Performance Based Study on Ultra High Reinforced Concrete

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***Abstract*—he present experimental investigation evaluates the rheological and mechanical properties of four UHPC mix designs developed with and without coarse aggregates. Two mixes incorporate 12.5 mm downgraded coarse aggregates, while the remaining two mixes are produced without coarse aggregates to examine their influence on fresh and hardened concrete behaviour. The fresh properties of the concrete are evaluated using Slump Flow, J-Ring, L-Box, V-Funnel, and U-Box tests in accordance with EFNARC (2005) guidelines to assess flowability, passing ability, and filling capacity. The hardened properties are assessed by determining the early-age compressive strength after three days of curing. In addition, the dynamic modulus of elasticity is evaluated using the Ultrasonic Pulse Velocity (UPV) method, while the static modulus of elasticity is determined following the relevant Indian Standard procedures. A comparative assessment of the dynamic and static modulus values is carried out to examine the elastic behaviour of UHPC and establish their relationship**

I. INTRODUCTION

The goal of the current experimental study is to assess the rheological properties of four ultra-high-performance concrete (UHPC) mix designs. Two of these mixes have coarse aggregates that have been downsized to 12.5 mm, while the other two mixes are made without coarse aggregates. By changing the water-to-binder ratio, each mix's fresh-state behavior is examined.

10% silica fume and 5% metakaolin are added to all mixes as additional cementitious materials, substituting cement by weight. Both quartz sand and manufactured sand (M-Sand) are utilized as fine aggregates; the quartz sand's particle sizes range from 45 to 150 µm. To reduce shrinkage and increase crack resistance, steel fibers are added in amounts ranging from 1% to 2%.

According to EFNARC (2005) guidelines, the slump flow, J-ring, L-box, V-funnel, and U-box tests are used to assess the fresh properties of UHPC. The concrete mixes' flowability, passing ability, and filling capacity are evaluated using these tests.

After three days of curing, the early-age compressive strength is determined. Additionally, the Ultrasonic Pulse Velocity (UPV) test is used to calculate the dynamic modulus of elasticity. The methods outlined in the applicable Indian Standards are used to evaluate the static modulus of elasticity. The elastic behavior of UHPC is then evaluated by comparing the dynamic and static modulus values.

II. LITERATURE REVIEW

Liu et al. (2024) The impact of coarse aggregates on the distribution of steel fibers and the flexural performance of ultra-high-performance concrete (UHPC) was thoroughly investigated by Liu et al. (2024). The goal of the study was to comprehend how the internal structure and mechanical behaviour of UHPC are impacted by the addition of coarse aggregate. According to experimental findings, the orientation and dispersion pattern of steel fibers within the concrete matrix were changed by the presence of coarse aggregates. Both the load-transfer capacity following cracking and the mechanism of crack propagation were impacted by this interaction. The researchers found that while coarse aggregates had little effect on the final flexural strength, they had a big impact on the material's ductility and post-cracking response. It was discovered that areas with higher concentrations of coarse aggregate particles had less uniform fibre distribution.

Huang et al. (2024): Important design factors affected the mechanical and physical characteristics of Ultra-High-Performance Concrete (UHPC) with coarse aggregates. The study looked at how steel fibre content, aggregate size, aggregate volume fraction, and curing conditions affected the concrete's overall performance. The researchers assessed the strength and durability properties of different UHPC mixtures using a thorough experimental program. The findings showed that when the mix proportions were appropriately optimized, the addition of coarse aggregates had no detrimental effects on the high-strength properties of UHPC. In mixes containing coarse aggregates, compressive strength values greater than 150 MPa were successfully attained, demonstrating the suitability of such mixtures for demanding structural applications.

