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Mechanical Properties of Ultra High Performance Concrete

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***Abstract*—**A research program is conducted to evaluate the mechanical properties of Ultra High Performance Concrete, target compressive strength at the age of 28 days being more than 150 MPa. The methodology to develop such mix has been explained. The material properties, mix design and curing regime are determined. The material attributes are understood by studying the stress strain behaviour of UHPC cylinders under uniaxial compressive loading. The load –crack mouth opening displacement (cmod) of UHPC beams, flexural strength and fracture energy was evaluated using third point loading test. Compressive strength and Split tensile strength results are determined to find out the compressive and tensile behaviour. Residual strength parameters are presented vividly explaining the flexural performance, toughness of concrete.Durability studies were also done to compare the effect of fibre to that of a control mix For all the studies the Mechanical properties were evaluated by varying the percentage and aspect ratio of steel fibres The results reflected that higher aspect ratio and fibre volume produced drastic changes in the cube strength, cylinder strength, post peak response, load-cmod, fracture energy flexural strength, split tensile strength, residual strength and durability. In regards to null application of UHPC in India, an initiative is undertaken to comprehend the mechanical behaviour of UHPC, which will be vital for longer run in commercialization for structural applications.

***Keywords*—**Ultra High Performance Concrete, Reinforcement Index, Compressive Strength, Tensile Strength,Flexural Strength, Residual Strength, Fracture Energy,Stress-Strain Relationships, Load-Crack Mouth Opening Displacement and Durability.

I. Introduction

FOR the last decade UHPC has been one of the keen interest areas for the researchers. The conventional concrete is economical but the problem posed is the low tensile and flexural strength. UHPC is a modified Reactive Powder Concrete having compressive strength generally more than 150MPa, better resistance to failures occurring due to bending, tension, and compression. The selection of appropriate raw materials, micro- and macro-structural behaviour, mechanical properties, durability, methodology for construction and design specifications have been still not clearly understood. They are developed for application in special structures which in absence of codal provisions can only be practically implicated from the literature and past experimental investigations.

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The material standards are yet not defined and research knowledge there is almost null application in India using this concrete. To answer this questions a detailed investigation was done on mechanical properties of UHPC.

There has been lot of discretion regarding the proper definition of UHPC. The Association Française de Génie Civil (AFGC) Interim Recommendations for Ultra High Performance Fibre-Reinforced Concrete states UHPC to have the following properties: Compressive strength that is greater than 150 MPa, internal fiber reinforcement to ensure non brittle behaviour, and a high binder content with special aggregates. The constituents are cement, fine sand, silica fume, quartz powder, superplasticizer, a low water-cement ratio, and inclusion of either high-strength steel fibers or non-metallic fibers [1]. The composition of the ingredients almost being the same, the methodology of curing, post processing techniques,application of prestressing process do differ. This concrete is being traded all around the globe by different companies with different brand to name them - Boygues and Lafarge-patented it as Ductal®, CoreTUFF by US Army Corps of Engineers, BSI, Densit and Cemtec-UHPFRC (Ultra High Performance Fibre Reinforced concrete) are popular in Europe while Reactive Powder Concrete (RPC),Ductal in Australia., and UHSFRC (Ultra-high strength fiber reinforced concrete) in Japan.

II. Past Investigations

Journals, international standards technical notes were referred as guidelines to design the mix proportion, curing techniques and to conduct experiments. The observations from the literature review are as follows

Collepardi et al. (1996)[2] investigated in three sets (i) replacement of ground fine quartz sand(0.15-0.40 mm), (ii) a part of (cement + silica fume) of the cementitious binder and (iii) the whole of fine sand by graded natural aggregate (max size 8 mm). Studies revealed that (i) there is no change in the compressivestrength of the RPC at the same water-cement ratio. (ii) An increase in the water-cement ratio is observed, due to whichthere is reduction in the cement factor, and hencedecrease incompressive strength. (iii) Flexural strength was lower when graded coarse aggregate replaced all the quartz sand. Steam curing done at 90°C and 160 °C provided lower drying shrinkage and creep strain.*Feylessoufi.A. et al.*, (1997)[3] stated that xonolite is one of the most important crystalline hydrates in RPC. The heating mode studied were putting the specimen directly in the oven preset at 300°C, conventional thermo gravimetric analysis(TGA) in vacuum at a rate of 100 °C andkinetically controlled thermal curing (CRTA) technique. Results showed control rate of heat treatment at a definite water vapour pressure is required in order to get precise control of hydrate crystallization.

