

Impact Analysis of Ultra High Performance Fiber Reinforced Concrete Using Finite Element Analysis

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Abstract:

Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) has emerged as an advanced construction material due to its exceptional mechanical properties, including high strength, enhanced strain capacity, improved toughness, and superior energy absorption capability. In addition, it exhibits excellent durability characteristics such as low permeability, reduced creep, high fatigue resistance, and improved corrosion resistance. These advantages have attracted significant research interest for its application in structures subjected to extreme loading conditions. However, conducting impact tests on UHPFRC is challenging due to the complexity of experimental setups and the lack of standardized testing procedures. To address these limitations, this study employs Finite Element Analysis (FEA) using the commercially available ANSYS software to simulate the impact behavior of UHPFRC. A detailed numerical model is developed in ANSYS Workbench, and material properties are defined in ANSYS Mechanical using the 8-noded SOLID65 element. The LS-DYNA hydrodynamic solver is utilized for dynamic analysis and post-processing instead of the default AUTODYN solver. The numerical results are validated with experimental data obtained from laboratory testing. Furthermore, critical parameters such as toughness, energy absorption capacity, crack propagation, and failure patterns are analyzed through the simulation. The study highlights the effectiveness of FEA in predicting the impact response of UHPFRC and provides a reliable alternative to experimental testing, especially in the absence of standardized methods.

Keywords: Concrete, FRC, UHPFRC, Finite Element Analysis.

1. Introduction

Image Ultra-high performance concrete (UHPC) is one of the high strength concrete invented in the last decade of 20th century. It is characterized by cement weight higher than 600Kg, fine aggregate size less than 6mm, pozzolanas and the water/cement ratio less than 0.2 per cubic meter volume [1]. The mixture of above constituents in correct proportion leads in a dense and low interconnected pores with compressive strength higher than 150MPa. With the advancement of technology, researchers added fibre in UHPC to arrest the crack propagation in the concrete arising specially during the impact loads. It results in better properties than UHPC such as higher compressive and tensile strength, toughness and other

parameters. The concrete thus obtained was termed UHPFRC (Ultra high performance fibre reinforced concrete). UHPFRC includes better durability properties like low permeability, low creep strain, and higher service period. The primary problem in concrete is its brittle failure and strain softening behaviour. The strain softening behaviour in concrete is observed due to pull out resistance of fibre which leads to the stable propagation of crack. The fibre bridging effect in UHPFRC makes it suitable for higher load applications without loss of considerable strength. Fibre bridging results in lesser crack width, hence UHPFRC helps in fulfilling the “Limit state of serviceability” criteria [1].

Fibre: As per ACI, “A slender and elongated solid material, generally with a length at least 100 times its diameter”. “Fibre is a small piece

of reinforcing material possessing certain characteristics properties. They can be circular or flat. The fibre is often described by a convenient parameter called ‘aspect ratio’. The aspect ratio of the fibre is the ratio of its length to its diameter. Typical aspect ratio ranges from 30 to 150”[3].

Cementitious matrix: It can be defined in many ways as:

- The cement paste (It can also include mineral admixtures i.e. fly ash, silica fume, slag etc.) in which the fine aggregate particles in mortar are embedded
- The mortar in which the coarse aggregate particles in concrete are embedded
- The material which holds the fibres in dispersed phase and helps in load transfer mechanism is called matrix[4]

High Performance Concrete: As per ACI, “High Performance concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practices”[5]

Fibre-Reinforced Concrete: As per ACI, “Concrete containing dispersed, randomly oriented discontinuous fibres is known as fibre-reinforced concrete”[3]. As per ACI 116R, “The term fibre-reinforced concrete is defined as concrete containing dispersed randomly oriented fibres”.

Ultra-High Performance Fibre-reinforced Cementitious Composites: As per ACI, “High-performance fibre-reinforced cementitious composites (UHPFRCCs) are a group of fibre-reinforced cement-based composites which possess the unique ability to flex and self-strengthen before fracturing”.

Performance Specification: “A performance specification is a set of instructions that outlines the functional requirements for hardened concrete depending on the application. The instructions should be clear,

achievable, measurable and enforceable. For example, the performance criteria for interior columns in a building might be compressive strength and since durability is not a concern. Conversely performance criteria for a bridge deck might include strength, permeability, scaling, cracking and other criteria related to durability since the concrete will be subjected to a harsh environment”[6].

