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Review

Review of high and ultrahigh performance cementitious composites incorporating various combinations of fibers and ultrafines

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ABSTRACT

The outcomes of the research in modern cementitious composites have paved the way for their wide use in construction industry. The introduction of short, discontinuous and randomly distributed fibers to these composites has altered their inherent brittleness. Extensive research has been carried out on the effects of using of mono-fibers in a cementitious composite. However, limited reports in the approachable references on the use of hybrid fibers are available. The synergetic interaction between hybrid fibers have beneficial impact on cementitious composites. The incorporation of micro- and nano-pozzolanic materials, such as fly ash and silica fume have been used to develop high performance cementitious composites such as reactive powder concrete, DUCTAL and CEMTEC multiscale. Further developments were recently achieved by the development of ultra-high performance cementitious composites. The matter of developing high and ultrahigh cementitious composites using various kinds of fibers and particles has received enormous attention from the scientific community. This paper presents a comprehensive critical literature review on the area of high and ultra-high performance cement-based materials.

Contents

1. Introduction

For more than 200 years ago, the blended materials containing cement have been widely used in construction (Brandt, 2009). The improved comprehension of the interactive material mechanics and the associated technological advances have minimized the deficiencies of these materials, which boost their demand and applications. By the contributions of several researchers, many of

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the deep-rooted weaknesses of cement-based composites have been controlled. The use of steel bars has become an efficient technique to mitigate macro-cracks caused by flexural tensile stresses. However, cementitious composites continue to be subjected to micro-cracking due to its inherent low tensile strength. To overcome this problem, the use of short fibers unsystematically dispersed in the material was invented. Many researchers have demonstrated the effectiveness of using fibrous materials to improve the properties of a cementitious composite. The development of fiber-reinforced cementitious composites establish a notable revolution in their modern technology (Bentur and Mindess, 2006). The failure in a cementitious composite begins with the formation of micro-cracks that propagate and eventually coalesce to generate macrocracks, which cause fracture if not controlled. The existence of fibers in a cementitious matrix mitigates and stops the propagation of micro-cracks and macro-cracks (Banthia and Gupta, 2004). The use of a single type of fiber as reinforcement in a cementitious composite has been extensively investigated. Incorporation of fibers in cement-based mixes does not affect its compressive strength much, however, its residual strength after fire exposure notably improves as a result of using fiber reinforcement (Al Qadi and Al-Zaidyeen, 2014).

The inclusion of micro- and nano-pozzolanic materials, such as fly ash and silica fume, has been demonstrated to produce high performance cementitious composite (HPCC) and improve their short- and long-term durability. The inclusion of fibers as reinforcement to improve fracture resistance in all loading configurations is a common practice. Fibers prohibit and interrupt the mechanisms of crack formation and propagation by acting as stress-transfer bridges. The inclusion of fibers prevents the propagation of existing and/or initiated cracks by improving the crack tip plasticity that increases the fracture toughness of the composite. The hybrid mixture of fibers can be described as combination of several fibers of diverse dimensions, shapes and mechanical properties. This mixture was suggested to synergistically interact with HPCC matrix to develop a super-hybrid composite of HPCC (SHC-HPCC) (Khan et al., 2014). Recent reported research authenticated the capability of using fiber hybridization to enhance various properties of SHC-HPCC. The matter of developing HPCC and ultrahigh cementitious composites (UHPCC) using various kinds of fibers and particles has received enormous attention. However, a critical literature review for reported research on this area is needed to address the current needs for research programs. The objective of this paper is to present a comprehensive critical literature review on the area of high and ultra-high performance cement-based materials.