M.M. Red et al (1999)[4] produced innovative UHPC mixtures containing carbon fibres which had better strength and fracture toughness of the matrix with more resilient post cracking character. The examination of micro carbon fibres under SEM has shown these fibres to have a no smooth surface, which favors a better bond between these fibres and the cement. He also reported that mixes having both silica fume and silica flour possessed dense and uniform microstructure which was observed using SEM micrographs. No significant portlandite (CH) was detected by XRD. The thermal curing converted weak CH to strong C-S-H gel during hydration, the main hydration products identified had d-values in the range of 2.5 Å and 3.5 Å. Different phases of crystallized-S-H were observed. Very strong and moderately permeable Xonolite (C6S6H) was a major product in mixtures. *Qian and Li (2001)[5]*observed the effects integrating metakaolin on stress - strain relationships (tension and compression) and flexural strength for concrete at 0%, 5%, 10%, and 15% Metakaolin. The test results showed that addition of Metakaolin is directly proportional to increase in modulus of rupture, compressive strength, tensile strength and peak strain while tensile elastic modulus showing minor changes. The descending area of over-peak stress is enhanced with 5% and 10% of replacement of cement by metakaolin.But the brittleness of the concrete also increases with increasing metakaolin content. *Jianxin Ma andJörg Dietz (2002)[6]* studied the self-compacting properties UHPC with strength about 150MPa. They conducted flow tests with pastes constituting different water to powder ratios or different superplasticizer dosages with a flow cone similar to self-compacting concrete. He concluded optimal dosage ofsuperplasticizer to be 2% of the powder mass. The slump flow of UHPSCC should be more than 700 mm instead of 650 mm, to reduce the air content to a minimum level which is donebyincrease of the paste volume in concrete rather than incrementing the SP dosage. The results also reflected that the compressive behaviour of UHPSCC is not so strongly depending on the slenderness of the test specimen as conventional high strength concrete. This is the same case as in conventional self-compacting concrete. This phenomenon can be explained by the high powder content and the small size of the coarse aggregate. *O. Bayard, O. Pl (2003) [7]* studied the material modeling and did experimental investigations using fracture mechanics approach on RPC. Linear approach was usedto focuses on the formation and the propagation of the crack. He explained the micro-structural stress and strain concentration, a model for crack initiation and propagation based on the micro-plane method is obtained. Tensile tests in fiber-reinforced concrete showed the development of a pseudo-strain-hardening behaviour associated with a given orientation of fibres. A relative influence of the local anisotropy induced by the process of casting was observedwhich and can be used to optimize the mechanical behaviour of RPC reinforced by fibres. *Fehling (2004) [8]* studied the compressive and tensile properties of hardened Ultra High Performance Concrete. The observations made were that the compressive strength of UHPC lied in the range of 150 to 220 MPa. Till 70 to 80 % of the compressive strength, UHPC showed a linear elastic Behaviour while the failure was explosive for those without fibres having no descending branch in the stress-strain-diagram. UHPC with fibres (UHPFRC) had pronounced descending branch depending on fibre content, fibre geometry (length, diameter), fibre length in relation to maximum aggregate size, fibre stiffness (in case of fibre cocktails) and fibre orientation. Direct tension tests on UHPC without fibres delivered tensile strength values between 7 and 10 MPa failures being brittle while those with fibres in had the tensile strength in the range of 7 and 15 MPa and failure being ductile. *Habel, Denarie and Bruhwiler (2006) [9]* looked for the probable possibilities for the potential usage of UHPFRC as the rehabilitation materials in combination with structural elements. His research aimed at Time dependent behaviour of elements combining ultra-high performance fiber reinforced concretes (UHPFRC) and reinforced concrete for the determination of durability and serviceability. A numerical model was proposed for composite UHPFRC-concrete beams and validated with the test results. The experimental results and a parametric study performed with the numerical model showed that UHPFRC and normal strength reinforced concrete are compatible in the long-term and that the critical period of composite "UHPFRC-concrete" elements are the first 90 days after the casting of the UHPFRC layer. Thus, the high potential of such composite elements can be exploited also in the long term. *Redaelli and Muttoni (2007) [10]* investigated the behaviour of reinforced UHPC ties byconductingtests on unreinforced and reinforced UHPC beams, to investigate the effect of the amount and type of reinforcement.The paper describes the influence of the initial slope of the stress-crack opening relationship on the structural response in the first cracking stages predicting that the force in a reinforced tie continues to increase even during softening of the fibres. The differential equations of the cracking behaviour of reinforced UHPFC are solved with a numerical technique to gain a better understanding of some governing physical parameters. The paper focuses on the pre-peak zone. *Benjamin Graybeal and Marshall Davis (2008) [11]* investigated an experimental studyto determine alternative methodology for computing compressive strength of an ultra-high-performance fiber-reinforced concrete (UHPFRC) in the strength range from 80 to 200 MPa (11.6 to 29 ksi). The lack of appropriate testingfacilities provoked him to provide empiricalfactorsbetween varying cube and cylinder sizeHe concluded that 1.The 102 mm (4 in.) diameter cylinders, 76 mm (3 in.)diameter cylinders, and 100 mm (4 in.) cubes are acceptable and interchangeable test specimens for the determination of the compressive strength of UHPFRC; 2. The 70.7 mm (2.78 in.) cube is an acceptable alternatives specimen type for determination of UHPFRC compressive strength. A factor of 0.96 should be applied to convert the cube strength result into an equivalent 76 mm (3 in.) diameter cylinder result; 3. The 51 mm (2 in.) cylinders and cubes exhibit the greatest strength variations and least correlation when compared with 76 and 102 mm (3 and 4 in.) diameter cylinder strength results. In /particular, the 51 mm (2 in.) cylinders exhibit a significantly increased coefficient of variation; and 4. The exclusion of the fiber reinforcement from the mixture design of UHPFRC may result in an increase in the coefficient of variation of the compressive strength results. *Garas, Kahn, and Kurtis (2009)[12]* conducted trials to study the stress/strength ratio, thermal treatment and fiber reinforcement