Silva et al. (2024) A thorough literature review on the impact of constituent materials on the mechanical performance of Ultra-High-Performance Concrete (UHPC) was presented by Silva et al. in 2024. Cementitious binders, additional cementitious materials, steel fibers, fine aggregates, and coarse aggregates were among the components whose effects on the strength and durability properties of UHPC were examined in the study. The authors noted that in order to create a more homogeneous matrix and a highly dense particle packing structure, traditional UHPC mixtures are usually designed without coarse aggregates

Anish and Logeshwari (2024) provided a thorough analysis of Ultra-High-Performance Fibber-Reinforced Concrete (UHPFRC) incorporating nanomaterials and its numerous engineering applications. The study looked at how nanomaterials could enhance UHPC's microstructure, strength, and durability. According to the authors, in order to produce a denser, more homogeneous matrix with improved particle packing, conventional UHPC mixtures frequently remove coarse aggregates. The superior mechanical performance of UHPC is largely due to this refined microstructure. The review also emphasized how adding nanomaterials, like nano-silica and other nano-sized additives, improves hydration and decreases pore connectivity in the concrete matrix. These enhancements result in greater durability, improved crack resistance, and higher compressive strength. Furthermore, it was discovered that nanomaterials strengthened the bond between fibers and the cementitious matrix, leading to better structural performance

Tian et al. (2024) used a combination of experimental, numerical, and analytical methods to examine the flexural behaviour and design features of prestressed Ultra-High-Performance Concrete (UHPC) beams. The load-carrying capacity, cracking behaviour, stiffness, and ductility of prestressed UHPC structural members under bending loads were the main objectives of the study. The findings showed that because of its dense matrix and fibre reinforcement, UHPC has remarkable tensile strength and crack-bridging ability. Even after cracking started, the researchers found that prestressed UHPC beams retained a high degree of structural integrity, improving their durability and serviceability.

Selection of Materials

The study's materials were chosen according to how well they would produce UHPC. The main binding material was Ordinary Portland Cement (OPC). To enhance microstructural densification, strength development, and particle packing, silica fume and metakaolin were added as additional cementitious materials. Due to its uniform grading and hardness, quartz sand was utilised as a fine aggregate. To assess its impact on UHPC performance, crushed coarse aggregate was added to a few mixtures. To increase tensile strength, ductility, and crack resistance, steel fibres were added. To obtain the necessary workability at low water-to-binder ratios, a high-range water-reducing admixture (superplasticizer) was utilised.

III. MATERIAL CHARACTERIZATION

All materials underwent laboratory testing to characterise them before mix preparation. Using pertinent Indian Standard methods, physical characteristics like specific gravity, bulk density, fineness, and particle size distribution were ascertained. Additionally noted were the characteristics of steel fibres, such as their diameter, length, and aspect ratio. UHPC mixtures were developed using the material properties that were obtained.

Development of UHPC Mixes

For the experimental study, four distinct UHPC mixtures were created. The purpose of the mixtures was to compare the behavior of UHPC with and without coarse aggregates while adjusting the ratio of water to binder. To achieve the required workability and strength properties, the ratios of cement, silica fume, metakaolin, quartz sand, steel fibers, coarse aggregate, and superplasticizer were changed. In order to achieve satisfactory fresh properties, trial batches were prepared and adjusted.

Mixing Procedure

A laboratory concrete mixer was used for the mixing procedure. To guarantee even distribution, all dry materials, such as cement, silica fume, metakaolin, quartz sand, and coarse aggregate (if applicable), were first thoroughly blended. After that, water was gradually added while the mixture was still being mixed with the superplasticizer. In order to avoid fiber balling and to guarantee uniform dispersion throughout the concrete matrix, steel fibers were finally added gradually. Until a consistent and feasible UHPC mixture was achieved, mixing was continued.

Evaluation of Fresh Properties

The fresh properties of UHPC were assessed immediately after mixing. The EFNARC (2005) guidelines were followed in the evaluation of rheological behavior and filling ability. The tests listed below were carried out:

Slump Flow Test

The flowability and self-compacting properties of UHPC were assessed using the slump flow test. After lifting the slump cone, the average spread diameter was determined.

J-Ring Test

The J-Ring test was conducted to assess the passing ability of UHPC through congested reinforcement conditions. The distinction between J-Ring flow and slump flow was noted and examined.

L-Box Test

The L-Box test was used to evaluate the ability of UHPC to pass through reinforcing bars without segregation or blockage. The blocking ratio was calculated to determine passing performance.