2. High performance cementitious composites

The use of fine materials, such as silica fume, ground quartz, fly ash and many other well-known materials, is mandatory in the production of ultra-high performance and durable cementitious composite. The synergistic interaction at very low water-to-binder ratios among different combinations of cement, fine materials and chemical admixtures helps the production of high performance composite and ultra-high performance cementitious composite (HPCC and UHPCC, respectively). The only drawback of HPC and UHPC is their elevated brittleness, which can be overcome by the introduction of fiber. A HPCC is required to satisfy one or more of the following properties: 1) good workability, 2) high strength and strength gain rate, 3) long-term durability, and 4) low plastic and drying shrinkage (Folliard and Berke, 1997; Chang, 2004; Elahi et al., 2010). A HPCC can be developed by one or more of the following methods: 1) decreasing the water-binder ratio, 2) filling the gaps of the grain particle distribution, and 3) utilizing advanced techniques for mixing, placing and curing. In 2007, the a UHPCC was defined to have compressive strength varied in the range of 200–800 MPa (Hammer, 2007), whereas the majority of researchers have agreed that a cementitious composite with compressive strength in the range of 60–120 MPa is classified as HPCC.

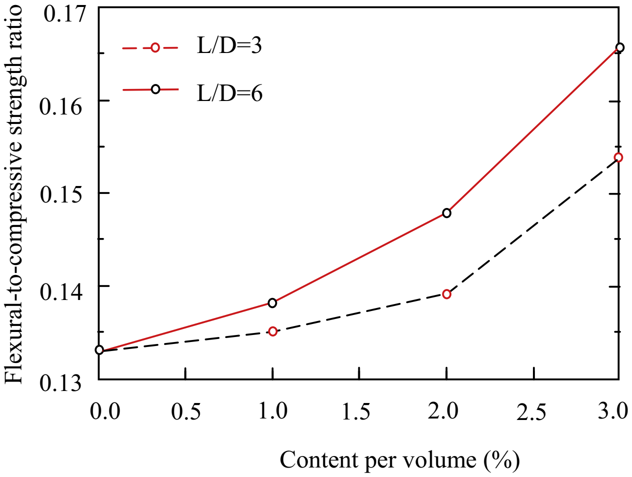

Fig. 1. Influence of steel fiber content of the flexural strength of very high performance cementitious composite (Long et al., 2002).

The replacement of cement in the development of HPCC using binary and ternary combinations of micro-filler minerals, such as fuel ash, silica fume, slag, and metakaolin, have become a common practice. However, the superior compressive strength of HPCC is associated with brittle behavior. Many attempts have been conducted to overcome this drawback. The use of steel fibers (with aspect ratios (L/d) of 30 and 60 and steel tubes attached to specimens were proposed (Long et al., 2002). In this study, the flexural to compressive strength (f/c) ratio increases with an increasing in steel fiber content, as shown in Fig. 1.

2.1. Inclusion of metallic fibers

The majority of metallic fibers are composed of steel in the form of short and discrete fibers with an aspect ratio that ranges from approximately 20–100. The geometry of discontinuous steel fibers can be 1) straight and smooth, 2) hooked, or 3) twisted (Bentur and Mindess, 2006). These fibers exhibit relatively high tensile strength, elasticity modulus and resistance to corrosion, which is attributed to the alkalinity of the cementitious composites. An improved steel-matrix bond can be achieved using deformed or high-friction fibers. Stainless steel fibers exhibit superior performance during long-term loading and in harsh environmental conditions, particularly when exposed to high temperatures. It is worthnoting that the response of the stainless steel fibers to harsh environmental conditions, with high temperature fluctuations and corrosion potential, are dependent on the strengths of the fibers. Studies on modern cementitious composite technology have prompted the efficient use of steel fiber cementitious composites. The use of mineral (e.g., fly ash and silica fume) and chemical admixtures (e.g., superplasticizers and accelerators) has facilitated the casting of shotcrete in thick layers. The use of micro-fine mineral admixtures, such as silica fume, has produced durable shotcrete composites.

2.2. Inclusion of synthetic fibers

Synthetic fibers are manufactured fibers that are developed by petrochemical and textile industries. Synthetic fibers are bendable

Table 1
Advantages and disadvantages of synthetic fibers.

