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State of the Art: Mechanical Properties of Ultra-High Performance Concrete

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Abstract

During the past decades, there has been an extensive attention in using Ultra-High Performance Concrete (UHPC) in the buildings and infrastructures construction. Due to that, defining comprehensive mechanical properties of UHPC required to design structural members is worthwhile. The main difference of UHPC with the conventional concrete is the very high strength of UHPC, resulting designing elements with less weight and smaller sizes. However, there have been no globally accepted UHPC properties to be implemented in the designing process. Therefore, in the current study, the UHPC mechanical properties such as compressive and tensile strength, modulus of elasticity and development length for designing purposes are provided based on the reviewed literature. According to that, the best-recommended properties of UHPC that can be used in designing of UHPC members are summarized. Finally, different topics for future works and researches on UHPC's mechanical properties are suggested.

Keywords: Durability; Tensile Strength; Cracking; Fiber Reinforcement Polymer; Bond Properties.

1. Introduction

Concrete, along with steel, is the most widely used material in the construction of infrastructures. The reliable foundation provided by concrete makes it an appealing choice for traditionally non-concrete structures [1, 2], dams [3], pavement [4, 5] and bridges. However, the low tensile strength, flexural strength, and durability of concrete have been the main concern in designing of the elements. Therefore, the development of science and material in the recent decades has led to the production of Ultra-High Performance Concrete (UHPC). UHPC is a new class of concrete that exhibits remarkable mechanical and durability properties, as compared to the conventional concrete which is available commercially since 2000 [6]. The main components of UHPC which make UHPC properties special are an optimized gradation, fiber reinforcements, and its water to cementation ratio less than 0.25 which is less than conventional concrete [6, 7]. The special properties of UHPC cause the extensive interest in using UHPC in precast, pre-stressed, and field cast bridge connections. Bridge decks [8], movable decks [9], roof panels [10], precast piles and foundation of bridges on loose soils [11] are the structural elements that UHPC have been utilized to construct them.

Habel [12] demonstrated that UHPC has self-consolidation feature. This feature showed that UHPC could have a compressive strength over 150 MPa without applying any special curing during its casting. Moreover, the cost of UHPC mix design was investigated, and it was concluded that with the moderate cost it is possible to produce UHPC with enough workability [13]. Graybeal [14] investigated that the mixing procedure of conventional concrete can be implemented for UHPC mixing procedure. However, UHPC needed more input energy in its mixing procedure; therefore, ice should be used in the mixing of UHPC instead of water to produce no overheated mix.

The high energy absorption capacity is another unique feature of UHPC in high-rate loading which can prevent the collapsing of infrastructures during the earthquake and cycling loading [15]. To improve the energy absorption

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capacity of UHPC, the concrete durability [16], the compressive encasing region of the concrete member [17], the percentage of steel reinforcement in the member [18] and the percentage of fibers in the concrete should be increased [19].

UHPC is a recently developed type of concrete which is desirable to be used in the construction of concrete members to improve design life, member strength and reduce the construction cost and weight. However, it needs more research to define its properties properly [20]. In this article the followings UHPC properties topics were discussed: UHPC constituent components, mechanical properties of UHPC such as compressive strength, compressive strain-stress behavior, tensile strain, modulus of elasticity, density, concrete cover, and bond properties of UHPC. Finally, some topics which need to be investigated were recommended.

2. UHPC Constituent Components

The UHPC was defined as concrete with a minimum 22 ksi compressive strength [21, 22]. The typical material composition of UHPC is represented in Table 1. In UHPC, fine aggregate instead of coarse aggregate combined with optimized granular mixture results homogenous, compact, and superior low porosity cementitious matrix, the same idea with epoxy grout [23]. These constituent components lead to improvement of mechanical performances, homogeneity, and ductility of UHPC in comparison with conventional concrete [24]. Implementation of fine aggregates in UHPC mix improves the homogeneity of concrete and results in different mechanical properties for UHPC [25]. UHPC's superior low porosity protects steel reinforcing bars from corrosion [26]. Fine aggregate also reduces the mixing time. As a result, the use of well-graded aggregate increased the dense packing and noticeably improves the mechanical properties of the material.

