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Research Article

A REVIEW ON MECHANICAL PROPERTIES OF ULTRA-HIGH-PERFORMANCE FIBER REINFORCED CONCRETE (UHPFRC)

Bhawani Singh[1] and Abhilash Shukla[2]

[1]PG Student, Department of Civil Engineering, JUIT Waknaghat, Solan (H.P.)
[2]Assistant Professor, Department of Civil Engineering, JUIT Waknaghat, Solan (H.P.)

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ABSTRACT

This study investigates the mechanical properties of ultra-high-performance fiber reinforced concrete (UHPFRC), considering various prominent factors to obtain fundamental details of its practical use. Therefore, this paper aims to review the mechanical properties of hardened UHPFRC. The influence of the curing regimes, coarse aggregate, mineral admixtures, fiber properties, specimen size, and strain-rate on the mechanical performance of UHPFRC were specifically investigated in its hardened state. It was clear that (a) hydration process is accelerated by the heat treatment which leads to higher strength; (b) fly ash, slag and rice husk ash can be used by replacing a portion of the silica fume as mechanical perspective is concerned; (c) at a static rate the use of deformed (hooked and twisted) or long straight steel fibers enhance the mechanical properties; and (d) mechanical properties are increased when the strain rate is increased. Alternatively, there are some dissent between the results from various 'size effect' tests and the potency of using twisted steel fibers at static and high rate loadings.

INTRODUCTION

The mechanical properties of concrete, which inherently affect its practical utilization in the field of construction, are mostly dependent on various factors such as the type of cementitious materials, curing regimes, loading rate, size of aggregates, size and shape of a specimen, etc. In particular, ultra-high-performance fiber reinforced concrete (UHPFRC), which was invented in the mid-1990s, due to its extremely high compressive strength (more than 180 MPa) it is very sensitive to these factors and flowable characteristics with high volume fractions of steel fibers (more than 3% by volume) [55,56]. To achieve such a high strength material, a low water-to-binder ratio (W/B) (normally W/B = 0.2) is applied with ultra-fine admixtures and heat treatment at 90°C. As a result, the mechanical properties of UHPFRC are more remarkably influenced by the class of cementitious materials, curing regimes and size of aggregate, as compared to those of ordinary concrete. General introduction of mechanical properties is discussed in this section.

Compressive strength

Compressive strength is the resistance of a material to withstand loads under compression. Some materials fracture at their compressive strength limit and others deform irreversibly, so a given amount of deformation may be considered as the limit for the compressive load. Compressive strength is one of the most essential properties of concrete as the design of structures is concerned. The concrete is mainly classified based on grades and it is standard industrial practice. Grade of concrete indicates the compressive strength of the concrete cube or cylinder. A compression testing machine is preferred for testing of the cube or cylinder samples to determine the compressive strength of concrete. The test standards differ from country to country based on the design code. As per Indian codes, the compressive strength of concrete is described in terms of the "characteristic compressive strength" of 150 mm size cubes tested at 28 days. The "characteristic strength" is defined as the strength of the concrete below which not more than 5% of the test results are expected to fall. For the fulfillment of design criteria, the value of compressive strength is divided by a factor of safety, whose value depends on the design philosophy adopted. This test is performed under the IS 516-2018.

Tensile strength

The ability of the concrete to resist the pulling force (Tensile Stress) without broke is known as the tensile strength of concrete. Ultimate tensile strength is measured by the maximum stress that a material can withstand while being stretched or pulled before breaking. Some materials break very sharply, without plastic deformation, in what is called a brittle failure. In the design of ductile members, tensile strength is rarely preferred, but it is essential in the design of the brittle members. The tensile strength of concrete is 1/10 times of

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Corresponding author:* **Bhawani Singh
PG Student, Department of Civil Engineering, JUIT Waknaghat, Solan (H.P.)

compressive strength, so additional reinforcement is provided to concrete to cop of this problem. Tensile strength is one of the major properties of concrete because concrete structures are highly vulnerable to tensile cracking due to various kinds of effect and applied loading itself. This test is performed by confirming IS 5816-2018.

