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Flexural Behavior of Ultra-High Performance Steel Fiber Reinforced Concrete: A State of the Art Review

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Abstract- *Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) is a cement based composite material with distinctive properties such as compressive and flexure strengths in the excess of 150MPa and 30MPa. This ultra-high flexure behavior is due to the incorporation of steel fibers in the matrix. The factors influencing the flexure behavior of UHPFRC are: 1.Materials used 2.Mix proportions 3.Steel fiber-content, shape and aspect ratio adopted. In context to that, this paper presents the state of the art review by focusing on the effect of above factors on flexural behavior of UHPFRC. It was observed that a portion of silica fume can be replaced by the substitute materials like fly ash, GGBS, and rice husk ash. Curing of the UHPFRC members at high temperatures is preferable to attain expected strengths. And 2% steel fibers by volume in the matrix will provide desired flexural properties.*

Keywords- Ultra-High Performance Fiber Reinforced Concrete, Steel fibers, Flexural behavior, Mechanical Properties.

1. Introduction

A significant breakthrough in concrete technology in the 20th century was the development of Ultra-high performance fiber reinforced concrete (UHPFRC), which is a cement based composite material that consists of the distinctive characteristics of the both ultra-high performance concrete and high tensile strength steel fibers with compressive strength over 150MPa [1], tensile strength over 8MPa and flexural strength over 30MPa along with enhanced durability and extremely low permeability compared to HSC/FRC/HPC. In brief, UHPFRC is a sustainable construction material with great amount of flexure capacity, ductility and strain hardening behavior which is suitable for use in the fabrication of precast members, bridge decks, and having several other structural applications in civil engineering. According to Federal Highway Administration (FHWA) tech-note, UHPFRC consists of fine granular materials with optimized grading curves, very high strength discrete micro steel fibers and very low water/binder ratio less than 0.25 and high silica fume content. UHPFRC is significantly durable compared to HPC due to the highly reduced and discontinuous pores (i.e. high homogeneity) which reduce the entrance of deteriorating materials such as chloride and sulfate ions. UHPFRC is formulated by combining Portland cement, silica fume, fine washed/sieved sand, super plasticizer, water, and steel fibers.

The material characteristics of UHPFRC are summarized as follows: The ultra-high strength is achieved by excluding the coarse aggregates and using sand with particle size between 150-600 Microns as the only aggregate to increase the homogeneity of the mix. The density of the mix is increased by using silica fume as partial cement replacement which in turn results in uniform material properties and satisfactory particle distribution. Further the increased toughness and ductility is achieved by the addition of steel fibers. To reduce the drying shrinkage, to improve the micro structure and to achieve high early age strength, high temperature curing at 90^{o}C is necessary. UHPFRC enables in reducing the cross sectional dimension of the structural members, its ultra-high strength properties significantly decrease the structural weight of a member by 1/2nd or 1/3rd of weight of general RC structures for identical external loads. UHPFRC can exhibit significant flexure strength, toughness and energy absorption capacity. Much of such properties enhancement is imparted to the concrete by the addition of steel fibers during the mixing procedure. Therefore a review on flexural behavior and mechanical properties of UHPFRC considering the various influential factors becomes more important for its applications and wide spread use.

2. Origin and Development

An ultra-high strength cement based paste with low porosity was first introduced by Roy et al. and Yudenfreund et al. in the early 1970s. Roy et al. achieved a cement based paste with almost zero porosity and a compressive strength of approximately 510MPa with special curing methods using heat 250^{o}C and pressure 50MPa. Yudenfreund et al. obtained a cement based paste having a compressive strength around 240MPa with normal curing 25^{o}C for 180 days using low water-cement ratio of 0.2. With the development of super plasticizers and pozzolanic admixtures such as silica fume in the early 1980s, Birchall et al. and Bache developed two types of ultra-high strength cement pastes with very low porosity, such as densified with small particles (DSPs) concrete and macro-defect free (MDF) paste. Birchall et al. used a pozzolanic admixture and a high-range water-reducing agent to develop a cement paste with compressive strength over 200MPa and flexural strengths of 60–70MPa. Bache developed DSPs concrete that had a compressive strength of 120–270MPa by using ultra-fine particles and extremely low water content, with a large quantity of high-range water-reducing agent.