Table 1. Material Composition of Typical UHPC mix [21, 27]

Material	Amount (lb/yd^3)	Present by Weight
Portland Cement	1,200	28.5
Fine Sand	1,720	40.8
Silica Fume	390	9.3
Ground Quartz	355	8.4
Super Plasticizer	51.8	1.2
Accelerator	50.5	1.2
Steel Fibers	263	6.2
Water	184	4.4

As shown in Table 1, steel fiber as the most important constituent component is the main content that makes the UHPC properties exceptional from conventional concrete [28]. Fibers improve the mechanical properties as well as ductility of the material. Fibers act similar to the reinforcing steel in conventional reinforced concrete, but on the micro level [29, 30]. Fibers are distributed all over the mix uniformly, therefore provides consistency of tensile strength to the material. Thus, fibers content significantly promotes the tensile and shear strength, and thereby potentially eliminate or greatly reduce the need for flexural and shear reinforcements.

Moreover, fibers postpone the formation of micro-cracks, as well as controlling the crack widths and spacing [31]. These characteristics increase the stiffness of structural elements at service loads that eventually diminishes the service deflection. The high service stiffness is paramount to the design of structural elements for serviceability. The high service stiffness effectively helps engineers to design smaller sections with minimal service deflection, while still meets the deflection requirements of the building code in force.

Also, fibers content lead to non-brittle ductile behavior at ultimate capacity [32]. Ductility is the result of fibers pulls out mechanism at high loads. The gradual and controlled cracks reduce the risk of sudden failure [24]. The non-brittle ductile behavior of UHPC at ultimate loads provides a higher level of safety to the building users by showing large deflection before failure. Figure 1. summarizes how fibers content in UHPC enhance the mechanical properties and ductility, and how it affects the design.

Overall, fibers content enhance the mechanical properties and ductility of UHPC as follows:

- Increase the tensile strength and as result shear strength
- Decrease the needed reinforcement ratio
- Control cracks width
- Provide non-brittle behavior