consequences on the tensile creep behaviour, tensile strength and free shrinkage using different UHPC mixes. They concluded that usage of fibers and the application of thermal treatment decreased 14-day drying shrinkage by more than 57% and by 82%. Increasing the stress-to-strength ratio from 40% to 60% increased the tensile creep coefficient by 44% and the specific creep by 11%, at 14 days of loading. Incorporating short steel fibers at 2% by volume decreased the tensile creep coefficient by 10% and the specific creep by 40%, at 14 days. Also, subjecting UHPC to a 48-h thermal treatment at 900C, after initial curing, decreased its tensile creep coefficient by 73% and the specific creep by 77% at7 days, as compared to ordinarily cured companion mixes. *S.Shihada and M. Arafa (2010) [13]* studied the properties of UHPC using the materials available in Gaza Strip local markets. The percentage of silica fume, quartz powder and mixing procedure were investigated. The results showed thatoptimum silica fume content necessary for producing UHPC is about 15% of cement mass, which also enhances dry density. At this percentage, compressive strength is about 60% more than the strength for the zero content of silica fume.He recommended addition of 40% of the quantity of superplasticizer during dry mixing of materials. At ultrafine to cement ratio of 0.50 a minimum of 120 MPa at 28 days compressive strength could be achieved. *Yang, Joh, and Kim (2011) [14]* investigated the ultra-high strength concrete beams reinforced with steel fibers. The parameters included steel rebar ratio less than 0.02 having no coarse aggregate and had a volumetric ratio of 2%. Under the Static loading flexural behaviour including cracking, failure pattern, deflection, ductility, and flexural strength were measured. The observations provide insight to develop model for the flexural strength and deflection of ultra-high strength concrete beams under bending conditions. Multi-micro cracking and a localized macro crack were used for the analysis; numerical predictions were done for the ultimate bending moment capacity for beams showing good agreement with the experimental results. *Park, Kim, Ryu and Ko (2012)[15]*reported the effect of mixingmacro- and microfibers on the tensile stress–strain response of Ultra High Performance Hybrid Fiber Reinforced Concrete (UHP-HFRC). He investigated four types of high strength steel macro-fibers, including long smooth (LS-), two types of hooked (HA- and HB-) and twisted (T-) fiber. The volume content of the macro fiber was held at 1.0% while the volume contents of the micro fibers were 0.0%, 0.5%, 1.0% and 1.5%.The main observations drawn werethat macro-fibermainly decidesthe tensile stress–strain curves of UHPHFRC whilemicro fibers in hybrid systems has apositiveimpact onstrain hardening and multiple cracking behaviour. The ranking of performance in terms of post-cracking strength at 1.5% micro fiber volume contents is as follows: T- > HA-> LS- > HB-fibers. 5. The ranking of performance in terms of strain capacity and multiple cracking behaviour at 1.5% micro fiber volume contents is as follows: T- > HB- > HA- > LS-fibers. *R.Deeb et al(2011)[16]* Investigated self-compacting properties of UHPC (with a nominal 28-day characteristic compressive strength of 100 MPa). The methodology is given to develop self-compacting high and ultra-high-performance concretes with and without steel fibres. The self-compacting properties of mixes without steel fibres could be verified by fulfillment of flow and cohesiveness criteria andfor the design of self-compacting concrete mixes with steel fibresthe passing ability criterion is a must. Micromechanical are used to determine the plastic viscosity of the mixes.

III. Experimental Program

A. Mix Design

The constituents are cement, fine sand, silica fume, quartz powder, superplasticizer, water with a low water-cement ratio, and inclusion of high-strength steel fibers. The basic philosophy lies in complete elimination of coarse aggregate to impart greater homogeneity, with mineral and chemical admixture to heighten stronger gel formation during hydration. Enhancing compacted density by optimizing granular mixture, application of pressure before and during setting, refinement of microstructure by heat treatment and provide ductility by addition steel fibers [17].

B. Materials Properties

1. Ordinary Portland cement

The cement used during the experiments is Ordinary Portland Cement of Grade 53 conforming to IS 12269:1987. According to IS 4031 the tested 28-day mortar compressive strength is 58 MPa. The specific gravity is 3.15; the initial and final setting times are 110 min and 260 min. The normal consistency being 28%and the particle size range lies between 31µm to 7.5µm. The chemical composition of cement is given in Table2. *Silica Fume* - The silica fume used in the experiment conforms to ASTM C1240 – 97b. The specific gravity being 2.25, percentage passing through 45µm sieve in wet sieve analysis is 92% and the particle size range lies between 5.3 µm – 1.8 µm. The chemical composition of silica fume is given in Table2. *Quartz Powder* - The specific gravity being 2.59, percentage passing through 45µm sieve in wet sieve analysis is 75% and the particle size range lies between 5.3 µm – 1.3 µm. *Sand* - The sand used for the experimental studies are Grade I Coarse (particle size range - 0.6mm -2.36 mm) and Grade III Medium (particle size range -0.075-0.15 mm) *Super Plasticizer*- Poly-Acrylic Ester based type SP waspreferred.

C. Mixing

A Planetary mixer machine (300kg capacity) was used to mix the UHPC trial mixtures.The advantage of the mixture being its ability to rotate the mixing drumand theblades simultaneously at the same time to provide a uniform blending of the materials.The dry binder powder was poured in the mixingpanand dry mixing was done for 10 minutes at slow speed. Around 30% of the water and super plasticizer was added and the level of mixing was increased to medium, which was continued for another 10 min.Again the 50% of the water and SP were added to inhibithomogeneity in the mix at high speed for 10 mins.The steel fibres are added to the mix manually throgh the open split available at the top of the drum.Finally remaining 20% of the SP and water are added and drum is rotated at very high speed for 10min.

D. Casting

For each series as given in Table I-(R1-R5) 160 Kg mix was cast, each mix consisted of twenty four cubes of (100x100x100)mm size, twenty cylinders of (100mm diameter x200mm height) and seven beams of (70 mm heightx70 breadth x350mm length). For all mixes after mixing, the fresh UHPC was transferred into steel moulds in three layers and compacted for 30 sec each using a vibrating table. The aim of vibrating the filled moulds, is to properly compact the materials, to make sure that the fibres distributed without aggregation. The specimens were given a proper finishing ensuring uniformity and perfect appearance. The specimens after casting were demoulded after the interval of 24 hours.For the mix R1 and R2 steel fibres having anaspect ratio of81 was chosen,length being 13mm, diameter 0.16 with 2.5% and 2.0 % of the volume of concrete respectively. Similarly for mix R3 and R4 steel fibres with aspect ratio of 40 was chosen,length being 6 mm, dia 0.16 with 2.5% and 2 % of the volume of concrete respectively.The mix R5 is control mix with 0 % fibre.