The high strength cement pastes are very brittle and to increase the ductility of the material, addition of fibers is essential. In the mid 1990s, Richard and Cheyrezy first introduced the concept of reactive powder concrete (RPC), which was the forerunner of UHPFRC. Very high strength and ductility was achieved by excluding coarse aggregate, optimizing the granular size by packing density theory and providing heat, pressure treatments. A 1.5%–3% by volume of straight steel microfibers, with a diameter of 0.15 mm and a length 13 mm, were also added. The RPC developed by Richard and Cheyrezy exhibited compressive strengths of 200MPa–800MPa and fracture energy 40 kJ/m^2. After the development of RPC, many researchers around the world have developed concretes that can be classified as UHPFRC. Bouygues, Lafarge and Rhodia developed UHPFRC with 2.5% short steel fibers and commercialized under the name DUCTAL. Multi-scale cement composite (MSCC) was developed by using a mixture of short and long steel fibers at LCPC in France which is known under the name CEMTEC. In 2002 the first technical recommendation for both material properties and structural design of UHPFRC was introduced in France (AFGC-SETRA 2002). In 2003 a state of the art report on UHPFRC regarding the materials and design aspects was published in Germany (DAfStB). In 2004 the Japan society of civil engineers (JSCE) published design recommendations for UHPFRC. In 2012 the Korea concrete institute (KCI) also developed a design code for UHPFRC.

3. Flexural Behavior of UHPFRC

The flexural strength is considered as a material property, which is defined as the stress experienced within a material just before it yields. It is also known as modulus of rupture. The knowledge of flexural behavior of a material is very important to understand the performance of structural members under different loading conditions, which in turn depends up on the deciding factors, such as the materials used in the preparation, mix design adopted and the fiber content. Katrin habel et al.[2] experimentally investigated the mechanical properties of specific type of UHPFRC (CEMTEC) at several ages between 3 and 365 days, and observed that the rate of development of mechanical properties was highest for the secant modulus, followed by the compressive and tensile strength. A.M.T Hassan et al.[6] studied modulus of elasticity, stress-strain curve and post-peak behavior in both compression and tension of UHPFRC reinforced with and without steel fibers by using closed-loop testing machines and linear variable displacement transducers (LVDTs) in a relatively straight forward manner and obtained complete stress-strain curve for UHPFRC. Duy Liem Nguyen et al.[7] investigated the size effect on the flexure behavior of UHPFRC, by testing three different sizes of specimens 50x50x150mm^3 (small) 100x100x300mm^3 (medium) and 150x150x450mm^3 (large) using four-point bending in a 3-dimensional scale and observed that as the size of the specimen decreased the flexure strength, normalized deflection and normalized energy absorption capacity of UHPFRC increased significantly.

Table-1: Comparison of mechanical properties of UHPFRC based on the different material compositions.

References	Materials Composition (kg/m^3)				Water/ Binder Ratio	Steel Fiber Amount (Vol%)	Compressive Strength (MPa)	Tensile Strength (MPa)
	Cement	Filling Powder	Silica Fume	Sand				
Habel [2]	1050	0	275	730	0.14	6	160	11
Yang [3]	657	430	119	1050	0.15	2	170	7
Corinaldesi [5]	960	0	240	960	0.16	2.5	155	10
Hassan [6]	657	418	119	1051	0.17	2	150	7
Aldahdooh [8]	360	290	214	1057	0.18	2	158	14
Maca [9]	800	200	200	976	0.17	2	152	10
Yu [11]	875	219	44	1055	0.19	2.5	156	11
Yuliarti [31]	795	0	192	1169	0.2	2	166	7
Toledo [37]	1011	79	58	883	0.19	2	156	10