The essence of prescription vs. performance- “The ‘Prescription to Performance’ (P2P) initiative is directed toward a shift in the focus of concrete specifications. A prescriptive specification focuses on the properties of the raw materials, mixture proportions, the batching, mixing and transport of the fresh concrete, and the full range of construction operations from placing to curing. Prescriptive specifications rely on observed or implied relationships between the details specified and the final, in-place, or ‘End Product’ or ‘End Result’, performance of the concrete”[6].

Finite element analysis- As per ACI, “The finite element method predicts the behaviour of larger more complex structures by separating the structure into smaller mathematically discrete parts called elements. These elements have a simple geometry and are easier to analyse. The method requires solving many algebraic equations simultaneously, which is completed with the aid of a computer”[7].

2. Finite Element Modelling

Since the compressive and tensile strength of UHPFRC should be checked before conducting the impact test to determine the quasi static properties. The Quasi static properties are also needed during the calculations of ‘Dynamic increase factor’ (DIF) and ‘Capacity increase factor’ (CIF). Few of the finite element modelling simulated in “Concrete Damage Plasticity model” are covered in this chapter. Since the direct tension test is not easy to conduct therefore some empirical equations are suggested to determine the same. And the procedure

adopted to simulate the drop impact test is also stated in this chapter.

Compressive strength of concrete

This is one of the most important parameter in assessing the properties of concrete. It signifies the magnitude of load that the concrete can withstand without failure. Although in case of UHPFRC, the compressive strength is primarily governed by the strength of matrix phase because the failure strain in concrete under compression is very less and fibers require higher strain to reach at their peak stress. The fibers are primarily introduced for ductility purpose which can withhold high strains.

CDP model: Strain controlled comp of concrete

Displacement controlled quasi static compression finite element test of concrete is simulated to validate the stress-strain data that obtained in the laboratory. The uniaxial stress strain data that inserted in the simulation was taken from a research paper published by K.V. Harish et al. [8]. Previously the tri-axial stress failure of concrete was considered according to ‘modified Drucker- Prager strength hypothesis’[82], which was a circular profile but’ Lubliner, Lee and Fenves’ modified the above criteria in terms of stress invariants[9], [10].

CDP model also requires some specific parameters during modelling which were kept default as suggested by ‘Kaminski’9] and ‘ABAQUS Analysis User's Manual version 6.12 documentation’[11].

Table 1: Input data of quasi static compression test simulation

μ	0.18
E	18000 MPa
Peak stress	25
Peak strain	0.0022

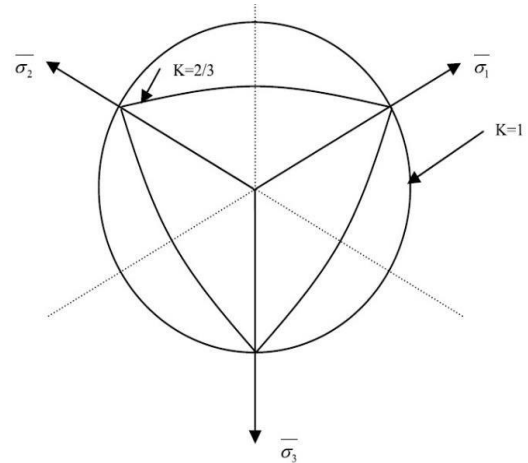


Figure 1: Failure profile in deviatoric plane [84]