Split tensile strength

It is a method of determining the tensile strength of concrete using a cylinder that splits across the vertical diameter. It is an indirect method of testing the tensile strength of concrete. Tensile strength for the concrete specimen is defined as due to application of the compressive load the tensile stresses developed in which the concrete specimen may crack. Concrete is a material, which is weak in tension, so it becomes very important to know the tensile strength of concrete used in designing structures. Finding tensile strength of concrete is done by using two methods which are "Direct Method" and the "Indirect method". The direct method is not more suitable to determine the design tensile strength of concrete, because it represents holding difficulties of specimen in the testing machine. Sometimes there is a greater possibility of load being applied eccentrically on the specimen of concrete. In the indirect method, compressive force is applied to the concrete sample to make the specimen fail after the development of tensile stresses in concrete. Tensile stress developed in the concrete at which the specimen shows failure is known as tensile strength in concrete, so split test is one of the indirect methods. This test is performed by confirming IS 5816-2018.

Flexural strength

Flexural strength (or the modulus of rupture) is the amount of force an object can take without breaking or permanently deforming. Flexural strength is related to the bending criteria and it is performed in three-point loading. Flexural strength, also known as modulus of rupture, or bend strength, or transverse rupture strength is a material property, defined as the stress in a material just before it yields in a flexure test [1]. The flexural strength would be the same as the tensile strength if the material were homogeneous. In fact, most materials have small or large defects in them, which act to concentrate the stresses locally, effectively causing a localized weakness. When a material is bent only the extreme fibers are at the largest stress so, if those fibers are free from defects, the flexural strength will be controlled by the strength of those intact 'fibers'. However, if the same material was subjected to only tensile forces than all the fibers in the material are at the same stress and failure will initiate when the weakest fiber reaches its limiting tensile stress. Therefore, it is common for flexural strengths are higher than tensile strengths of the same material. Conversely, a homogeneous material with defects only on its surfaces (e.g., due to scratches) might have a higher tensile strength than flexural strength. If we don't take into account defects of any kind, it is clear that the material will fail under a bending force which is smaller than the corresponding tensile force. Both of these forces will induce the same failure stress, whose value depends on the strength of the material. This test is performed under the IS 516-2018.

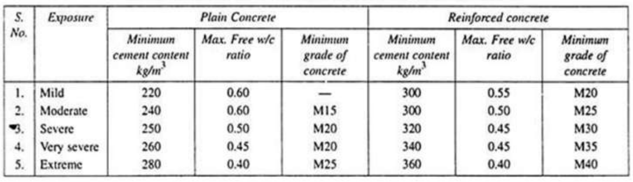
Durability

Durability is defined as the ability of concrete to show resistance against the weathering action, abrasion and chemical attack without affecting its essential engineering properties. Durability of different concrete depends on the severity of the environment and desired properties. For example, concrete exposed to tidal seawater has different durability requirements as compared to normal concrete. Following are the points should posses concrete to remain durable:

1. Dense cement paste structure leads to low permeability
2. It has entrained air to resist freeze-thaw cycle, during extreme conditions.
3. It should be made with the well-graded aggregates that are inert and strong.
4. Minimum impurities in the mix such as alkalis, Chlorides, sulphates and silt.

It has been reported that in industrialized countries more than 40% of the total resources of the building industry are spent on repairs and maintenance of concrete structures. In India also much money is spent on repair work. It is very unfortunate that not enough attention has been paid to the durability aspect even in repair works.

Table 2 Minimum Cement Content, Max. w/c ratio and minimum grade of concrete for different condition of exposure as per IS 456-2000 **[2].**



S. No.	Exposure	Plain Concrete			Reinforced concrete		
		Minimum cement content kg/m^3	Max. Free w/c ratio	Minimum grade of concrete	Minimum cement content kg/m^3	Max. Free w/c ratio	Minimum grade of concrete
1.	Mild	220	0.60	—	300	0.55	M20
2.	Moderate	240	0.60	M15	300	0.50	M25
3.	Severe	250	0.50	M20	320	0.45	M30
4.	Very severe	260	0.45	M20	340	0.45	M35
5.	Extreme	280	0.40	M25	360	0.40	M40