Petr Maca et al.[9] prepared an UHPFRC containing 2% fibers by volume with a compressive and tensile strengths exceeding 150Mpa and 10Mpa. He compared the properties of UHPFRC with HPC, FRC and conventional concrete and observed that the fracture energy of UHPFRC is 5 times higher than conventional FRC. The response of UHPFRC in tension exhibits strain hardening accompanied with multiple cracking followed by tensile softening. Chun-Chan Hung et al.[19] experimentally investigated the cyclic flexural performance of UHPFRC structural beams reinforced with high-strength steel having specified yielding strength of 680MPa. Six cantilever beams were prepared and tested under displacement reversals with experimental variables including the reinforcement ratio of the high-strength longitudinal rebar and the amount, location and length of steel fibers in the beams. The results showed that the beams reinforced with high-strength steel are able to show satisfactory cyclic flexural performance prior to failure. And the addition of steel fibers substantially enhances the damage tolerance ability of the beams. Kokakuma et al.[24] investigated the fundamental behavior of R-UHPFRC based on pullout tests and observed that deformed bars showed extremely high bond strength between the reinforcing bars and UHPFRC, which brought reinforcing bar fracture under the condition with 200mm of initial bond length. Slip-hardening behavior was observed using round bars in which the load continued to increase even during pullout.

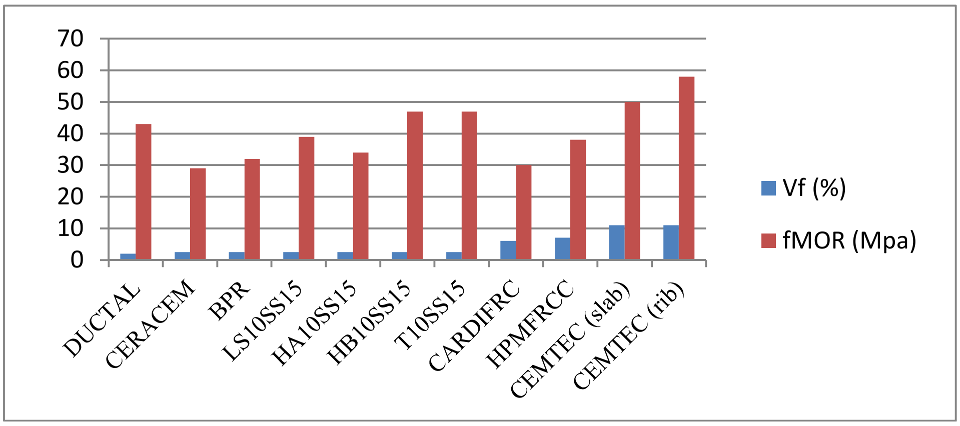

Figure-1: Comparison of Flexural Strengths of different UHPFRCs based on fiber content Dong jim kim et al. [4].

3.1. Materials

The fundamental materials used in the preparation of UHPFRC are cement, silica fume, sand, super plasticizers, steel fibers and water. Various attempts have been made world-wide to use replacement materials in place of cement and fibers. Both cement and silica fume are the major constituents of UHPFRC. S.L.Yang et al.[3] examined several possibilities for reducing the production price of UHPFRC by using Recycled glass cullet (RGC) and two types of local natural sand as the replacement for the more expensive silica sand. It was observed that the local natural sand can produce similar mechanical and durability to silica sand, but the use of RGC gave approximately 15% low performance in terms of compressive strength, flexure strength and fracture energy. M.A.A Aldahdooh et al.[8] developed a new type of green ultra-high fiber reinforced cement composites (GUHPFRCCs) in an experimental design based on response surface method (RSM), in which 50% of volume contains ultra fine palm oil fuel ash (UPOFA). The results showed that at 90days the optimum mix achieved 158.28MPa, 46.69MPa and 13.78MPa of compressive, bending tensile and direct tensile strengths indicating the usage of UPOFA as an efficient pozzolanic mineral admixture. R.Yu et al.[14] addressed the multiple effects of nano-silica and hybrid fibers on the properties of UHPFRC incorporating waste bottom ash (WBA). The results indicated that due to the existence of the metallic aluminum particles in WBA, the generated hydrogen can cause some visible cracks in the concrete, which could reduce the mechanical properties of the concrete and this negative influence can be effectively minimized by the simultaneous utilization of nano-silica and hybrid fibers (steel and poly-propylene fibers) and the flexural strength of the UHPFRC can be improved.

Table-2: Properties of steel fibers used in UHPFRC.