E. Curing

The curing regime included ambient air curing; water curing and hot air curing. The samples after demoulding were kept in water for 3 and 7 day after which they were exposed to thermal regime at (90°/150°/200°C) for duration of 24,48 and 72hrs. After the hot air regime the samples were then continued for water curing till the age of 28 days. The second strategy followed was to keep the specimens in air after the thermal regime was over

IV. Testing

A. Compressive Strength

According to ASTM C109, Compression test on UHPC was carried out on cubic specimens of size (100x100x100) mm. The strength was recorded at 7, 14, 21 and 28 day.The average reading of tested four cubes was recorded as the strength at respective age. The compression test is carried out in compression testing machine of 3000 KN capacity. The load is applied at the rate 0.2 kN/sec. The ultimate strength is recorded after the specimens fail to resist any more loads. The values are recorded and compressive strength is calculated using the equation 1.

$$\text{Compressive Strength (Fc)} = \frac{\text{Load(P)}}{\text{Cross Sectional Area(A)}} \quad (1)$$

B. Tensile Strength

According to BS 1881: 1983, split tensile test was carried on cylindrical specimen of 100 mm diameter and 200 mm height at the age of 28days. Tensile strength is one of the basic and important properties of concrete. The results arerequired for the design of concrete structural elements subject to transverse shear, torsion, shrinkage and temperature effects. Its value is also used in the design of prestressed concrete structures, liquid retaining structures, roadways and runway slabs.Diametric lines are drawn on each end of the specimen so that they are in the same axial plane. The specimen was placed on the plywood strip and aligned so that the lines marked on the ends are vertical and centered over the plywood strip. The second plywood strip and the bearing bar were placed longitudinally. The specimens were tested using a universal testing machine (UTM) of 1000kN capacity. The loading rate was kept constant until the splitting tensile stress failure occurs. For each mix, six cylinders were tested at the age of 28 days and the mean value of the recorded data using equation 2 is reported.

$$\text{Split Tensile Strength (ft)} = \frac{2\text{P}}{\pi\,\text{DL}} \quad (2)$$

where, P-applied load, D-diameter of the specimen, L-length of the specimen.

C. Flexural Strength

The flexural performance of UHPC is measured using the test method ASTM 1609 standard given for fibre-reinforced concrete using parameters derived from the load-deflection curve. The flexural strength is obtained by testing a simply supported beam under third-point loading using a closed-loop, servo controlled testing system. The residual strength values f_D150 and f_D600 are obtained when the residual loads P_D150 and P_D600 are inserted in the formula for modulus of rupture given in equation 3. as per ASTM 1609 standard. Toughness (T_D150) of the beam specimen of nominal depth D is area of load-deflection curve up to a net deflection of L/150. Equivalent flexural strength ratio$R^D{}_{T150}$ value obtained using equation4.

$$fb = \frac{PL}{bd^2} \quad (3)$$

where f_b – residual strength in MPa, P–first peak load, b-measured width in mm of the specimen, d-measured depth in mm of the specimen at the point of failure.

$$R^D{}_{T150} = \frac{150T^D{}_{T150}}{f_1 bd^2}\ x\ 100\% \quad (4)$$

D. Stress Strain Behaviour under Uniaxial Compressive Loading

The study focuses on the stress-strain behaviour of UHPC under uniaxial compression to find out the behaviour for different types and volume of fibre. To determine this compression tests were carried out on concrete cylinder specimens of size 100 mm diameter x 200mm height in a 3000 kN computer controlled servo hydraulic compression testing machine. The specimens were instrumented with two linear variable displacement transducer (lvdt) to measure axial deformation and readings being recorded by a HBM data logger connected to the control system. The tested cylinders were kept in cross head control with a constant deformation rate of 0.2mm/minute till the peak load while 0.05 mm/minute for post-peak stage. The test was preceded till the load dropped to more than 50% of peak load or until failure.

E. Determination of Load-Crack Mouth opening Displacement for UHPC

All the beam specimens were tested according to the RILEM TC 162 recommendations (RILEM 2002). This test method evaluates the tensile behaviour of steel fibre-reinforced concrete either in terms of areas under the load-deflection curve or by the load bearing capacity at a certain deflection or crack mouth opening displacement (CMOD)

obtained by testing a simply supported notched beam under three-point loading. The center-loaded notched concrete beams were tested under closed loop servo-controlled CTM having a capacity of 3000kN, with the rate of opening being 0.0005 mm/sec. The CMOD was measured by a clip gage that was attached to knife edges epoxied to the bottom flange on either side of the starter notch. The fastenings of the knife edges to the specimen are within 0.25 times of the initial notch length. The lvdt is rigidly fastened to the reference frame with the moving tips lying on a plate fastened to one of the two halves of the specimen. The tests were carried on beam of size (70 x 70 x 350) mm for mix R1, R2, R3, R4 and R5. Notch to depth ratio of the beam specimen was 0.3 and the span is 300 mm. The deflection observed from the beam and the clip gauge can be compared using data logger connected with the control.