Secondly, in the present age, all good and favorable sites of construction have been already used and the construction of concrete work has to be taken up in more hostile environments. Thirdly, all good concrete materials are in short supply. Thus the construction of modern concrete structures assumes much more importance for durability than in the past. Due to these reasons in revised IS 456-2000, the approximate values for cement content, maximum w/c ratio, and minimum grade of concrete have been suggested for different exposure conditions. These recommendations have been given in "Table 1" **[2].** Causes that affect the durability of concrete are divided into two parts. First is "External causes" in this Extreme Weathering Conditions, Extreme Temperature, Extreme Humidity, Abrasion, Electrolytic Action, Attack by natural or industrial liquids or gases are the main investigating points. Second is "Internal Causes" which is further divided into two-part, one is "Physical" and another is "Chemical" in this Volume change due to difference in thermal properties of aggregates and cement paste, Frost Action, Alkali Aggregate Reactions, Corrosion of Steel are the main investigating points.

Energy absorption

This property related to the behavior of the concrete to absorb the maximum impact energy to resist the perforation of bullets during the test like impact test, etc, This property helps to characterize the use of concrete in different areas.

Dynamic properties

This property is shown the influence of dynamic loading on the concrete specimen and shows the behavior of concrete in different strain rate loading. As the mechanical property has directly influenced the construction and use of concrete, generally the factor on which the mechanical property depends upon as discussed in [3] are the properties of cementitious materials, Curing regime, Size of the coarse material, Strain rate, Size and shape of the specimen.

As we discussed earlier the UHPFRC has very high strength up to or more than 150 MPa, to get this strength adequate amount of fiber fraction is required with the high dosage of admixture and heat treatment at 90^0C. So we can conclude that the mechanical property is highly influenced by the aggregate size, curing conditions and cementitious material as compared to the traditional concrete. So if we talk about the fiber, the distribution of fibers totally depends upon the way and method of casting and it is highly influenced the mechanical property of UHPFRC and especially when flexure and tensile loading is occurring as we discuss later [3-5]. But in the area where the ordinary or traditional concrete fulfill the desired requirement the UHPFRC is not used due to its high production cost, but for the reduction of the construction cost various researchers explained the methods which are given below:-

1. Using less amount of high strength steel fiber without compromising the mechanical property (mechanical properties – tensile and flexural) [3-7].
2. Using a less quantity of powders and by increasing the quantity of coarse aggregate [8].
3. Using a high pressure-process instead of heat treatment or compaction process.

So from the above points, it is clear that the mechanical property is affected by the coarse aggregate, steel fiber properties and also by curing conditions. Strain rate also influences the mechanical property and the rate of strain and it totally depends upon the loading and strength criteria [11-12]. It has been observed that the use of heat treatment and the addition of fiber in the matrix was improved the compressive strength if there was increase in the relative density [13,14].

After discussing all the mechanical properties UHPFRC is considered to be a promising material for impact- or blast-resistant structures [10], due to its highly enhanced strength, energy absorption capacity, and unique strain-hardening behavior with multiple micro-cracks, as shown in Fig. 1.

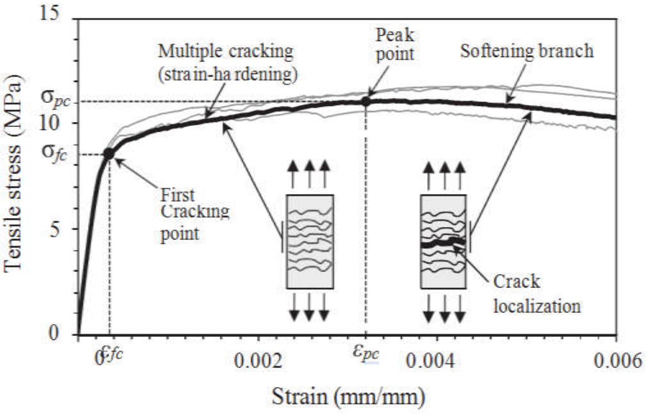


Fig 1 Typical tensile stress versus strain behavior of UHPFRC [10].

This paper aims to investigate the current state of knowledge regarding the mechanical properties of UHPFRC and to highlight some potential issues for further research. Investigation is specifically focused on the effects of the curing regimes, coarse aggregates, mineral admixtures, fiber properties, specimen size, and loading rate on the mechanical properties of UHPFRC.