Fiber	Length, lf (mm)	Diameter, df (mm)	Aspect ratio (lf/df)	Density (g/cm^3)	Tensile strength (MPa)	Elastic modulus (GPa)
Smooth Fiber(macro)	30	0.3	100	7.85	2580	200
Smooth Fiber(micro)	13	0.2	65	7.85	2788	200
Hooked Fiber	30	0.375	80	7.85	2311	200
Twisted Fiber	30	0.3	100	7.85	2428	200

Luay Hussein et al.[16] developed composite members of UHPFRC and NSC/HSC and experimental studies were carried out on prisms and beams without stirrups to investigate the flexural and shear capacity of the composite members. The beam specimen was designed to have the UHPFRC layer in tension and NSC/HSC layer in compression. The test results revealed that the performance of the proposed composite system in terms of flexural and shear capacity was successfully enhanced. All the composite beams failed in shear at a force that is 1.6-2 times higher than that of the resistance of NSC/HSC beams. It was also revealed that the bond strength between the two concrete material layers was significantly high. Hasan Sahan Arel [18] experimentally investigated the effect of silica fume fineness and fiber aspect ratio on the compressive strength and impact resistance of UHPFRC. The mixture was manufactured by combining silica fumes with different fineness (specific surface areas: 17200, 20000 & 27600 m^2/kg) and hooked-end steel fibers with various aspect ratios (lengths: 8,13&16mm) and the samples were subjected to standard, steam and hot water curing. The compressive strength tests were conducted after 7,28,56 &90 days curing period and the impact resistance was determined after the 90th day. The results indicated that a steam cured mixture of silica fume with a a specific surface area of 27,600m^2/kg and 16mm long fibers produce better results. Impact resistance increased with the fiber aspect ratio. Wei Huang et al.[23] investigated the replacement of high cost silica fume with calcined clay in UHPFRC mixes. The impact of two grades of calcined clay on the hydration and micro structural development of UHPFRC matrices was investigated where 54% of the cement by volume has already been replaced by limestone. It was seen that comparable mixes were obtained with replacement but a bit lower in strength values at 28days strength 10.4% and 2.3% lower than silica fume mix. The replacement refined the critical pore radius but did not enhance the compressive strength.

3.2. Mix Design

The general composition of UHPFRC mix can be adopted in terms of weight ratio. Matrix mixture by weight ratio was designed by J.J.Park et al,[27] and G.S.Ryu et al. [26]. This composition is widely adopted as standard mix proportion of UHPFRC for various research works carried out around the world. R.Yu et al.[11] addressed the mix-design by using the modified Andreasen & Andersen particle model and properties assessment of UHPFRC such as workability, air content, porosity, compressive and flexural strengths measured and analyzed. The results showed that by utilizing the improved packing model, it is possible to design UHPFRC with relatively low binder amount. He observed that after 28 days of curing, there is still a large amount of un-hydrated cement in UHPFRC matrix which can be replaced by fillers to improve workability and cost efficiency.

Table-3: Mixture ratio of constituent materials in UHPFRC by weight, J.J.Park et al, [27].

Cement	Silica fume	Silica sand	Filling powder	Super-Plasticizer	Water/ Binder ratio	Steel Fibers by vol. (%)	Compressive Strength (MPa)	Flexural Strength (MPa)
1.00	0.25	1.10	0.30	0.016	0.20	2	170	33

The preparation method carried out by J.J. Park et al,[27] in preparation of UHPFRC, using mixer of volume 50m^3 including the sequence of materials to be added, their mixing time and speed is depicted in the following figure.

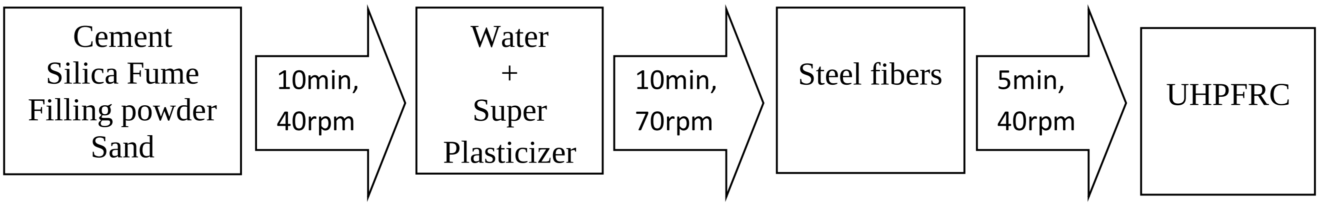

Figure-2: Preparation method of UHPFRC J.J. Park et al, [27].