F. Determination of Fracture Energy (G_f)

In this test method, a series of tests were completed on UHPC prisms to determine some of the basic behaviour of individual cracks. The area under the load – deflection plot indirectly measures the fracture energy. The fracture energy is calculated using Linear Elastic Fracture Mechanics approach. The critical stress intensity factor is calculated using the equation 5 and equation 6.

$$K_{ic}(MPa\sqrt{mm}) = \frac{6P}{td}\left(\sqrt{\pi a_0}\right)F(A) \quad (5)$$

$$F(A) = \frac{\frac{1}{\sqrt{\pi}}\left(1.99-(A(1-A)(2.15-3.93A+2.7A^2))\right)}{(1+2A)(1-A)^2}; A = \frac{a_0}{d} \quad (6)$$

a_o is the initial notch depth in mm, d is the depth of the beam in mm, t is the width of the beam in mm and P is the maximum load applied (N). The critical energy release rate (G_c) is related to K_{ic} as given by equation 7.

$$G_c = \frac{{K_{ic}}^2}{E}(Nmm) \quad (7)$$

Where, E is the Young's Modulus, The fracture energy (G_F) or specific fracture energy is the energy needed to create a crack of unit area and is given by (RILEM committee FMC-50 (1985)) The (G_F) and W_F is the work of fracture (equal to the area under the load deflection plot) in N-mm and is calculated by equation 8.

$$G_f = \frac{W_F + W_S\delta_0}{A_{lig}} \quad (8)$$

W_S is the sum of the weight of the specimens and fixtures in N, δ_o is the displacement caused due to the self-weight of specimens and fixtures in mm; A_{lig} is the area of the ligament that was intact before the test. Using the equations (5) - (8) the fracture parameters are determined. F(A) is independent of the experimental data and depends only on the initial notch depth and the depth of the beam. The value calculated for F (A) using the equation 3.9 is 1.24.

This value is substituted in equation 8 to get the Stress Intensity factor (K_{ic}) for the maximum load (P).

G. Durability

1. Water Absorption

The amount of water entering the concrete through its voids has a major role in determining its durability. Water absorption was studied using 50mm thick slices cut from cylinders of 100mm diameter and 200 mm height. The mass of portions are determined, and dried in oven at a temperature of 100 to 110°C for not less than 24 h. After removing each specimen from the oven, it is allowed to cool in dry air to a temperature of 20 to 25°C, after which the mass is determined. The procedure was repeated till the difference between any two successive values is less than 0.5% of the lowest value obtained. This last value is designated as A. The specimen is again immersed, in water at approximately 21°Cfor not less than 48 h and after surface drying, moisture removal the mass is determined and designated as B. The specimen is covered with tap water and boiled for 5 h after allowing it to cool by natural loss of heat for not less than 14 h to a final temperature of 20°C to 25°C, the surface-dried mass is noted as C. The apparent mass is calculated after immersion and boiling as D. The values are calculated by using equation (9-15).

$$\text{Absorption after immersion, \%} = \frac{(B-A)}{A} \text{ x } 100 \quad (9)$$

$$\text{Absorption after immersion and boiling, \%} \frac{(C-A)}{A} \text{ x } 100 \quad (10)$$

$$\text{Dry Bulk density } (G_1) = \frac{(A)}{(C-D)} \text{ x } \rho \quad (11)$$

$$\text{Bulk density after immersion} = \frac{(B)}{(C-D)} \text{ x } \rho \quad (12)$$

$$\text{Bulk density after immersion and boiling} = \frac{(C)}{(C-D)} \text{ x } \rho \quad (13)$$

$$\text{Apparent density} (G_2) = \frac{(A)}{(A-D)} \text{ x } \rho \quad (14)$$

$$\text{Volume of permeable pore space voids,\%} = \frac{(G_2-G_1)}{G_2} \text{x} 100 \quad (15)$$

A (g)= mass of oven-dried sample in air, B (g)=mass of surface-dry sample in air after immersion, C (g)= mass of surface-dry sample in air after immersion and boiling, D (g) = apparent mass of sample in water after immersion and boiling, G1 = Dry Bulk density, mg/m^3, G2 = Apparent density (mg/m^3) and ρ = Density of water = 1 mg/m^3.

According to ASTM C 642-06, Water Absorption test was performed on cylinders of size (100 x 50) mm of R2 and R5 mix.

2. Sorptivity Test

The performance of concrete subjected to aggressive environments mainly depends on the pore system. For this study, 50 mm thick slices were cut from cylinders of 100 mm diameter and 200 mm height. The slices were kept in the oven for 48 h at 100±5°C and then after taking out it were allowed to cool for 24 hours. The slices were put on a welded mesh to provide free access of water at the bottom surface. The water level kept was not more than 5 mm above the base of the specimen. The weights of the specimens were noted at interval of 30 and 60 min, after wiping off anyexcess water with a damp tissue. The quantity of absorbed water during the time period from 30 to 60 min was determined from the difference in weights. The sorpitivity is calculated by equation 16.

$$I = \frac{m_t}{a \, x \, d}. \quad (16)$$

where, I = sorptivity in mm (min) $^{1/2}$; t = elapsed time, min; m_t = the change in specimen mass in grams, at the time t; ΔW = weight after 60 min - weight after 30 min (increase in weight, g); a = exposed area of specimen through which water penetrates, mm^2; and d = density of water, g/mm^3.
This test was performed on cylinders of (100 x 50) mm dimension UHPC mixes R2 and R5.