Mechanical properties of hardened UHPFRC

There are various mechanical properties are there which influence the use of UHPFRC in various areas of construction and also according to desired demand of materials, but in present era demand of these type of construction material is increasing due to its outstanding properties and also these material prove it that they have the better resistance against the impact loading as compare to the traditional concrete, so examination of the mechanical property must be needed, in this section various researches on mechanical properties are shown and also the effect of fiber, curing, size of element, placement techniques of concrete and its effect on mechanical properties are discussed.

Now a literature review is presented in which the effect of curing, fiber orientation and volume fraction, placing techniques and size effect on the mechanical property is discussed.

Effect of curing Condition

Additional heat treatment increases the rate of hydration and the density of UHPFRC, which helps to get the extraordinary high compressive strength. Influence of curing ages on the compressive strength was also observed and there was increase in strength from a period of 28 days to 90 days (38 MPa) and from 90 days to 180 days there was little increase in the strength (7 MPa), it has been observed that the when UHPFRC was heated in the water tank at the temperature of 90^0C showed the maximum compressive strength as compared to heated in the air drying condition at the same temperature. In air drying condition UHPFRC showed the lowest strength, same specimen was also heated in the steam condition at 90^0C and it gave the intermediate value between the water tank and heated in the air drying condition [15]. It was also observed that to get the compressive strength of 180 MPa, 47 to 73 hours required at temperature 60^0C for curing and the maximum 95 hours at temperature 41^oC [16]. The curing process also affects bond between the fiber and the concrete, which is well known as interfacial bond [15], it was also observed that the to get the maximum interfacial bond strength (14.3 MPa) autoclave curing should be adopted and temperature and pressure should be 200^0C and 1.7 MPa respectively [15]. In a research it was concluded that if the SRAs are introduced in heat curing it decreased the mechanical property of the UHPFRC (resistance against the fiber pullout and mechanical property), DY Yoo *et al.* [17] explained why mechanical property decrease when the specimen subjected to the flexural and tensile loading, the points are given below:-

1. There was a reduction in the radial confinement pressure, which decrease the friction bonding between the matrix and fiber.
2. At the interfacial transition zone, there is a possibility for formation of high porosity between the matrix and fiber when SRAs used.
3. It was also discussed by DY Yoo *et al.* [18] that the tensile strength can be improved by using SRAs at curing temperature 24^0C without using heat treatment.

So without using heat treatment, the compressive strength up to 190 MPa and more can be achieved in 28 days, by using some commercially available material and the sand to cement ratio 1:4 [9]. Also by adding 1.5 percentage of the volume of steel fibers that has the twisted shape and without using special heat treatment, a UHPFRC can be achieved with high ductility and it had a tensile strength of crack occurred in the plastic region (Post cracking) 13 MPa and has the 0.6 % of strain capacity [19].

Effect of coarse aggregate

Coarse aggregate also influences the mechanical property as well as the construction cost. It has been reported that the use of coarse aggregate can easily mix with a whole matrix which leads to increasing the mixing time [8]. It was also observed that the 28 days and a temperature of 20^{o}C approximately compressive strength of UHPFRC noted was 150 -165 MPa and at 90^{o}C it was 190 MPa with or without coarse aggregate [8]. It was also noticed that the by replacing coarse aggregate with the maximum size of 8 mm and fine sand (0.15 – 0.46 mm) has no effect on compressive strength [40], but on the other hand, there was decrease in the strain capacity and increase in the elastic modulus was observed by using coarse aggregate [8] and low flexural strength [20], these all are happening due to low bond strength of fibers. The range of coarse aggregate was also decided from 7 to 16 mm and it gave the compressive strength up to or more than 178 MPa as compared to its standard concrete (164 MPa) [9]. For improving the bond strength and pull out energy, we can add silica fume up to 22 – 32 % [21]. It has been observed that in UHPFRC the silica fume content up to 30% increase the pullout energy up to 100% larger as compared to UHPFRC without silica fume it was occurring because of the reason that the matrix without silica fume, scratches occurred longitudinally but when the silica fume was used in the matrix silica fume collected close to the fiber and leads to increase the resistance against the fiber pullout [21]. There are also so many alternates are there like instead of using silica fume, fly ash and ground granulated blast furnace slag can be used, but the use should be restricted to 40% which enhances the toughness and flexural [22]. On the other side use of rice husk decrease the compressive strength. It was also mentioned that instead of silica fume, we also have fine admixtures (metakaolin, pulverized fly ash, limestone micro silica, siliceous micro filler and micronized phonolith), it is also a good alternate for use because it also gave the compressive strength above 150 Mpa [23].