S.L.Yang et al.[3] investigated the curing of UHPFRC cubes and prisms at 20ºC and 90ºC to determine the differences in both mechanical properties and ductility and observed that curing at 20ºC gave approximately 20% lower compressive strength, 10% lower flexure strength and 15% lower fracture energy than the specimens cured at 90ºC from 1 to 7 days. Valeria Corinaldesi et al.[5] studied soft cast (flow able at casting time) UHPFRC and the time development of compressive, flexure strength and elastic modulus was monitored by varying the water to cement ratio from 0.20 to 0.32 and observed that the optimum workability and mechanical performance was obtained with a water to cement ratio of 0.24. Doo-Yeol Yoo et al. [10] evaluated the basic material properties of UHPFRC at an early age by carrying out penetration resistance, shrinkage, tensile and ultra-sonic pulse velocity (UPV) tests and the results indicated that paraffin oil prevents the rapid water evaporation on the surface when the penetration test was performed. The initial and final sets were 0.6 and 2.1hours.

3.3. Fibers

The high flexural strength of UHPFRC is due to the presence of steel fibers in it, The fiber content present in the mix and their nature has the capacity to alter the properties of the concrete mix, the area which requires an extensive study. Dong jim kim et al.[4] investigated the flexural performance of four hybrid (H-) UHPFRCs with different macro fibers according to ASTM standards, the fibers were long smooth (LS-) steel fibers two types of hooked (HA-&HB-) steel fibers and twisted (T-) steel fibers and one type of micro fiber short smooth (SS-) steel fiber was blended. The order of flexural performance according to the types of macro fiber was HB- > T- > LS- > HA-.

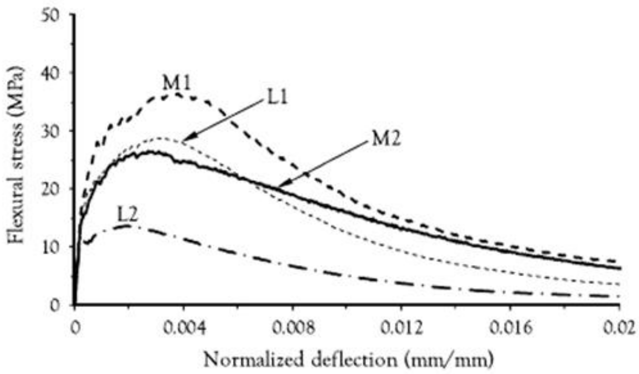

Figure-3: Average flexural stress versus normalized deflection curves under quasi-static loading Dong jim kim et al. [4].

M, L, 1, and 2 indicate the medium beam, the large beam, the beam with placement method P1, and the beam with placement method P2, respectively

Doo-Yeol Yoo et al.[12] investigated the effect of fiber content on the material and interfacial bond properties of UHPFRC. Four different volume ratios of micro steel fibers (V_f= 1%, 2%, 3% &4%) were used within the identical mortar matrix and observed that 3% steel fibers by volume yielded the best performance in terms of compressive strength, elastic modulus, shrinkage behavior and interfacial bond strength, the parameters improved as the fiber content was increased up to 3% volume. Higher cohesive stress and fracture energy were achieved with higher fiber content. Safeer Abbas et al.[13] studied a number of UHPC mixtures with varying steel fiber lengths (8, 12, & 16mm) and dosages (1%, 3% & 6%) by mixture volume. The results indicated an increase in mechanical properties as the fiber dosage increased and it was also observed that UHPC mixtures incorporating short steel fibers exhibited enhanced flexural properties compared to that of mixtures with similar volume of longer steel fibers. Kinda Hannawi et al.[15] investigated the effect of adding different types of fibers on the micro-structure and the mechanical behavior of UHPFRC, the fibers were distinguished mainly by their differing nature (steel, mineral and synthetic), their dimensions (macroscopic or microscopic). The experimental results showed that the fiber has a relatively slight influence on te compressive strength and elastic modulus except for the steel fiber which improves the strength because of its intrinsic rigidity. The fibers clearly restrain the cracking process in concrete under the mechanical loading.