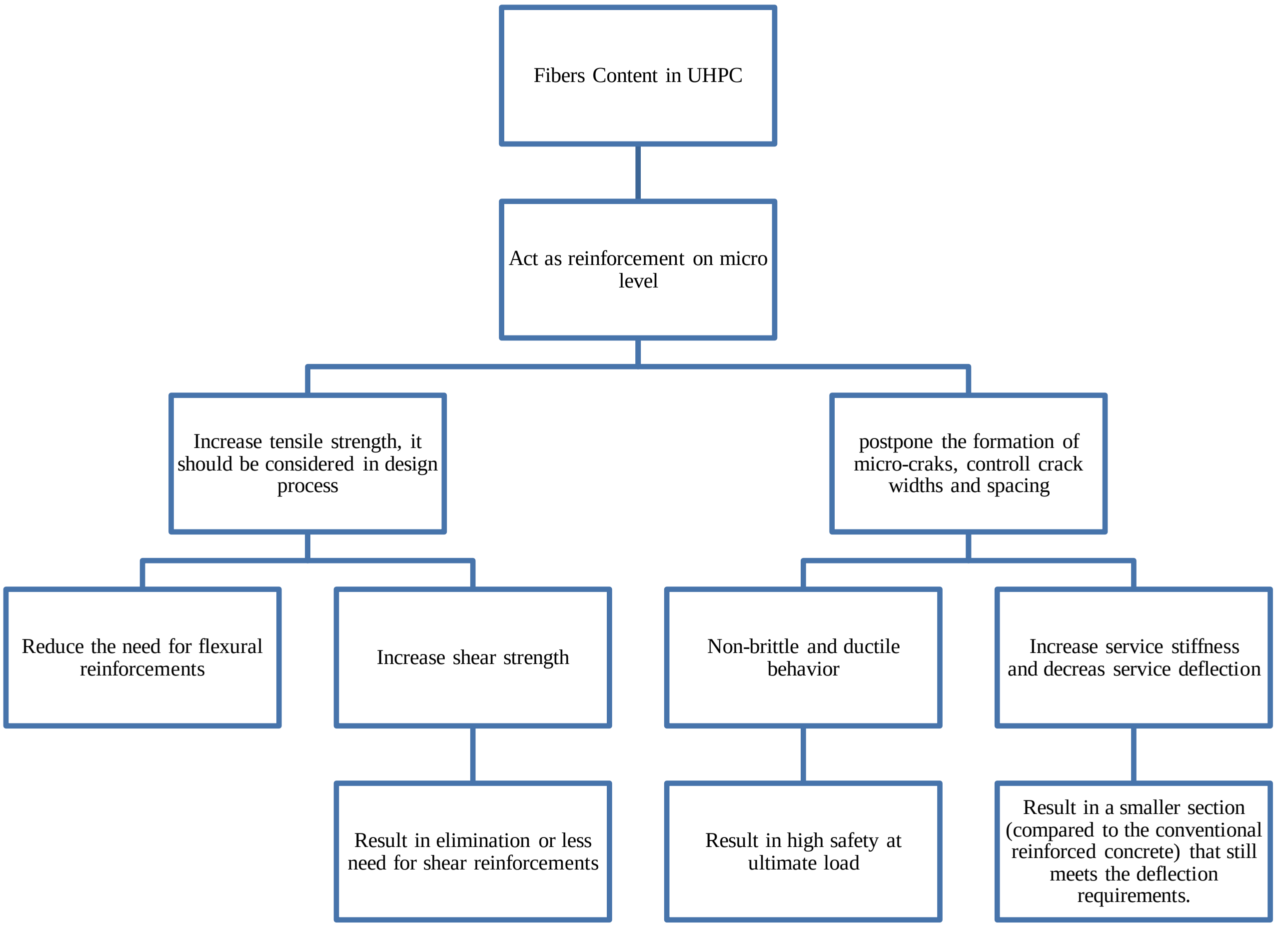

Figure 1. Fibers content in UHPC and its influence on the mechanical properties and characteristics of UHPC

3. Compressive Strength

The compressive strength of UHPC is one of the important features that are necessary for designing a member. As UHPC has different ingredients from typical concrete, it may show different behavior, especially due to the steel fibers content. Based on the research by Aaleti, Petersen [21], the 28-days compressive strength of UHPC (f'_c) depends on the curing type process. It was defied that for steam-cured and air-cured conditions, the compressive strength of concrete should be considered 24 ksi and 18 ksi, conservatively. It is even much stronger than epoxy grouts that are used in bridges cast-in field joints, and pourbacks of post-tensioned bridges [23].

Graybeal and Baby [33] recently developed an equation for UHPC which represents compressive strength gain at any age after casting cured under standard laboratory condition. By using Equation 1, it is possible to obtain concrete compressive strength by the age based on the concrete strength at 28 days.

$$f'_{ct} = f'_c \left[1 - \exp\left(-\left(\frac{t-0.9}{3}\right)^{0.6}\right)\right] \quad (1)$$

Where:

f'_{ct}: is UHPC compressive strength at age t days

f'_c: is UHPC compressive strength at 28 days

t: is time after casting in days.

To investigate the bond properties of UHPC, Graybeal [34, 35] performed an experimental test and identified that the average compressive strength of UHPC with 1 and 7 days age were 13.9 and 19 ksi, respectively. When the compressive strength of UHPC with 28 days age substitutes in the Equation 1, it cannot result in proper compressive strength for one day age concrete. Due to that, it can be concluded that this equation result may not be exact in some conditions. Thus, predicting the strength of UHPC from 28-days age concrete needs more research.

4. Compressive Strain-Stress Behaviour

For designing of members, knowing the compressive strain-stress behaviour of UHPC is essential. The strain at the peak of UHPC compressive strength is the key point in defining the concrete behaviour. It was assumed that the stress-strain behaviour of UHPC is linear and the compressive stress at the strain of 0.0035 and 0.004 can be used for air and steam-cured condition, respectively [21]. Moreover, French [36], Australian [37], and Japanese [38] UHPC designing manual recommend stress-strain behaviour as a trilinear curve, which is shown in Figure 2.

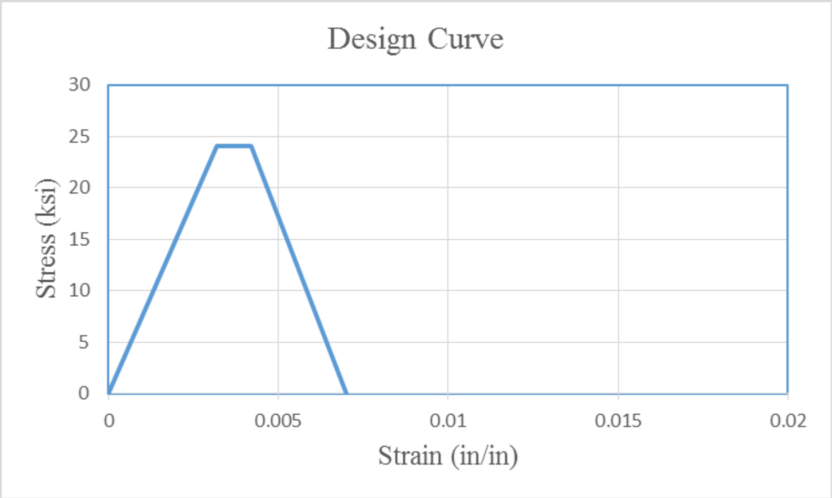

Figure 2. Trilinear stress- strain behavior [36-38]