Effect of Length, fiber geometry and volume content

In the 1990s a twisted steel fiber that became famous for its twisting property along its axis, it got its twisting property due to its polygon cross-section geometry, it was well known by a name "Torex", the material used for making of these fibers was high strength steel wires [24]. Post cracking of composite was related to the fiber intrinsic efficiency ratio, so the basic purpose to evaluate the sectional geometry of the Torex fiber was depended upon the FIER, it was observed that the when the triangular and square shapes fiber are compared to circular shaped fiber the effect to increase the FIER was 28 – 12% respectively for the same cross-sectional area [25]. So with increment in the FIER, the friction and boundary component regarding adhesion was improved and by the twisting nature of fiber leads to improve the mechanical bond [26], K Wille andAE Naaman [26] concluded that the twisted and hooked end and steel fiber were able to resist the stress up to three times higher from the straight steel fiber, so by using twisted and hooked end steel fiber the tensile strength and post cracking strain capacity of UHPFRC were improved [7]. Tensile strength of the specimen by using 2 % volume twisted steel fibers was 15 Mpa and 0.62% strain capacity that was the approximately 30 to 200 % higher as compared to the short straight steel fibers used with the 2% of volume, in addition twisted steel fibers were also used in the UHPFRC beams and result of flexural strength was 1.7 times more as compared to the tested flexural strength by using short straight steel fibers 32.5MPa and 19.5MPa [27]. But it was also represented by some researches that use of straight steel fibers can improve the flexural property and also improve fracture energy capacity, It was also observed that the increase in the fiber length, toughness, deflection capacity and flexural strength was improved [3,28] and fracture energies by using long steel fibers as compared to the medium and short steel fibers were 120 and 36 % higher respectively [3], the reason behind that was by increasing the length fiber, it leads to giving a more area for interfacial bond between the matrix and fiber and this bond gave the fiber to additional resistance against pullout and slip capacity [29]. So the estimated idea was also given for fibers per unit area and that was for short fiber it should be 34/cm^2 and for the medium, it should be 33.22/cm^2 and for long fiber, it should be 35.8/cm^2 [3]. The addition of the short straight steel fibers volume fraction up to 5% gave the approximate post cracking flexural strength value of 64 MPa which was seven times more than the post cracking flexural strength without using fiber [30].

So it is well known that the compressive strength is highly influenced by the homogeneous distribution and amount of adequate steel fiber volume fraction, various researchers gave different results regarding that. In a similar way, it was observed that the addition of steel fiber ranges from 1 to1.5% improved the flexural strength and split tensile strength up to two times as compared to their normal counterparts. However, there was little change in the compressive strength, from the results it was clear that the effect of the volume of steel fiber is more prominent in flexural strength.They also concluded that the range of fiber content also improves the fracture toughness and improve the strength [53]. It was mentioned that using 2-3% of fiber volume fraction gave the highest compressive strength and the length was 13mm and geometry was long and straight, steel [54]. Fiber volume content in the range from 0.5 - 2% also used in the high strength concrete, they observed that the influence of fiber volume on split tensile strength, compressive strength and modulus of rupture and they concluded that the compressive strength was increased up to 1.5% of fiber content and then slightly decrease when 2% fiber volume was used but on the other side split tensile strength and modulus of rupture was improved when up to 2% fiber volume was used. Researchers also used various toughness indexes and they find out the toughness index was also increased when the fiber volume was increased up to 2% [54]. But some researches also showed that using fiber content more than 2% like they used 4% volume fraction of steel fiber gave compressive strength up to 50 MPa [31].

