	2.9	5.2	8.7	10.1
	M2	2.1	2.4	5.5	9.2	10.7
	M3	2.2	2.4	5.4	9.6	11.2
	M4	2.1	2.5	5.8	9.9	10.9

4.4. Tensile and shear strength- Table 4.3 presents compiled data on Split tensile strength and Shear strength, along with their relative changes compared to conventional mix. Tensile strength increases by 29% with Ultrafine addition. Shear strength notably improves with ultra-fine mineral additives, particularly Ultrafine, with a increase for Ultrafine in conventional mix, a 27% improvement for ordinary mix. These enhancements in mechanical parameters can be attributed to potential microstructural modifications induced by Ultrafine, fostering stronger bonding between aggregates and hydrated phases [10,11].

4.5. Water permeability- Table 4.3 presents observations from the Water permeability test. Mix, comprising OPC and FA, shows water penetration up to 7 mm, indicating reasonable permeability. However, ternary blend mixes exhibit increased resistance to water penetration. For instance, M3 records a depth of 1 mm. The reduction in capillary and micro pores, coupled with improved void filling and particle packing facilitated by Ultrafine, contributes to this enhanced resistance to water ingress. The fig 4.2 is shown SEM value of M3 specimen.

Table 4.3

Mechanical parameters of selected mixes.

Mix ID	Split Tensile strength, MPa	Shear strength, MPa	Water penetration, mm
CM1	4.1	5.9	7
M1	5.2	7.2	4
M2	5.6	8.3	2
M3	5.8	8.5	2
M4	5.9	8.6	1

Fig.4.1. Flexural Testing Machine.

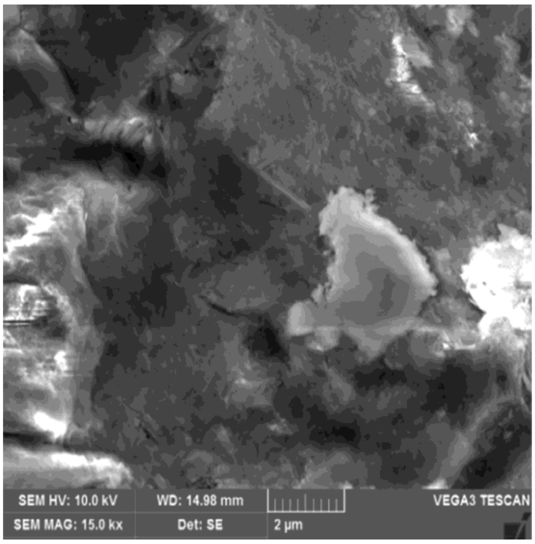


Fig. 4.2. SEM of mix M3.

5. Conclusions

The present study explores the use of fly ash and ultra-fine additives to enhance the mechanical properties of High Performance Concrete (HPC), focusing on early strength gain, flexural performance, and microstructure. Based on experimental results, the following conclusions can be drawn:

1. Early Compressive strength at 24 hours shows significant improvement with Ultrafine addition, reaching 28 MPa for the optimal mix (M3), marking a 39 % increase compared to the reference conventional mix.

2. Ultimate Compressive strength at 28 days exceeds 100 MPa for optimal concrete mixes, with the highest recorded compressive strength reaching 108 MPa at 56 days, demonstrating continuous performance improvement.

3. Flexural strength increases upon Ultrafine addition compared to reference conventional mix, with increments of 26%. Additionally, Flexural Toughness nearly doubles with Ultrafine.

4. The proposed HPC, produced through standard production and curing methods, proves suitable for practical use in construction, especially for Fast-track infrastructure projects and Pre-cast concrete industries requiring high early strengths for accelerated service periods.

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