5. Tensile Strength

As previously stated, steel fibers in UHPC act as reinforcing steel in a micro level and cause an improvement in tensile and shear strength of the concrete compare with the typical concrete. Another important factor that affects the tension strength of UHPC is the curing type and condition. Aaleti, Petersen [21] recommended that cracking tensile strength of UHPC should be taken 1.3 ksi and 0.9 ksi for steam and air-cured condition as shown in Figure 3. Graybeal and Baby [33] also obtained Equation 2. to compute the tensile strength of UHPC using measured compressive strength.

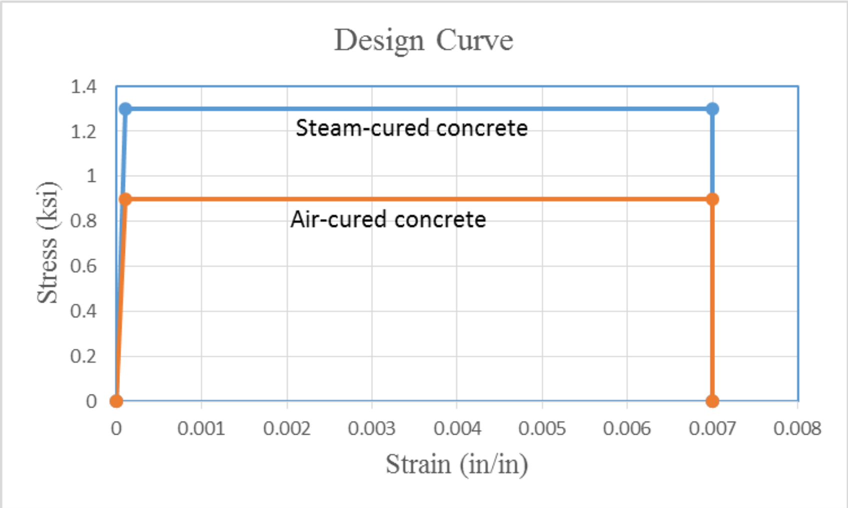

Figure 3. Tensile stress-strain behaviour [21]

$$f_t = K\sqrt{f'_c} \tag{2}$$

Where:

f_t: is tensile strength

f'_c: is compressive strength of 28 days age in psi unit

K: is a constant factor which is 6.7, 7.8 and 8.8 for the untreated, air-cured, and steam-cured specimen, respectively.

However, by comparing UHPC with conventional concrete, UHPC offers about a four-fold increase in tensile strength. In the designing of elements with conventional reinforced concrete, tensile strength is neglected due to its very low strength. However, it is totally different in UHPC in which high tensile is greatly beneficial in the design process of structural elements, and results in the magnificent lower need for reinforcing steel bars. As previously stated, the high tensile capacity of UHPC originated from the fibers used in UHPC. Accordingly, the tensile strength of UHPC is high enough to be considered in the designing of elements. Another difference in tensile strength is that UHPC showed very similar post cracking and pre-cracking capacity, as opposed to the conventional concrete that cannot carry loads after cracking [39]. This tensile capacity means UHPC still can almost maintain its ultimate capacity even after cracking. This phenomenon, high post-cracking strength, also brings a higher level of safety to the elements made by UHPC.

6. Modulus of Elasticity

As discussed, UHPC displays a linear stress-strain behaviour. There are some methods suggested to find the relationship between compressive strength and modulus of Elasticity. The best equation that meets the experimental results is suggested by Graybeal [39]. It is based on the general form of AASHTO equation and value of f'_c between 4 and 28 ksi. Also, it was suggested that in the absence of exact concrete strength, the value of 7,500 ksi can be used as the UHPC modulus of elasticity. Moreover, other studies suggest the value of 7,600 ksi [40], 8,100 ksi [41], and 7,300 ksi [42] as the UHPC modulus of elasticity.

$$E = 46{,}200\sqrt{f'_c} \tag{3}$$

Where:

E: is modulus of elasticity in psi unit
f'_c: is compressive strength at 28 days age in psi

7. Density

In the absence of coarse aggregates, UHPC has a self-compacted feature. It is much compacted than typical concrete. It is recommended that unit weight of UHPC should be considered between 155 lb/ft^3 and 160 lb/ft^3 [21, 27].