V-Funnel Test

The V-Funnel test was performed to measure the viscosity and flow time of UHPC. The discharge time through the funnel was recorded for each mixture.

U-Box Test

The U-Box test was carried out to determine the filling ability and resistance to blocking of UHPC under simulated field conditions.

Casting and Curing of Specimens

After evaluating the fresh properties, concrete specimens were cast using standard steel molds. Cube specimens were prepared for compressive strength testing, while cylindrical specimens were cast for modulus of elasticity determination and ultrasonic pulse velocity (UPV) testing. To stop moisture loss, the specimens were covered and compacted as needed. After 24 hours, the specimens were demoulded and cured under controlled conditions until the specified testing age.

Compressive Strength Test

The early-age compressive strength of UHPC was determined at 3 days of curing. Cube specimens were tested using a compression testing machine in accordance with relevant Indian Standard specifications. The maximum load at failure was recorded, and the compressive strength was calculated. The results were used to compare the strength development of the different UHPC mixtures

Ultrasonic Pulse Velocity Test

The Ultrasonic Pulse Velocity (UPV) test was conducted as a non-destructive method to evaluate the quality and uniformity of UHPC. The pulse travel time through the specimen was measured, and the pulse velocity was calculated. The obtained values provided information regarding concrete density, integrity, and internal defects.

Determination of Dynamic Modulus of Elasticity

The dynamic modulus of elasticity was calculated using the UPV results and the density of the concrete specimens. This parameter reflects the elastic behavior of UHPC under dynamic loading conditions and provides an indication of material stiffness.

Determination of Static Modulus of Elasticity

The static modulus of elasticity was determined through compression testing on cylindrical specimens in accordance with Indian Standard procedures. Stress–strain measurements were recorded during loading, and the modulus of elasticity was calculated from the stress–strain relationship.

Correlation Between Dynamic and Static Modulus

The dynamic modulus and static modulus values found for each UHPC mixture were compared. The two parameters were correlated using statistical techniques. The relationship developed from this analysis can be used to estimate the static modulus of elasticity from non-destructive UPV measurements.

IV. ANALYSIS OF RESULTS

The results obtained from fresh property tests, compressive strength tests, UPV measurements, and modulus of elasticity evaluations were analyzed and compared. The influence of coarse aggregate incorporation, water-to-binder ratio, and constituent materials on UHPC performance was assessed. The findings were interpreted to identify the optimum UHPC mixture and to evaluate the feasibility of using coarse aggregates in UHPC production.

Table 1 Mix proportion Details for Mix 1

Materials	% by Weight	W/c Ratio
Cement	1	0.30, 0.28, 0.26, 0.24, 0.22
Micro Silica Fume	0.1	
High Reactivity Metakaolin	0.05	
M-Sand	1.72	
Coarse Aggregate	-	
Quartz Sand	0.32	
Steel Fibers	0.00575	

Table 2 Mix Proportion Details for Mix 2

Materials	% by Weight	W/c Ratio
Cement	1	0.30, 0.28, 0.26, 0.24, 0.22
Micro Silica Fume	0.1	
High Reactivity Metakaolin	0.05	
M-Sand	0.85	
Coarse Aggregate	0.77	
Quartz Sand	0.32	
Steel Fibers	0.00575	

Table 3 Mix Proportion Details for Mix 3

Materials	% by Weight	W/c Ratio
Cement	1	0.30, 0.28, 0.26, 0.24, 0.22
Micro Silica Fume	0.1	
High Reactivity Metakaolin	0.05	
M-Sand	1.72	
Coarse Aggregate	-	
Quartz Sand	0.32	
Steel Fibers	0.0062	

Table 4 Mix Proportion Details for Mix 4

Materials	% by Weight	W/c Ratio
Cement	1	0.30, 0.28, 0.26, 0.24,
Micro Silica Fume	0.1	

High Reactivity Metakaolin	0.05	0.22
M-Sand	0.85	
Coarse Aggregate	0.77	
Quartz Sand	0.32	
Steel Fibers	0.0062	