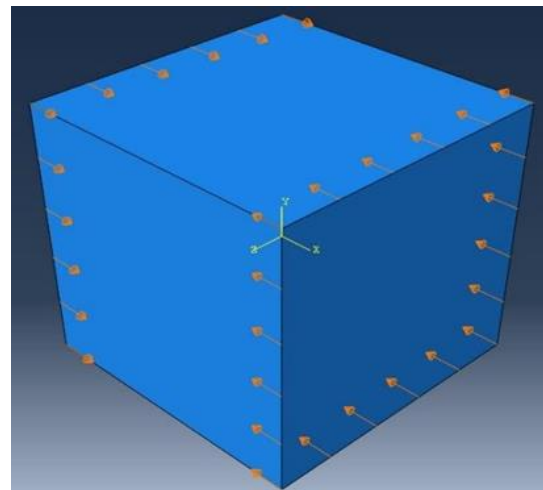


Figure 2 (a): Displacement controlled load in CDP model

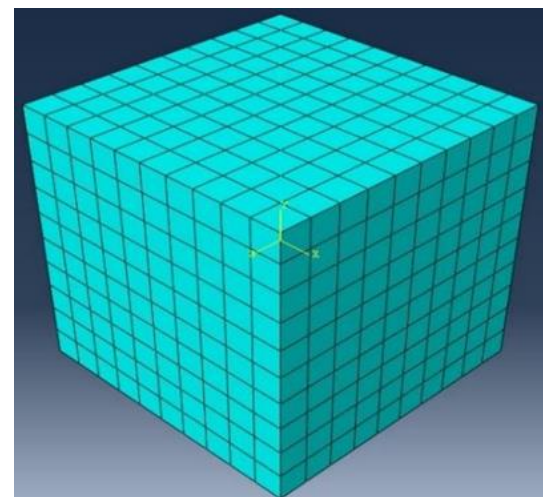


Figure 2 (b): Meshed element in CDP model

Figure 2: Displacement controlled static compression test of concrete

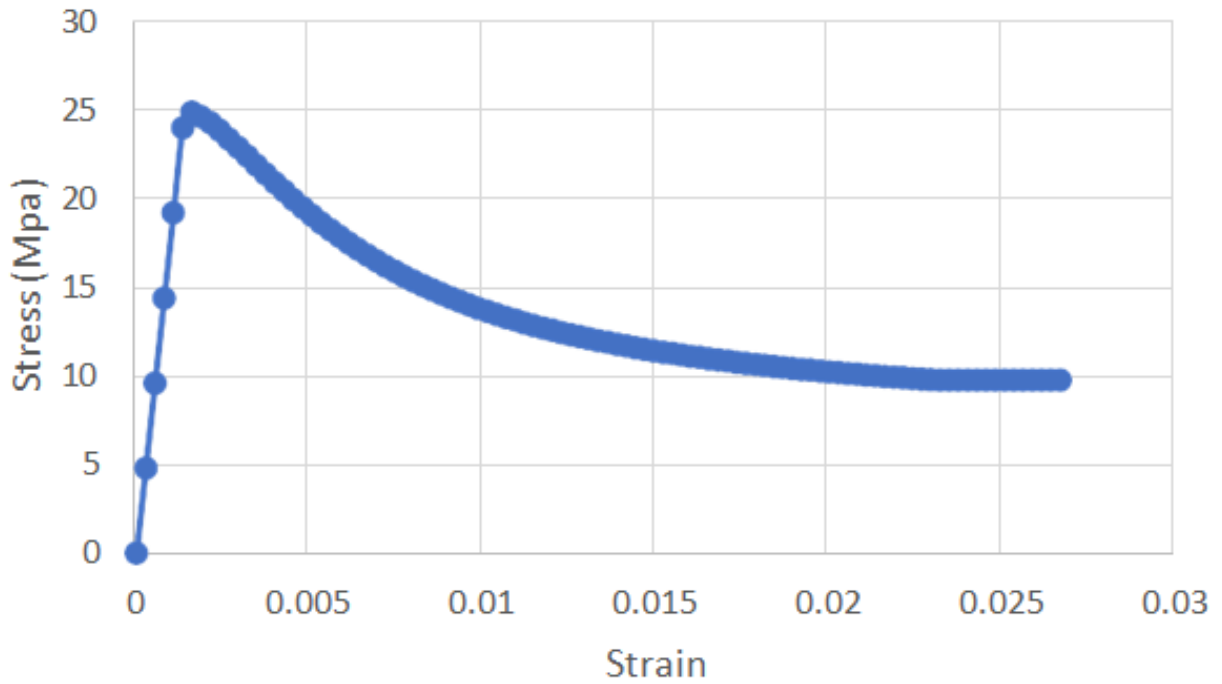


Figure 3: Displacement controlled compressive stress v/s strain curve in CDP model

CDP Model: Displacement Controlled Tension Test Of Concrete

A displacement controlled quasi static tensile finite element test is simulated over a dog bone shaped specimen with gauge length of 50mm and the grip length of 50mm at both the ends. The displacement is provided at both the ends of the specimen.