3. Rapid chloride permeability test (RCPT)

This test has been developed as a quick test to measure the rate of transport of Chloride ions in concrete. Corrosion is mainly caused by the ingress of chloride ion into concrete annulling the original passivity. According to ASTM C 1202-12, this test method consists of monitoring the amount of electrical current passed through 50-mm thick slice of 100-mm nominal diameter cores or cylinders during a 6-h period. A potential difference of 60V DC was maintained across the ends of the specimen, one of which was immersed in a sodium chloride solution, the other in a sodium hydroxide solution. In order to calculate the RCPT value of UHPC, 50 mm specimen was cut from the R2 and R5 sample. The side of the cylindrical specimen is coated with epoxy, and after the epoxy is dried, it was put in a vacuum chamber for 3 hours. The specimen was vacuum saturated for 1 hour and allowed to soak for 18 hours. It was then placed in the test device. The left-hand side (–) of the test cell was filled with a 0.5N Sodium Chloride (NaCl) solution while the right-hand side (+) of the test cell was filled with 0.3N sodium hydroxide (NaOH) solution. The readings are taken every 30 minutes and at the end of 6 hours the sample is removed from the cell and the amount of coulombs passed through the specimen was calculated. The current was recorded at 30 min interval, based on the trapezoidal rule the total charge passed is calculated by equation 17.

$$Q = 900\,(I_0 + 2I_{30} + 2I_{60} + \ldots + I_{330} + I_{360}) \quad (17)$$

Where Q = Charge passed (Coulombs), I_0 = Current (amperes) immediately after voltage is applied, I_{360}= Current (amperes) at 360 min after voltage is applied.The total charge passed, in coulombs, has been found to be related to the resistance of the specimen to chloride ion penetration. The procedure evaluates the permeability of the concrete.

V. Results and Discussions

A. Curing

By various trials conducted at the laboratory,it was found that the optimisedpotential of the mix can be obtainedby exposing the specimenstothermal regime.The curing cycle followed for the specimens in the study are as follows.The specimens after demoulding are keptin water for 3 days and then exposed to hot air curing at 200°C for the duration of 48 hours after which they were allowed to attain thermal equilibrium with the atmosphere and then kept in water till the age of 28 days.

B. Compressive Strength

The compressive strength of mix (R1-R5) evaluated at 7, 14, 21 and 28 days are shown Table II. It is observed that the specimens attain 90% of the compressive strength around the age of 14 days. The mixes having same fibre volume irrespective of aspect ratio produced 25% increment in compressive strength, to that of the control mix. The results showed that the compressive strength didn't depend too much on the reinforcement index of fibre. The specimens attain 90% of the compressive strength at the age of 14 days.

C. Stress – Strain behaviour of UHPC

The difference in the stress strain response of UHPC were recorded by uniaxial loading on cylinders and tabulated in Table III.The ascending and descending portion of the stress strain response of cylinders are plotted in Fig -1. The results showed that long fibres had a better post peak to that of small fibres. Fibres of higher reinforcement index had higher peak load,elastic modulus,ultimate strain and strain ratio.

TABLE I
Cube Strength evaluated at 7, 14,21 and 28 day for R1,R2,R3,R4 and R5

Mix ID	Compressive Strength (N/mm^2)			
	7 Days	14 days	14 Days	28 Days
R5	104	123	126	132
R4	129.8	149.7	156	164
R3	149.5	167.2	172	178.7083
R2	147.2	162.3	167.3	170.29
R1	152.67	168.5	176.4	180.28

D. Split Tensile Strength

The results of the split tensile tests carried out on the cylinders are shown in Table IV. It can be seen from theresults that there is a good amount of enhancement in the tensile strength of the concrete upon addition of steel fibers. The value increased about 200% at the fiber volume of 2.5% when compared with control mix. Small fibres showed a lesser tensile strength than long fibres. One of the major objectives of adding the steel fibers in concrete is to enhance its tensile strength. The fibers used in this study have achieved the objective.

E. Flexural Strength

Flexural strength test was carried out at the age of 28 Days. Table IV shows the result of the flexural strengthfor R1,R2, R3, R4 and R5.The flexural strength and reinforcement index of the mixes results showed a linear relationship.

F. Residual Strength

This test method evaluates the residual loads, residual strength, toughness and equivalent flexural strength ratio of fiber reinforced concrete using ASTM 1609.The span of the specimen is (L) 300mm. Load deflection curves for R1,R2, R3, R4 and R5 are given in Fig2.The Residual Strength, Toughness and Equivalent Flexural Strength Ratio are evaluated in Table V. The first-peak strength characterizes the flexural behaviourof the fiber-reinforced concrete up to the onset of cracking, while residual strengths at specified

deflections characterize the residual capacity after cracking. Specimen toughness is a measure of the energy absorption capacity of the test specimen. The first-peak strength, peak strength, and residual strengths determined by this test method reflect the behaviour of fiber-reinforced concrete under static flexural loading[18].

G.Determination Of Load-Crack Mouth Opening Displacement

The load –CMOD of the mix (R1-R5) are arrived according to the RILEM TC 162 recommendations (RILEM 2002). The results are given in figure 3.The CMOD are measured till (3-3.5) mm due to the limitations of the clip gauge. The higher reinforcement index mix had more flat slope. The mix with longer fibres had very higher bridging action due to which the beam has very high resistance to crack. The mix with smaller fibre had a more dropping type of curve. The control mix (R5) however had brittle failure. The results signifies that the fracture energy and toughness of the mix are in the order of R1>R2>R3>R4>R5.The results clearly signifies the increase in (G_F) and stress intensity factor is due to presence of fibres as the post peak was more flatter and more ductility is observed with increase in reinforcement index. These fracture parameters are helpful in predicting the fracture energy of the concrete mixes which in turn signifies the energy absorbing capacity of the concrete mixes which was improved due to the addition of fibres.

H.Fracture energy (G_f)

Fracture parameters indicate the behaviour of concrete ductility, the higher the energy (G_f), the higher the concrete ductility. The fibre reinforced concretes have larger fracture energies due the fiber's ability to bridge the cracks. There are several testing setups generally used to determine fracture energy: splitting, direct or flexural tests. The most common is the 3- point's flexural test on notched beams, measuring the F-CMOD curves (load force-crack mouth opening displacement) and/or the F-LPD (load force-load point displacement). The RILEM standard specifies the use of F-CMOD curves while the Japanese standard specifies that either F-CMOD or F-LPD curves can be used. The various fracture parameters are calculated in the Table VI.