8. Concrete Cover

The concrete cover is important for durability and development of concrete bond strength. The Japanese Society of Civil Engineering [38] and Australian code for UHPC [37] require a minimum of 0.75 inches of concrete cover for uncoated concrete. The research performed by Aaleti, Petersen [21] suggested that the minimum concrete cover should be 1.5 times of the strand diameter for prestressing strands. They also suggested that reinforcement with strands should have a clear spacing of 3.25 times the reinforcement diameter or 1.5 inches, which one is greater.

9. Summary of Mechanical Properties of UHPC

Table 2. summarizes the mechanical properties of UHPC for designing purpose, based on the reviewed studies and comparison of different paper results.

Table 2. Summary of UHPC mechanical properties

Characteristic	Property
Compressive Strength	It depends on the percentage of fiber reinforcements in UHPC. For the designing purpose, using 18 and 24 ksi as 28-days age UHPC were recommended for the steam-cured and air-cured condition, respectively.
Tensile Strength	Its range is between 0.9 and 1.3 ksi. Using the following equation was conservative. $f_{ct} = 6.7\sqrt{f'_c}$
Modulus of Elasticity	$E(psi) = 46{,}200\sqrt{f'_c}(psi)$ or 7,300 to 7,500 ksi for 28-days age UHPC
Strain at peak compressive strength	Its range is between 0.0035 and 0.004. Using 0.0032 was recommended.
Density	Its range was between 155 lb/ft^3 and 160 lb/ft^3.
Poisson's ratio	0.2

As shown in Table 2, the UHPC has unique properties and high density in comparison with conventional concrete.

The high density of UHPC causes the small permeability of UHPC and leading the high durability of UHPC. Moreover, the maximum residual tensile strain of 0.13 in low permeability in tensile deformation test was observed [43].

10. Bond Properties of UHPC

As the ingredients of UHPC are different from conventional concrete, it shows different behavior and development length. The existence of fiber reinforcement in UHPC allows the material to have the tensile capacity beyond the cracking of cementations matrix, which can cause a reduction in development length of reinforcement bar. The amount of fiber reinforcement can be the important component that effects on the UHPC behavior and consequently represents different bond behaviour. The purpose of this section is an investigation on different factors that can influence the bond behaviour of UHPC and development length of rebars.

The term that is important in investigating bond properties of UHPC is the average bond strength at bond failure. This term exhibits the load transfer between reinforcement bar and surrounding concrete, which it is represented as equation bellow [21].

$$\mu_{Test} = \frac{f_{s,max}\, \pi\, {d_b}^2/4}{\pi\, d_b\, l_d} = \frac{f_{s,max}\, d_b}{4\, l_d} \tag{4}$$

Where:

l_d: Embedment length
μ_{Test}: Average bond strength of at bond failure
d_b: Bar size
$f_{s,max}$: Reinforcement stress at failure

Saleem, Mirmiran [44] investigated the development length of #10 and #22 reinforcing Grade 60 steel bars. They showed that #10 and #22 rebar require 12 and 18 times the rebar diameter development length. Another recent study represented that 20 to 40 times of rebar diameter is needed for development length of UHPC elements [45]. Also, it was concluded that casting orientation did not make an effect on the bond behavior of UHPC [34]. It was reported that increasing the embedment length improved the bond strength. Furthermore, bond strength and bond length relation are nearly linear.

Side cover C_{s0} is another factor that has effect on the development length. It is the factor that defines the failure mode of a member. The concrete failure may happen in concrete cover, if the side cover being less than half of the bar spacing (C_{si}). It was found that maximum bar stress at bond failure increased as side cover increases. When the side cover is large enough, the bar spacing controls the bond strength of UHPC [46].

Graybeal [34] reported that when bar spacing is less than half of the side cover ($2C_{si} \leq C_{s0}$), the bond strength controls by bar spacing ($2C_{si}$). If the bar spacing being between side cover and lap splice length l_s times ($tan\,\theta$), ($C_{s0} < 2C_{si} \leq l_s\, tan\,\theta$) -- θ is angle between diagonal cracks and testing bar -- the bond strength controls by side cover. Finally, if ($2C_{si} > l_s\, tan\,\theta$), the bond strength controls by mechanical properties of UHPC. Thus, the compressive strength, material properties, and compressive strength effect on the bond strength of UHPC should be considered, because the UHPC properties cannot be effectively represented by the μ_{Test} and f'_c [47].