Effect of fiber orientation

According to the investigation that the flowable UHPFRC exerts forces and moment on the fiber so that the fibers are rotated by various flow velocity [35], so additional displacement methods were investigated on fabricated steel bar reinforcement UHPFRC beams, the methods are (1) in the formwork placing of concrete at one end and it goes to another end without applying any resistance, (2) in the forms placing concrete at the center and it goes to both ends without applying for any resistance and support, so they concluded that the in placing method where concrete was applied at one end gave the higher load and it was 15 % higher on other placing method on which concrete was placed at the center, the reason behind that due to flowable characteristics of UHPFRC it allowed the fiber to set in a position or direction which is longitudinal to the beam length [32]. In addition, different placement methods are also applied on the rectangular slab to investigate the fiber orientation and its effect on flexural strength of UHPFRC [33,34]. Results emphasized that the beams which were positioned in the vertical direction of the casting flow had very poor flexural performance when it compared to the beams which were oriented in the direction of the flow, it was happened due to the alignment of the fibers were in perpendicular to the beam length. Placement of concrete was done at one short edge but when the placement of the concrete was done at the center (radial flow) the results were opposite, beams which were in the direction of the flow showed very low load resisting capacity as compared to the beams perpendicular to the flow [34]. Now from the above observation, it has been clear that the orientation of fiber influence the mechanical property and also the structural behavior during tension and flexural. K Wille and GJ Parra-Montesinos [36] observed that from the type of casting method (layer casting, middle casting) and casting speed and its effect on flexural behavior of UHPFRC, they concluded that the thinner layer and with adequate fiber alignment in the casting of beam improved the flexural strength instead of using another method (snake-like flow pattern), they also mentioned that the beam on which placing of concrete was done in the middle showed the intermediate flexural strength as compared to casting of beam performed by high casting speed rate and low casting speed rate [36]. DY Yoo and N Banthia [3] mentioned that the casting technique was influenced the fracture energy because there was decrease in the ultimate stress, they also preferred image analysis to ensure that in the middle casting method fibers are located in the middle (maximum bending area) as compared to edge casting method. So from the above result, it is clear that the middle casting method gives the higher flexural strength to the specimen as compared to the other placing methods like casting at the periphery, random casting, costing at one edge. Various researchers proved by various analysis that the steel fibers are located at the center when the center casting method was adopted and fibers are aligned perpendicular to the direction of flow because of the gradient of the flow velocity, so higher flexural strength and toughness was adopted when improved fiber alignment was used, when the casting is done at the center as compared to the other placing technique.

Size effect

Various researchers investigated the size effect of the element in UHPFRC [36,38-41] with various percentages of fiber. Size effect on compressive strength of UHPFRC was analyzed by using various cubes of different sizes and concluded that the large size cubes have less compressive strength as compared to smaller specimen [41]. It was also mentioned that the percentage of fiber also influences the size effect . It was also investigated that the flexural strength was not sensitive to the size effect because of high ductility of UHPFRC [38,36,42]. A Spasojevic *et al.* [42] concluded that the high tensile ductility UHPFRC was less sensitive to size effect as compared to UHPFRC with lower ductility (if flexural performance, flexural strength, normalized deflection, normalized toughness is taken under consideration). S Kazemi and AS Lubell [43] reported that there were increases in compressive strength, first and post cracking flexural strength, direct shear strength when the small size UHPFRC was used as compared to the large sample. In a similar way KH Reineck and S Greiner [44] and B Frettlöhr *et al.* [45] also concluded that there was decrease in flexural strength and axial tensile strength when the specimen size increased. DY Yoo and JM Yang [37] mentioned that the fiber bridging capacity was affected by the post cracking flexural behavior rather than the strength of the matrix, but from the above searches researchers did not include the fiber orientation which investigates the size effect, so to find out the fiber distribution characteristics (fiber orientation, fiber dispersion, number of fiber per unit area) image analysis was performed on UHPFRC beam after conducting the various flexural tensile tests with different image analysis was done on the localized crack. DL Nguyen *et al.* [39], KH Reineck and S Greiner [44] also performed the flexural test and applied concrete at one end and there was decrease in flexural performance as the specimen size increased, type of fiber were twisted and straight with aspect ratio ranges from 65 to 100, so the main reason of size effect was distribution of fiber, DY Yoo *et al.* [40] concluded that due to the different fiber distribution characteristics the size effect influence the flexural strength, so to eliminate the size effect 2% by volume steel fibers should be adopted.