Table 2: Input data of quasi static tension test simulation

μ	0.18
E	18000 MPa
Peak stress	12.5
Peak strain	0.0022

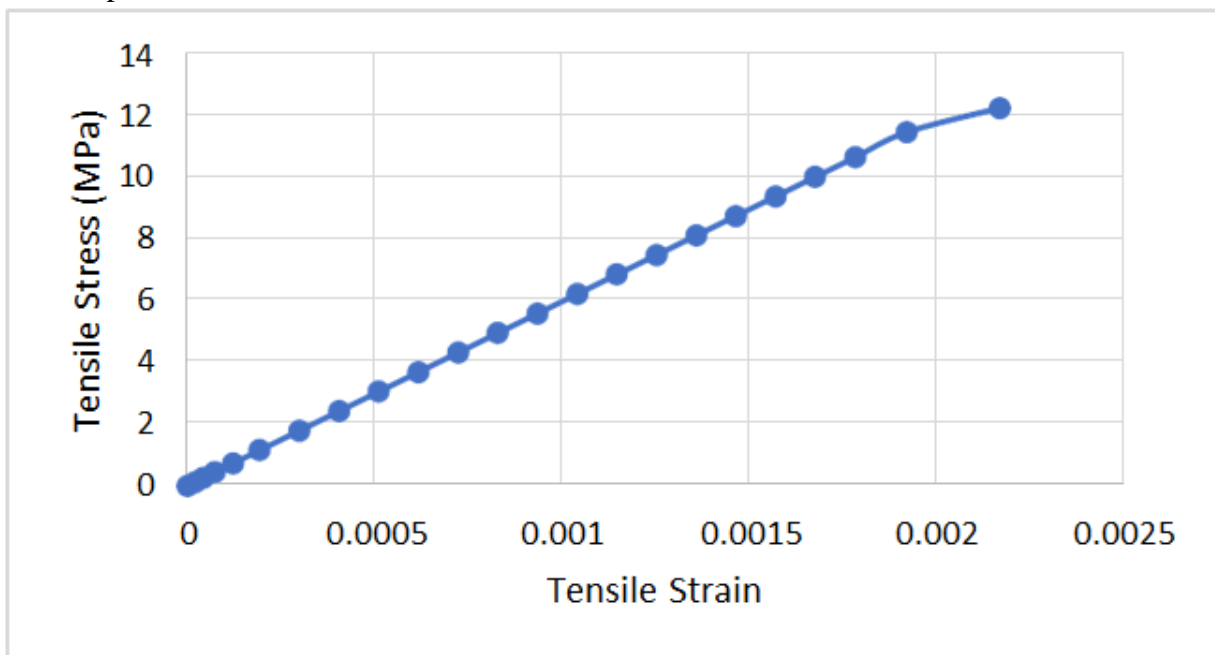


Figure 4: Displacement controlled tensile Stress v/s strain curve in CDP model

The strain softening region is not obtained in the above curve due to convergence issue which occurred because the material with negative tangent modulus cannot be directly simulated in ‘Concrete damage plasticity model’ in ABAQUS. To obtain the strain softening region, “Crack band model of

Bazant and Oh” (CBBO) [12] is used. Introduce the fracture energy as an input and the finite element will show the fracture behaviour of concrete. It is also known as strain softening rule [13].