Table 5 Detail of Specimen of Compression Test

	Mix	days	Water Cement Ratio					Total number of cubes
			0.28	0.26	0.24	0.22	0.2	
100x100 x100mm cubes For com-pressive Strength Test	Mix 1	3days	3	3	3	3	3	15
		28days	3	3	3	3	3	15
	Mix 2	3days	3	3	3	3	3	15
		28days	3	3	3	3	3	15
	Mix 3	3days	3	3	3	3	3	15
		28days	3	3	3	3	3	15
	Mix 4	3days	3	3	3	3	3	15
		28days	3	3	3	3	3	15
Total								120

Table 6 Detail of Specimen for Modulus of Elasticity Test

100mm dia and 200mm height Cylinder for modulus of Elasticity Test	Mix	`	Water Cement Ratio			Total number of cubes
			0.3	0.26	0.22	
	Mix 1	28days	3	3	3	9
	Mix 2	28days	3	3	3	9
	Total					18

V. RESULTS ON SLUMP TEST

Table 7 Results - Slump Flow Test - Mix 1 of 0.22 W/C

Trial No.	Admixture Dosage in %	Slump Spread	
		Horizontal (mm)	T_{50} cm (sec)
1	1	460	23
2	1.05	470	18
3	1.1	510	15
4	1.2	540	10
5	1.25	610	8
6	1.3	660	5
		600-800	5

Table 8 Slump Flow of Mix 2 of 0.22 W/C

Trial	Admixture Dosage in %	Slump Spread	
		Horizontal (mm)	T_{50} cm (sec)
1	0.9	490	18
2	1	530	12
3	1.1	580	9
4	1.2	630	5
Values		600-800mm	05 sec

Table 9 Specifications and Results of Slump Flow Test - Summary

Water Cement Ratio		0.3	0.28	0.26	0.24	0.22	Specifications
Mix 1	Paste Content in %	49.5	48	46.4	44.8	43.2	
	Admixture Dosage in %	0.65	0.7	0.85	1	1.3	
	Horizontal Flow in mm	780	750	710	690	660	600to 800
	T50 cm Flow Time in sec	2	3	3	4	5	5
Mix 2	Paste content in %	51.7	49.7	48	46.4	44.7	
	Admixture Dosage in %	0.55	0.65	0.75	0.9	1.2	
	Horizontal Flow in mm	760	720	680	640	630	600to 800
	T50 cm flow Time in sec	3	3	4	4	5	5
Mix 3	Paste Content in %	49.5	48	46.4	44.8	43.2	
	Admixture dosage in %	0.7	0.75	0.9	1.1	1.25	
	Horizontal Flow in mm	770	740	700	670	640	600to 800
	T50 cm Flow Time in sec	3	3	4	5	5	5
Mix 4	Paste Content in %	47.5	46	44.4	42.9	41.4	
	Admixture Dosage in %	0.6	0.7	0.8	0.95	1.3	
	Horizontal Flow in mm	730	680	660	610	600	600to 800
	T50 cm Flow Time in sec	2	3	4	5	5	5

J Ring results

Water Cement ratio		0.3	0.28	0.26	0.24	0.22	
Mix	Paste Content in %	49.5	48	46.4	44.8	43.2	

1	Admixture Dosage in %	0.65	0.7	0.85	1	1.3	
	T_{50} cm Flow in sec	4	5	6	7	8	10
Mix 2	Paste Content in %	51.7	49.7	48	46.4	44.7	
	Admixture Dosage in %	0.55	0.65	0.75	0.9	1.2	
	T_{50} cm Flow in sec	5	7	8	9	10	10
Mix 3	Paste Content in %	49.5	48	46.4	44.8	43.2	
	Admixture Dosage in %	0.7	0.75	0.9	1.1	1.25	
	T_{50} cm Flow in sec	4	6	7	8	9	10
Mix 4	Paste Content in %	47.5	46	44.4	42.9	41.4	
	Admixture Dosage in %	0.6	0.7	0.8	0.95	1.3	
	T_{50} cm Flow in sec	6	7	9	10	10	10