I. Durability

The results depicted from Table VII showed that Rapid chloride ion permeability test on UHPC with fibres provided less resistance to that of the UHPC without fibres.However the values are negligible and very low and recommended for use in nuclear containment structures.The presence of fibres induces more sorpitivity in the UHPC as shown inFig4. From the table VIII, it observed that the UHPC without fibers has more volume of voids than the UHPC with fibers. Finally, it can be concluded that UHPC has excellent corrosion resistance and highly durable.

VI. Summary

The present paper reviews the past investigations done on the UHPC. The mixing methodologyand the curing procedure have been discussed.The mechanical properties are evaluated at the age of 28 days. The cube and cylinder strength observed for mix R1, R2, R3, R4 and R5 recorded were in the range of (180 - 132) MPa and (171 -93)MPa respectively. The ultimate strength obtained from cube (10cm) were almost representative to and cylinder (100 x 150) strength.The stress-strain characteristic shows that pre peak region has linear ascending portion and strain at peak stress increases with increase in strength and reinforcement index. The post peak curve is strongly dependent on the fiber type and fiber content and it is almost as steep as ascending curve for lower fiber contents and may be more gradually sloping for the higher fiber contents.The Flexural and Split tensile strength showed a linear relationship between values at the age of 28 days and reinforcement index. The flexural and tensile strength for the mix (R1-R5) at the age of 28 days were in the range of (44-16) MPa and (23.8-11.3) MPa. Fibres with higher aspect ratio are recommended for better flexural and tensile strength. The residual strength test method shows behaviour of UHPC under static flexural loading. The results reflect that even after cracking the residual capacity is very high for both long fibres and short fibres.The durability results RCPT, Water absorption and sorpitivity clearly shows that it has very high corrosion resistance, low water absorption and good sorptivity to make is usable in all types of aggressive environments.

Acknowledgment

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TABLE II
COMPOSITION OF INGREDIENTS (R1,R2,R3,R4,R5)

Mix ID	Cement kg/m^3	Silica-fume, kg/m^3	Quartz, kg/ m^3	Fine aggregate kg/ m^3	Water, l/ m^3	SP, l/ m^3	Reinforcement Index	Steel Fibres	W/C ratio
R1	788	197	315	866.8	173	14.77	2.0312	S1-2.5%	0.22
R2	788	197	315	866.8	173	14.77	1.625	S1-2%	0.22
R3	788	197	315	866.8	173	14.77	0.9375	S2-2.5%	0.22
R4	788	197	315	866.8	173	14.77	0.75	S2-2%	0.22
R5	788	197	315	866.8	173	14.77	0	Nil	0.22

S1 (Steel fibres) -13 mm length, 0.16mm diameter, S2 (Steel fibres)-6 mm length, 0.16mm diameter

TABLE III
STRESS STRAIN RESPONSE OF UHPC WITH DIFFERENT REINFORCEMENT INDEX

Mix Type	R1	R2	R3	R4	R5
Peak Stress (MPa	171.27	162	163	149	93
Elastic Modulus GPa	40	39	44	40	32
Strain at peak load $\acute{\varepsilon}_p$	.006258	0.005764	0.004397	0.004565	0.00275
Ultimate Strain$\acute{\varepsilon}_u$	0.01545	0.01224	0.0097	0.0090	0.0029
Strain Ratio, $\acute{\varepsilon}_u/\acute{\varepsilon}_p$	2.46	2.12	2.13	1.98	1.07

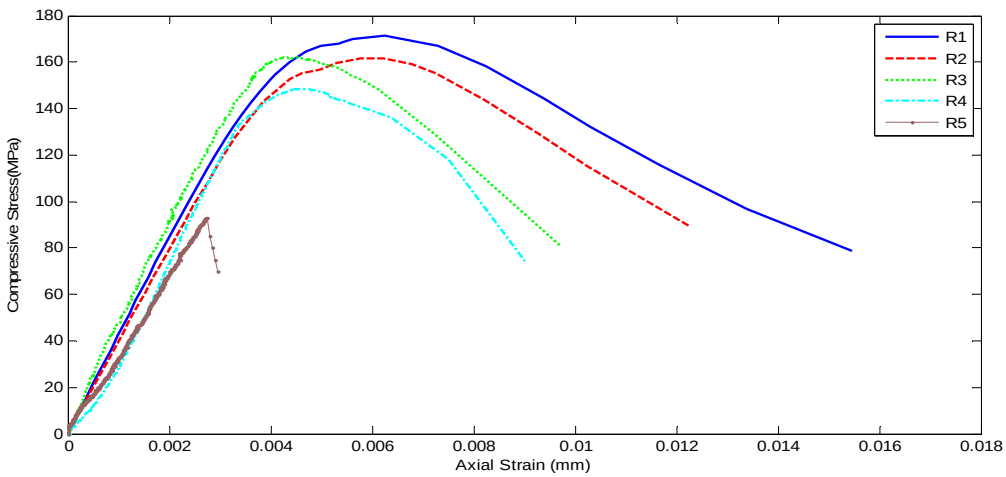

Fig. 1 Compressive Stress(MPa) versus Axial Strain(mm)

TABLE IV
FLEXURAL STRENGTH AND SPLIT TENSILE STRENGTH OF UHPC,R1-R5

Mix ID	R1	R2	R3	R4	R5
Flexural Strength(N/mm^2)	44	42	34.7	32	16
Split Tensile Strength(N/mm^2)	23.8	22.6	20.2	18	11.3