Contour plots of Tension test in CDP model

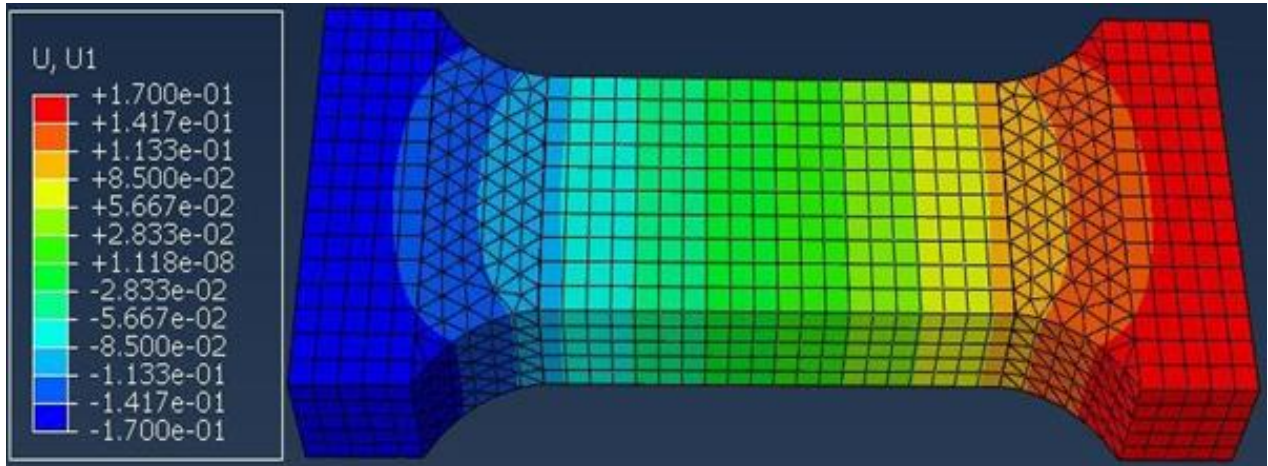


Figure 5 (a): Tensile displacement

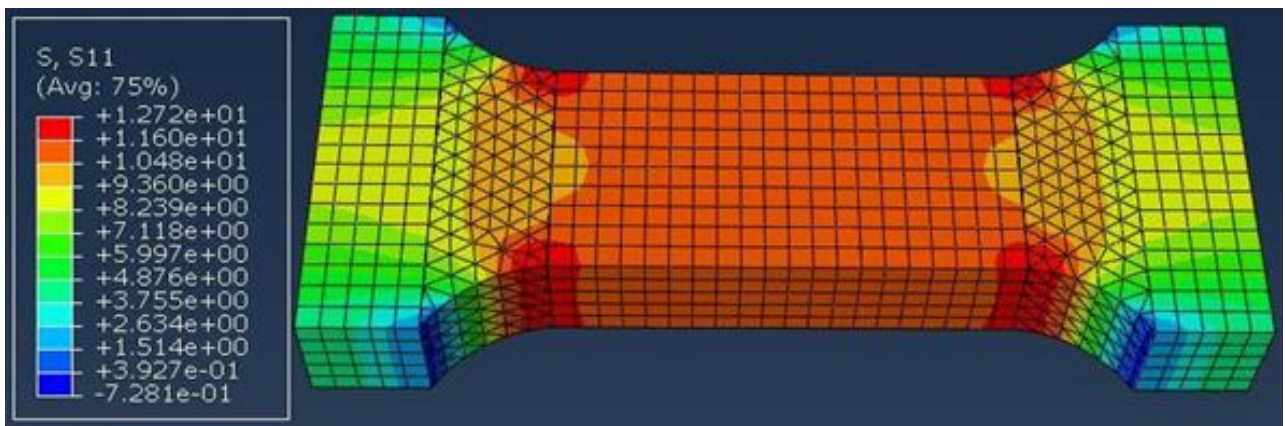


Figure 5 (b): Axial stress

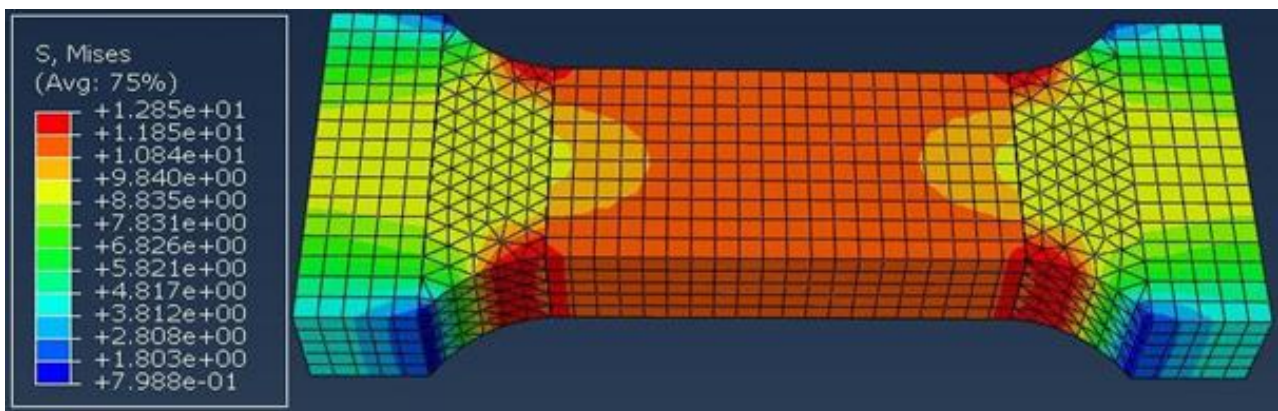


Figure 5 (c): von Mises stress

Figure 5: Contour plots for displacement controlled static tension test of concrete

Finite element modelling of Impact test over UHPFRC

Modelling Mechanism: The impact test over concrete includes the moving components which cannot be constituted in ‘Static structural’, so it is modelled in ‘Explicit dynamic’ case. Explicit dynamic modelling require long run time and high computational cost.