U-Box Test results

Water cement ratio		0.3	0.28	0.26	0.24	0.22	
Mix 1	Paste Content in %	49.5	48	46.4	44.8	43.2	
	Admixture Dosage in %	0.65	0.7	0.85	1	1.3	
	Difference in Height in mm	0.5	0.5	1	1	1	30
Mix 2	Paste content in %	51.7	49.7	48	46.4	44.7	
	Admixture Dosage in %	0.55	0.65	0.75	0.9	1.2	
	Difference in Height in mm	0.5	0.5	1	1	2	30
Mix 3	Paste Content in %	49.5	48	46.4	44.8	43.2	
	Admixture Dosage in %	0.7	0.75	0.9	1.1	1.25	
	Difference in Height in mm	2	1	1	1	0	30
Mix 4	Paste Content in %	47.5	46	44.4	42.9	41.4	
	Admixture Dosage in %	0.6	0.7	0.8	0.95	1.3	
	Difference in Height in mm	1	1	1	1	2	30

L Box Test results

Water Cement Ratio		0.3	0.28	0.26	0.24	0.22	
Mix	Paste Content in %	49.5	48	46.4	44.8	43.2	

1	Admixture Dosage in %	0.65	0.7	0.85	1	1.3	
	Blocking Ratio (H_2/H_1)	0.95	0.95	0.9	0.90	0.85	0.8- 1
Mix 2	Paste Content in %	51.7	49.7	48	46.4	44.7	
	Admixture Dosage in %	0.55	0.65	0.75	0.9	1.2	
	Blocking Ratio (H_2/H_1)	0.9	0.9	0.85	0.85	0.85	0.8- 1
Mix 3	Paste Content in %	49.5	48	46.4	44.8	43.2	
	Admixture Dosage in %	0.7	0.75	0.9	1.1	1.25	
	Blocking Ratio (H_2/H_1)	9	0.9	0.9	0.85	0.8	0.8- 1
Mix 4	Paste Content in %	47.5	46	44.4	42.9	41.4	
	Admixture Dosage in %	0.6	0.7	0.8	0.95	1.3	
	Blocking Ratio (H_2/H_1)	0.9	0.85	0.85	0.8	0.8	0.8- 1

V-Funnel results

Water Cement Ratio		0.3	0.28	0.26	0.24	0.22	
Mix 1	Paste Content in %	49.5	48	46.4	44.8	43.2	
	Admixture Dosage in %	0.65	0.7	0.85	1	1.3	
	Tr - Flow Time in sec	8	9	10	11	12	12
	Flow at T5 min in sec	11	13	13	14	15	≤ Tr+3
Mix 2	Paste Content in %	51.7	49.7	48	46.4	44.7	
	Admixture Dosage in %	0.55	0.65	0.75	0.9	1.2	
	Tr Flow Time in sec	9	10	11	12	12	12
	Flow at T5 min in sec	10	12	13	14	15	≤ Tr+3
Mix 3	Paste Content in %	49.5	48	46.4	44.8	43.2	
	Admixture Dosage in %	0.7	0.75	0.9	1.1	1.25	
	Tr Flow Time in sec	9	9	10	11	12	12
	Flow at T5 min in sec	11	12	13	15	15	≤ Tr+3
Mix 4	Paste Content in %	47.5	46	44.4	42.9	41.4	
	Admixture Dosage in %	0.6	0.7	0.8	0.95	1.3	
	Tr Flow time in sec	10	11	13	14	12	12
	Flow at T5 min in sec	11	13	13	14	15	≤ Tr+3

Compressive Strength Test Results

Water Cement Ratio		0.3	0.28	0.26	0.24	0.22
Mix 1	Paste Content %	49.5	48	46.4	44.8	43.2
	3days Strength in MPa	47.55	53.12	57.26	60.28	66.23
	28 day	100.1	105.53	111.83	115.93	119.5
Mix 2	Paste Content %	51.7	49.7	48	46.4	44.7
	3days Strength in MPa	44.62	50.32	54.62	57.59	61.54
	28 day	89.5	95.32	97.23	98.65	105.36
Mix 3	Paste Content %	49.5	48	46.4	44.8	43.2
	3days Strength in MPa	40.6	43.61	48.62	55.59	59.62
	28 day	75.5	78.32	83.56	89.72	100.23
Mix 4	Paste Content %	47.5	46	44.4	42.9	41.4
	3days Strength in MPa	39.5	42.59	45.59	50.29	54.61
	28 day	79.3	81.23	83.52	89.26	93.5