Strain - rate (Loading rate) effects

M.F.Ashby and D.Cebon [1] observed that the concrete was affected by the different strain rates, which depend upon the various types of load conditions. Intension concrete showed maximum susceptibility towards the strain rate and minimum in compression and intermediate in flexural. The strain rate is briefly discussed for the mechanical properties of UHPFRC in the following section:

Effect on compression

Z Rong *et al.* [46] and J Lai and W Sun [47] used the Split Hopkinson pressure bar with different percentage of fibers to investigate the compressive nature under dynamic load and they conclude that the different fiber content affect the compressive behavior of UHPFRC and they also specify the type of model like ZWT and JHC models for LS- DYNA for analysis.

Effect on tension

High strain rates influence the mechanical property, prismatic UHPFRC specimen was used for the testing. Unconfined and rapid tensile loading applies to various strain rates, which was from 10^{-6} to 5/s. Results indicated that there was about 70% increase in tensile strength as strain rate increase from 10^{-6} to 5/s [48]. Similarly, K Wille *et al.* [49] find out that the strain rate from 10^{-4} to 10^{-1} /s with various percentages of fibers and then concluded that the strain hardening increased by 20% and 40% there was increase in the energy absorption at the same rate of strain. NT Tran *et al.* [50] mentioned that UHPFRC showed high tensile strength in high strain rates as compared to the static rate, although the use of twisted steel fiber showed the high tensile resistance in a static load, and in other hand strengths like post cracking, strain capacity and toughness was obtained in UHPFRC by using straight steel fibers, reason behind that the straight steel fibers can resist the high strain rate as compared to twisted steel fiber. K Wille *et al.* [51] investigated that the straight steel fiber gave the high tensile strength of UHPFRC as compare to twisted steel fiber.

Effect on flexural

K Habel and P Gauvreau [52] concluded that flexural energy increased when a specimen of UHPFRC loaded under dynamic load conditions as compared to the static load the performed the test by using drop weight impact. V Bindiganavile *et al.* [12] concluded that there was increase in 2 times of flexural strength and 4 times energy dissipation capacity in compacted reinforced concrete as compared to the fiber reinforced concrete (FRC).

CONCLUSIONS

This paper reviewed the mechanical properties of ultra-high-performance fiber-reinforced concrete (UHPFRC). Based on the literature review and discussions, the Specific findings of this literature review include the following:-

1. Heat treatment increases the hydration process and density, which ultimately contributes to the ultra-high strength. Besides, the replacement of fine sand with coarse aggregate with a maximum size of 8 mm has no significant effect on the compressive strength, whereas the flexural strength was decreased.
2. The hydration process of UHPFRC is accelerated by using silica fume (SF), whereas the use of fly ash (FA) and slag retarded the hydration process.
3. Mechanical properties of UHPFRC are improved by using the deformed (hooked-end and twisted) steel fibers as compare to straight steel fibers, i.e., the use of twisted steel fibers increased the tensile strength, strain capacity, and flexural strength.
4. Casting method was more prominent to flexural strength of UHPFRC, as compared to fracture energy.
5. A smaller sample of UHPFRC provided higher mechanical strengths as compared with bigger samples. Because the larger specimens led to poor fiber orientation and fewer fibers.
6. High strain-rates increase the mechanical properties of UHPFRC. Increasing the strain rate from10^{-6} to 5/s and 10^{-4} to 10^{-1}/s the tensile strength and energy absorption capacity was increased by approximately 70% and 40% respectively.

Based on the review, the following issues are highlighted for further research

1. There is a contrast between the results from various ‘size effect’ tests for UHPFRC. Thus, the fiber distribution characteristics should be well defined when the size effect in UHPFRC has taken under investigation.
2. While it is clear that twisted steel fibers improve tensile or flexural performance at a static rate as compared to straight steel fibers, but some researchers have reported that using twisted steel fibers decreases the tensile strength at high rate loading as compared to straight steel fibers.
3. Efforts must be made to reduce the production cost of UHPFRC to promote its use worldwide.

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