Model Geometry: A circular slab is drawn as concrete material and a spherical geometry is also drawn to act like a ball which has to fall over the concrete specimen to determine the dynamic impact parameters of concrete. The concrete is assigned as flexible material which the steel ball is assigned as rigid material, just to observe the deformation of concrete specimen only.

Engineering Data

In our case the concrete properties are inserted manually like the uniaxial compressive and tensile plastic strain. Other properties like density, specific heat, shear strength, biaxial or tri-axial strength, shear strength and other criteria’s can also be inserted for defining the material.

- In the case under consideration, the uniaxial stress-strain data for tension and compression are calculated according to the research papers published by Dr. K.V. Harish, J.K. Dattatreya and M. Neelamegam [14].

According to the availability of bodies in the model, ANSYS define vague contact region. Although the predefined contacts need not to be always correct so the contact definition between the concrete specimen and falling steel ball mass is defined manually. A friction coefficient of 0.15 is also introduced which is a general value defined for contact between steel and concrete. According to the codes running behind to solve the problems are designed such that, the rigid body must be defined as ‘target face’ and the other should be defined as ‘contact face’.

Meshing: Meshing is one of the very important parameters among different kind of properties which are introduced in ANSYS for the solution of problem. The results obtained are highly sensitive to the mesh density, therefore Mesh sensitivity analysis is performed to find the suitable mesh size. Different kinds of meshing are introduced for different types of model geometries but in this case, the meshing is done through number of divisions over the edge.

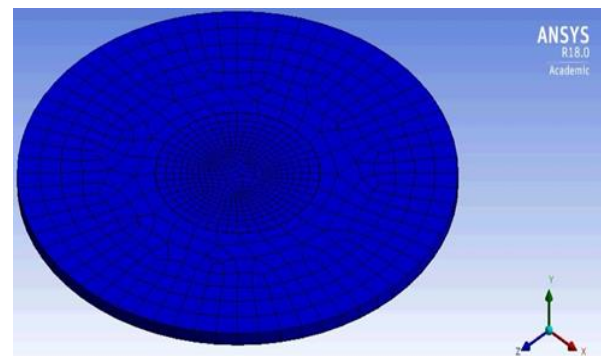


Figure 6: Meshed model with different meshing size in ANSYS

If the meshing size is higher then, the results obtained may need not to be accurate, and if the mesh size is very low then the solution require long run time and high computational cost. Therefore mesh sensitivity analysis is mandatory. Therefore in the model drawn, two different mesh sizes are adopted i.e. higher mesh density in in the area where the steel ball have to fall over the concrete specimen and low mesh density in the adjoining area. 8 noded SOLID10x elements is used in the case under consideration.

Load and Support Conditions : The load and support conditions can be defined according to the problem. In the figure shown in fig 6.7, fixed support was provide to check the stress profiles. However in the report, only simply supported beams subjected to impact loading are considered. The ‘Standard earth gravity’ load is assigned to the steel ball.

Analysis and Results: Different kind of parameters such as ‘End time’, loss of material strength, pin ball radius and other important parameters are assigned in analysis setting.

After that the required solution can be defined to be obtained in post processing mode. Like the stress, strain, deformation, velocity or any other energy criteria can be assigned here.

3. Results and Discussion

Some of the test results obtained through research papers are given here. The fibers are primarily introduced in concrete to increase the ductility, post cracking behaviour toughness of

the concrete. The quasi static strength are needed to represent the results of impact resistance capacity, so some of the results static compressive and tensile strength results are also presented in this chapter. At the last of this chapter, CIF and DIF graphs are also presented to see how the dynamic increase factor vary with the rate of loading.

Property assessment of UHPFRC under static loading [R. Yu. Et al.]