VI. CONCLUSIONS

a. Volume of Paste

Based on the discussions of paste volume in different mixes, it can be inferred that a concrete mix's paste volume increases with its cementitious content. Concrete with coarse aggregates has a higher void content, which raises the need for paste.

b. Slump Flow Test

 Another factor that regulates the mixes' flow behavior is their paste volume. This relationship is demonstrated by the slump flow of mixes 1 and 3, which had comparable flow characteristics and the same amount of paste volume. Mix3 has a lower paste volume, so its flow diameters are smaller than those of Mix2, which has a higher paste volume. Therefore, it can be said that increasing the paste volume of UHPC mixes can enhance their flow characteristics. The presence of coarse aggregates and the ensuing decrease in paste volume may be responsible for the decreased flow.

c. J ring Result

 With the exception of a w/c ratio of 0.22, the T50 time requirement of mixes with a J-ring test at various w/c ratios corresponds to the volume of paste of the mixes, suggesting that even with the highest admixture dosage requirement, achieving the necessary flow property is challenging at very low water-cement ratios.

d. U Box Test Results

 At a lower w/c ratio, a higher admixture dosage is needed, and vice versa. There is less variation in the U-Box test results between the mixes with and without coarse aggregates.

e. L Box Test

 Higher admixture dosages are needed to reach the necessary blocking ratio range of 0.8 to 1.0 at lower paste contents of UHPC mixes. The lower w/c ratios of 0.22 and 0.24 exhibit similar behavior.

f. V-Funnel Test

The amount of time needed to empty the V funnel decreases as the admixture dosage is increased. The flow time decreases as the w/c ratio rises. This experiment demonstrates that the amount of admixture needed increases and the emptying time decreases at higher w/c ratios.

Higher paste volumes can cause mixes to become more cohesive and less flowable. The mixes' inter-particle friction could be the cause of these changes. The flowability and fillability of UHPC mixes are reduced at lower w/c ratios of 0.22 and 0.24, which is similar to other fresh properties of the mixes.

g. Compressive Strength

By adjusting the cement and aggregate contents, the early (3 day) compressive strength of M40–M65 can be attained. For UHPC mixes without coarse aggregates at a lower w/c ratio of 0.3 and M90–M100 at a very lower w/c ratio of 0.22, the grade of M75–M80 at cementitious content of 650 kg/m3 (mix3 and mix4) can be attained after 28 days of curing.

According to IS, the value of the constant C is greater than that of regular concrete (5000). 456-2000. For UHPC without coarse aggregate, the average value of C is 5696; for UHPC with coarse aggregate, it is 6215. For UHPC without coarse aggregate, the constant value C is 14% higher than that of regular concrete, and for concrete with coarse aggregate, it is 24.3% higher. The suggested formulas for UHPC's E are

For UHPC without coarse aggregates, E = 5696* (Sqrt fck)

E is equal to 6215* (Sqrt fck). for UHPC in the absence of coarse aggregates.

A. Static and Dynamic Modulus of Elasticity

1. UHPC mixes have a Static Modulus of Elasticity (E) between 58.95 and 62.21 GPa. The evaluated Dynamic Modulus of Elasticity (Ed) is marginally higher than E and falls between 60.26 and 64.03 GPa. IS 456-2000 permits a 20% variation, so since the difference between E and Ed is less than 10%, it can be disregarded.

It can be inferred from the study on the rheology of UHPC mixes that the necessary rheology of mixes is achieved by varying the admixture dosage from 0.5% to 1.3% at various w/c ratios. In general, the dosage at which the flow characteristics could be attained is between 1.1% and 1.3%. According to EFNARC 2005, all of the UHPC mixes at various w/c ratios met the requirements of the SCC of the wet mixes.

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