R.Yu et al.[17] appropriately designed and tested UHPFRC with ternary fibers. The flow-ability, mechanical properties and flexural toughness were measured and analyzed. The results showed that based on the optimized particle packing and hybrid macro, micro fibers it is possible to produce UJPFRC with a relatively low binder amount (about 620kg/m^3) and low fiber content (2%volume). The flexural toughness was dominated by the hooked steel fibers. Fabien Lagier et al.[20] investigated the influence of fiber content on the strength of tension lap-splice of reinforcing bars in UHPFRC without additional transverse reinforcement. Different splice lengths were tested and internal strain measurements were used to capture the force transfer mechanism and the evolution of longitudinal strain distribution along with associated bond stresses. The results indicated that for short lap-splices, the bearing action of all ribs along the splice length contributes equally in resisting the applied force.

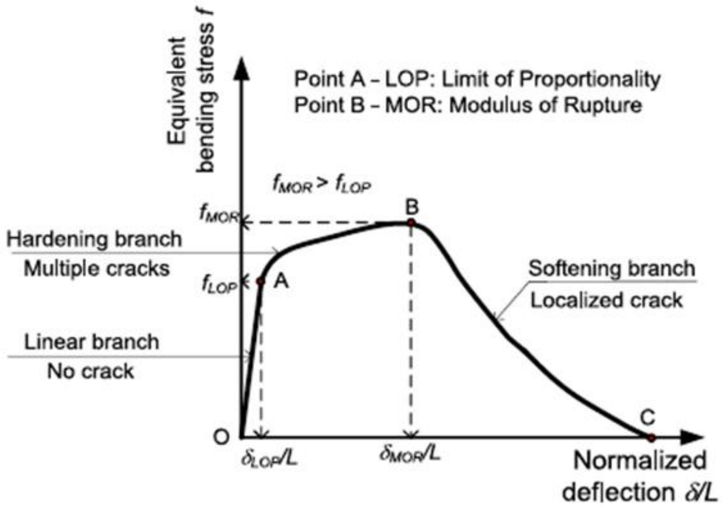

Figure-4: Typical Deflection-Hardening Flexural behavior of UHP-HFRC. Nguyen et al.[43]

Ourania Tsioulou et al.[21] examined the UHPFRC with different amount of steel fibers (0%,1%&3%) and conducted compressive and tensile tests alongside with ultrasonic pulse velocity (UPV) and rebound hammer (RH) measurements as part of non-destructive testing (NDT). Based on mechanical testing, the compressive strength of UHPFRC with 3% steel fibers is higher (almost 5%) compared to the UHPC (without steel fibers). The post-cracking response of the material is significantly enhanced with increase in steel fiber percentage. The combined SonReb method offered high level of accuracy since in all the examined cases, error below 10% has been achieved. Doo-Yeol Yoo et al.[22] investigated the effect of fiber orientation on the flexural behavior of UHPFRC under quasi-static loading according to ASTM standards and impact loadings with two different potential energies (0.48& 1.13kJ) using a drop-weight impact test machine. The test results indicated that under quasi-static loading conditions, higher flexural strength, normalized deflection capacity and toughness were obtained in the beams that contained better fiber orientation in the direction of the tensile load. Under impact loading conditions, the flexural strength and energy absorption capacity were both increased with better fiber orientation.

4. Conclusion

This paper presents the state of the art review on the flexural behavior of UHPFRC considering the influential factors. Based o the review the following conclusions can be made:

1. Natural sand available locally can be used in place of expensive silica sand and UPOFA can be used as an efficient pozzolanic material to reduce the cost of production of UHPFRC.
2. High temperature curing of UHPFRC members is required to attain greater strengths.
3. The addition of 3% steel fibers by volume is most suitable in yielding the best performance of UHPFRC.
4. The composite members of UHPFRC and HSC/NSC can be successfully used in structural applications.

Scope for further research:

1. Incorporating suitable alternate materials in UHPFRC and to study their effect on flexural behavior leading to reduction of cost.
2. Study of structural behavior of UHPFRC in terms of reverse cyclic loading, punching shear to further evaluate the performance.
3. More in depth work is required to understand the flexural behavior of composite UHPFRC members and usage of hybrid fibers.

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