Table 3: Constituents of UHPFRC [15]

Materials	UHPC1 (kg/m ³)	UHPC2 (kg/m ³)	UHPC3 (kg/m ³)
CEM I 52.5 R	874.9	612.4	699.9
Limestone	0	262.5	0
Quartz	0	0	175.0
Microsand	218.7	218.7	218.7
Sand 0-2	1054.7	1054.7	1054.7
Micro-silica	43.7	43.7	43.7
Water	202.1	202.1	202.1
Superplasticiser	45.9	45.9	45.9
Water/cement ratio	0.23	0.33	0.29

Table 4: Comparison of binder amount and comp strength of UHPFRC at 28 days [15]

Sample ID	Cement (Kg/m ³)	GGBS (Kg/m ³)	SF (Kg/m ³)	w/b Ratio	Steel fiber (Vol %)	Compressive strength at 28 days (MPa)
UHPC 1	875	0	44	0.19	2.5	156
UHPC 2	612	0	44	0.19	2.5	142
UHPC 3	700	0	44	0.19	2.5	149

UHPFRC is primarily employed in case of high strength concrete where ductility is needed such as in case of structures subjected to impact loads. Although the addition of fibers mainly increases the flexural and tensile strength but it also affects the compressive strength. However the compressive strength of UHPC or UHPFRC is primarily dependent over the cement content and pozzolanic content keeping the other factors constant. The compressive strength of concrete reduces with the introduction of pozzolanas. In the above

cases UHPC1 is the control mixture with the cement content of 874.9 Kg/m³. 262.5 Kg/m³ cement is replaced by limestone with reduction in compressive strength of 9%, and 175 Kg/m³ cement is replaced by quartz with reduction in compressive strength of 4.5%. Hence it can be observed that keeping the other factors constant, the cement content can be replaced with suitable pozzolanas to approach the economy because the less w/b ratio in UHPFRC reduces the hydrated cement content and it needs to be replaced with pozzolanas.

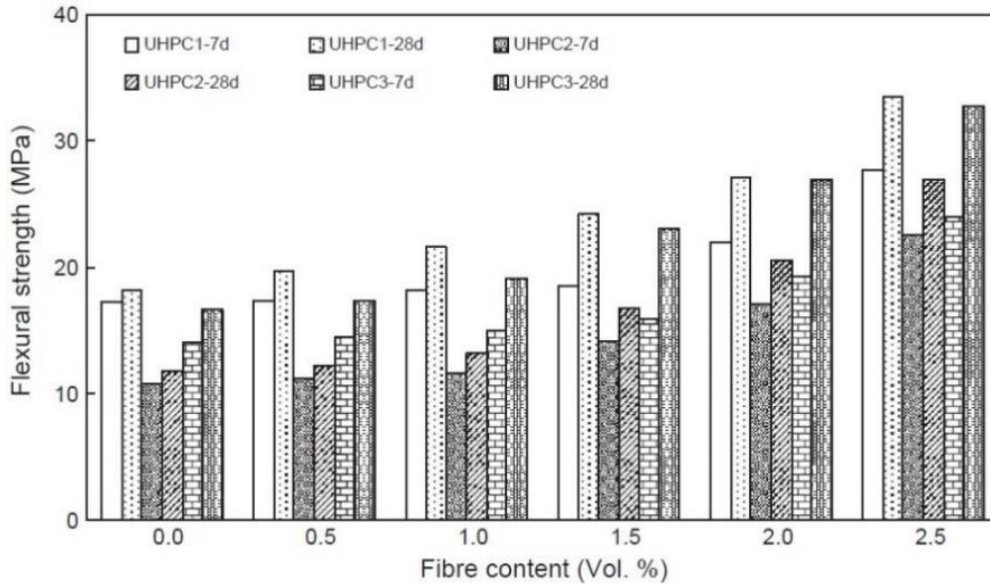


Figure 7: Flexural strength of UHPFRC after 7 and 28 days [15]