TABLE V
RESIDUAL STRENGTH, TOUGHNESS AND EQUIVALENT FLEXURAL STRENGTH RATIO

Id	P1 (N)	P_D600 (N)	P_D150 (N)	f1 (MPa)	f_D600 (MPa)	f_D150 (MPa)	(T_D150) (N-mm)	R_DT,150
R1	42281.07	40398.84	29469.72	36.98	35.33	25.77	70.70	83.61
R2	38823.4	38484.83	26864.85	33.95	33.66	23.49	66.18	85.24
R3	34946.99	34447.38	22100.70	30.56	30.12	19.33	55.97	80.08
R4	32411.52	31506.32	21060.59	28.34	27.55	18.42	52.70	81.30

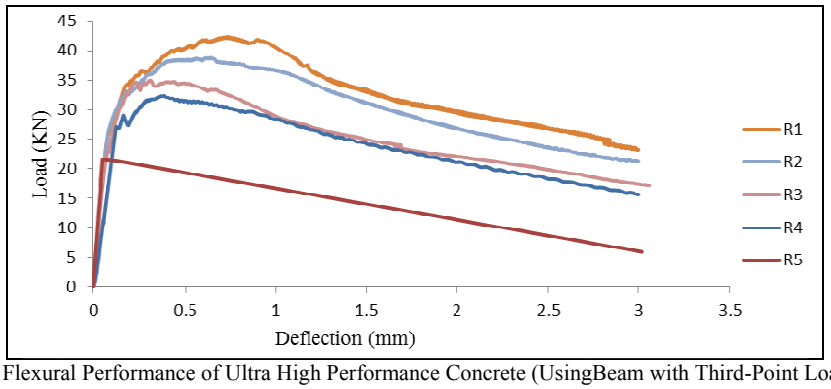

Fig. 2 Flexural Performance of Ultra High Performance Concrete (UsingBeam with Third-Point Loading)

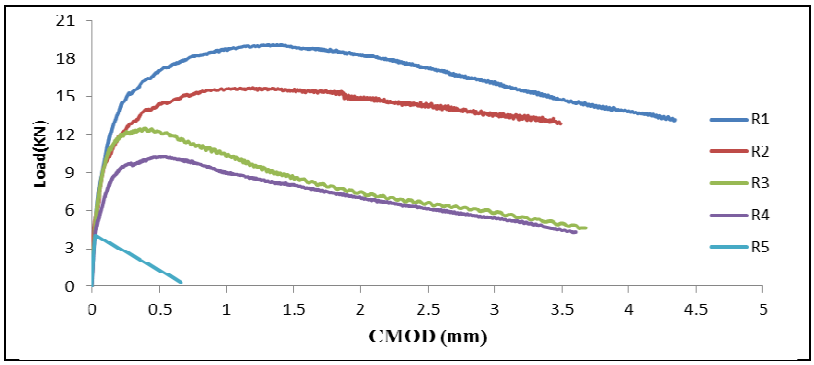

Fig. 3 Load (KN) versus CMOD (mm)

TABLE VI
FRACTURE PARAMETERS AND FRACTURE ENERGY

Properties	R1	R2	R3	R4	R5
Peak load experiment(N)	19104	15715	12496	10295	4034
K_{ic} MPa√mm	3.925	3.22	2.56	2.11	.828
$G_c=K_{ic}^2/E$ (Nmm)	$3.85x10^{-4}$	$2.65x10^{-4}$	$1.49x10^{-4}$	$1.11x10^{-4}$	$2.21x10^{-5}$
W_F (Nmm)	59414	49532	29939	26220	1449
$W_S\times\delta_o$(Nmm)δ_o (mm)	0.0384	1.9531	.02280	0.564	0.048
G_F (N/mm)	17.32	14.44	8.72	7.644	.422

TABLE VII
COMPARISON OF RCPT OF (R2) VERSUS (R5)

Mix Id	R2	R5
Cumulative Charge passed in Coulombs	176	523
ASTM C1202 classification	Negligible	Very Low

TABLE VIII
RESULTS FOR WATER ABSORPTION TEST

Mix ID	A(g)	B(g)	C(g)	D(g)	G1	G2	G3	V	Avg
Top –R5	821	825	829	449	2.161	2.171	2.182	3.686	2.637
Mid –R5	853	860	855	393	1.846	1.861	1.851	1.337	
Bot-R5	863	869	869	492	2.289	2.305	2.305	2.889	
Top –R2	899	904	884	477	2.209	2.221	2.172	2.105	1.377
Mid-R2	909	914	899	452	2.034	2.045	2.011	0.433	
Bot –R2	895	901	881	529	2.543	2.560	2.503	1.592	

*Bulk density dry-G1 Bulk density after immersion-G2 Bulk density after immersion and boiling- G3Vol. of voids in %- V

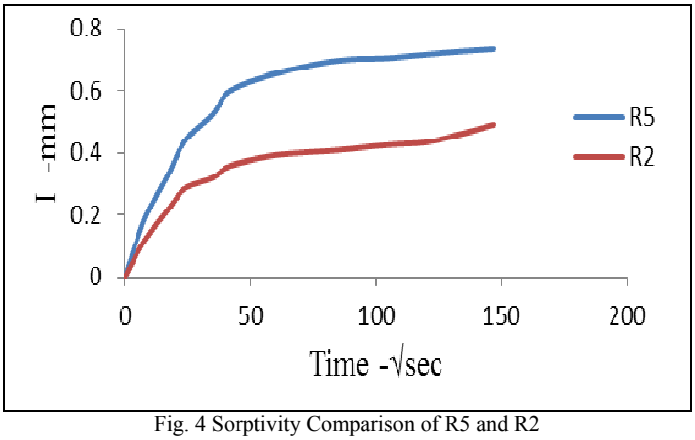

Fig. 4 Sorptivity Comparison of R5 and R2