Based on the Graybeal results, the minimum development length is $8d_b$ with minimum side cover of $3d_b$; bar spacing between $2d_b$ and $l_s\, tan\,\theta$; and minimum compressive strength of 13.5 ksi. For lap splice l_s a minimum of 75 percent of embedment length was suggested. In a situation, which the side cover is between $2d_b$ and $3d_b$, the minimum embedment length should increase to $10d_b$. Another recently conducted research also concluded that $8d_b$ development length is enough for rebars with $3d_b$ side cover [48]. The results indicated that bars with larger diameter have less bond strength in comparison to smaller bar size; therefore, larger bar diameter needs larger embedment length.

Saleem, Mirmiran [44] suggested that for #10 and #22 bars with compressive strength of 24 ksi in 28-days age, and a clear side cover of 0.51 inches, development length should be $12d_b$ and $18d_b$, respectively. Moreover, they indicated that ACI 318-08 and AASHTO are overestimated the development length; while ACI 408R-03 provided a reasonable development length. Another research showed that about $20d_b$ to $40d_b$ transfer length is needed for UHPC sections [49].

11. Discussion

Using UHPC in the construction of bridges and buildings has been in high interest. Due to its high strength and durability, UHPC is using wide-spread. However, regardless of needed special inspection in selecting the UHPC material, components, and curing process, it needs special techniques and attention for its designing. These critical inspections and attention are needed to be sure about the produced elements strength and durability which can cause different mechanical properties for produced UHPC. One of the UHPC constituent components which play an essential role in the mechanical properties of UHPC is the fiber. The using fibers percentage in the UHPC can change the UHPC properties significantly. Fibers should be uniformly distributed in the mixing process. Therefore, the effect of different percentage of fibers in the UHPC on the required development length and bond properties of UHPC can be one of the interesting topics that need more research.

Based on the review of published and experimental works on mechanical properties and bond behaviour of UHPC, UHPC provides two major exceptional mechanical characteristics: (1) High compressive strength, and; (2) High tensile strength, compared to the typical concrete [50]. In addition, UHPC's high tensile strength and strain hardening properties improve serviceability performance through the increased stiffness, reduced deflection, and postponement of formation of localized macro-cracks [12]. As compared to conventional reinforced concrete, it is clear that there is no general information about the mechanical properties, bond behavior, and especially the required development length and bond properties of UHPC. Moreover, UHPC which has amended properties shows high early compression strength, durability, and ease of placement. Several technical papers were reviewed, and the typical UHPC properties that can be used in designing the members constructed by UHPC was recommended. It should be noted that UHPC with the different component may represent different properties. However, these topics need more research. For example, the effect of different rebar size on the bond behaviour and development length of UHPC. As UHPC has high strength capacity, using High Strength Steel (HSS) in UHPC is valuable to increase the strength capacity of the member [10, 51]. Thus, determining the required development length of HSS bar in the UHPC sections is worthwhile.

The UHPC has a compressive strength of 22 ksi and greater, which is four to eight times of the conventional concrete, and high tensile strength of 0.9 to 1.3 ksi [35, 39], opposed to the 0.3 to 0.7 ksi of normal concrete. Both pre and post-cracking strength of UHPC are noticeably greater than the conventional concrete [39]. These significant improvements, especially tensile strength, considerably enhance the design of flexural elements made of UHPC. Unlike the approach utilized in the design of traditional reinforced concrete-- that neglects the tensile strength of conventional concrete -- the tensile strength of UHPC should be considered in the design process. High compressive strength significantly reduces the size of compressive elements (e.g. columns), while tensile strength greatly affects the size of flexural elements and members subjected to shear forces. Thus, UHPC's high compressive and tensile strength result in superior structural elements in a small section size.

12. Conclusion

In this article, the mechanical properties of UHPC and its differences with the conventional concrete is reviewed, and the recent developments in the defining the properties of UHPC are reported. It is obvious that there are no globally acceptable properties for the UHPC to be used in the designing of the members with UHPC. In this case, according to the reviewed researches, the acceptable properties of UHPC by different researchers which can be used in the designing of the UHPC members are recommended. Moreover, some special topics which need more research are identified.

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