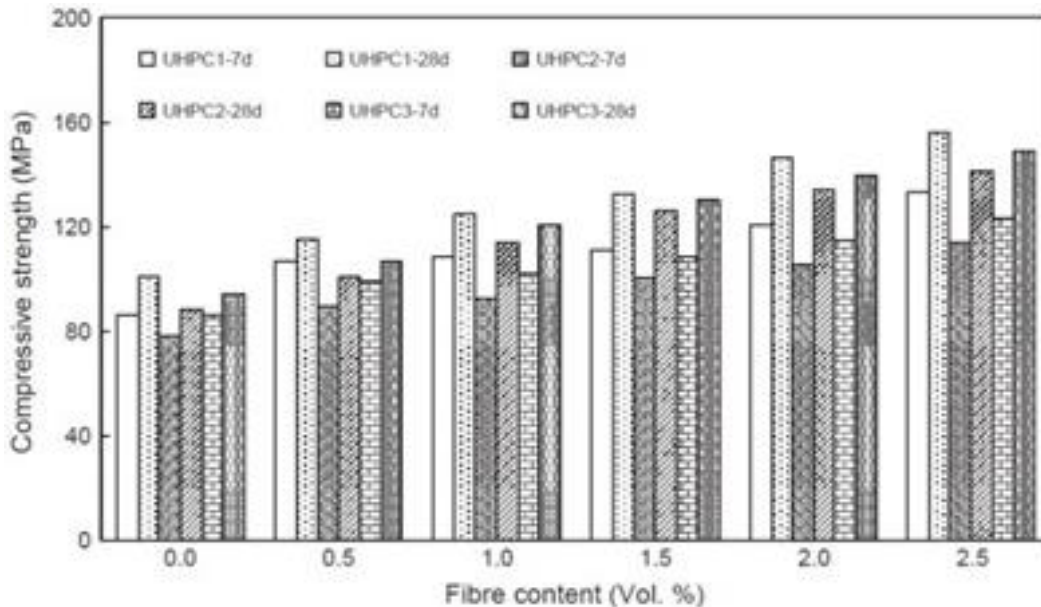


Figure 8: Compressive strength of UHPFRC after 7 and 28 days[15]

The flexural strength and compressive strength both increase with the increase in fiber content. But the increase in compressive strength is 58%, 55% and 56% respectively with addition

of 2.5% steel fibers at 28 days. While the increase in flexural strength is 89%, 117% and 106% respectively with the addition of 2.5% steel fibers at 28 days.

Static test over UHPFRC [M. Popa. Et al.]

Table 5: Constituents of UHPFRC [16]

Constituents	No fibers		With fibers	
	M1	M2	M3	M4
Cement	1	1	1	1
w/b ratio	0.27	0.25	0.27	0.25
Super plasticizer	0.04	0.04	0.05	0.05
Silica fume	0.27	0.25	0.27	0.25

Quartz powder	0.70	0.65	0.70	0.65
Fiber	0	0	0.13	0.22
Sand	0.54	0.50	0.54	0.50
Andesite	0.92	0.85	0.92	0.85

*mix proportions by weight of cement

Table 6: Properties of UHPFRC [16]

Strength	Age (Days)	No fibers		With fibers	
		M1	M2	M3	M4
fcm	1	65.1	86.9	86.6	90.1
	7	88.7	110.9	115.4	120.1
	28	91.7	138.6	145.7	160.4
fctm	28	6.9	8.8	14.9	15.5

The results represented above show the variation of compressive and tensile strength with the introduction of fibers. M1 & M3 mixtures have same properties except that M3 includes 0.13 steel fibers by weight of cement, which increases the compressive strength by 58.9% while the compressive strength is increased by 116% at 28 days. M2 & M4 mixtures have same properties except that M4 includes 0.22 steel fibers by weight of cement, which increases the compressive strength by 15.7% while the compressive strength is increased by 76.1% at 28 days.

4. Conclusion

UHPFRC is a highly sustainable material for future infrastructure development due to its superior strength characteristics and effective crack-arresting mechanism, which enables it to satisfy the limit state of serviceability requirements. The incorporation of pozzolanic materials such as slag, fly ash, and silica fume enhances the strength properties of fiber reinforced concrete; however, their effectiveness depends on the type of fiber used and the water-to-binder (w/b) ratio. These materials also contribute to reducing autogenous shrinkage by up to 30%, although the performance of metakaolin varies with the w/b ratio, showing significant shrinkage reduction at a ratio of 0.28, while minimal effect is observed at 0.35. Additionally, the dynamic stress and strain capacity of UHPFRC are influenced by specimen

dimensions due to inertial effects under sudden loading conditions. It is also observed that no single impact testing method can be universally standardized, as different tests are based on varying principles, leading to inconsistencies in results.

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