Fibers	Advantages	Disadvantages	Remarks	Ref.
High modulus Polyethylene (PE)	• About 2.6 GPa tensile strength and 117 GPa elasticity modulus 5–8% ultimate strain and 0.97 specific gravity. • Good durability characteristics, which make them suitable for aggressive environments (seawater, alkalis and acids…etc.). • Fair residual strength at elevated temperatures up to 80 °C. • Good creep performance as for metallic fiber reinforced concrete. • Efficient for enhancing flexural toughness and impact resistance. • Stable with concrete alkalinity. • Does not cause balling during mixing. • Increases the ultimate compressive stain.	• Poor fire resistance, • Sensitive to sunlight and oxygen, • Decreases the workability of concrete. • Does not increase compressive strength. • Decreases the shear strength of concrete.	• Tensile strength and elasticity modulus comparable to Carbon fibers. • The disadvantages are resolved by embedment in concrete and using water reducing admixtures. • There is no agreement between researcher on the PP fiber –matrix interfacial bond and effect of PP fiber on the flexural and tensile strength of fiber reinforced concrete.	(Bilodeau et al., 2004; Kim et al., 2011; Deeb et al., 2012; Altun et al., 2013; Banthia et al., 2014)
Polyvinyl alcohol (PVA)	• High aspect ratio • High tensile strength • Good affinity with cement and water • Fast drainage rate • No health risks • Good interfacial bond with matrix, because they have non-circular cross sections and chemical bond with matrix • Positive effects on the bending strength	• Poor cement particle retention capacity • Tensile strength and Young's modulus of the fibers may decrease considerably under autoclaving conditions • Fiber reinforced concrete with high volume of PVA fibers has poor performance at elevated temperatures. • Workability loss increased much with fiber content compared to glass, steel, and carbon	-	(Banthia and Trottier, 1995; Sivakumar and Santhanam, 2007a,b; Deeb et al., 2012)
Nylon	• Low cost compared with PP fibers, • With low volume content, they can drastically improve the impact resistance	• Poor bonding strength with cement matrix • High cost compared to PP fibers • Very little effect on tensile strength	• Limited commercial potential	(Chen and Liu, 2005; Sivakumar and Santhanam, 2007a,b)
Aramid	• Perform as steel fibers when subjected to static flexure and drop weigh impact, • Good corrosions resistance compared to steel fibers, • Better performance compared to PP fibers • Workability is as for steel fibers (max 2–2.5% to avoid balling). • 100–200% increase for shear strength for 1% of fibers, • Low creep compared with synthetic fibers	• Creep deflection for beams is as or plain concrete		(Chen and Liu, 2005; Sivakumar and Santhanam, 2007a,b; Topcu and Canbaz, 2007)
Polyester	• High modulus of elasticity • Increase the impact resistance, • Slightly increase the compressive flexural and tensile strength	• Does not enhance the modulus of elasticity and the shear strength of concrete • Rapidly lose strength in cement matrix	• In effective as discontinuous reinforcement for cement matrix due to their chemical degradation	(Banthia and Nandakumar, 2003; Mehta and Monteiro, 2006; Topcu and Canbaz, 2007; Deeb et al., 2012)

and uniform materials with high aspect ratio and a small size. These fibers are manufactured from naturally occurring macromolecules and synthetic polymers (Zheng and Feldman, 1995). Different types of synthetic fibers have been incorporated in cementitious composite, such as acrylic, aramid, carbon, nylon, polyester, polyethylene (PE) and PP fibers. Some of these fibers, such as carbon, PE and PP fibers, have been intensively employed; however, few studies have utilized other fibers. Typically, cast-in-situ comprises cementitious composites that contain maximum concentrations of 0.4% synthetic fibers, whereas shotcrete composites with enhanced toughness indexes contain maximum concentrations of 0.75% synthetic fibers. In slab-on-grade applications, the fatigue life is significantly improved with 0.3% of PP fibers (Mindess, 2014).

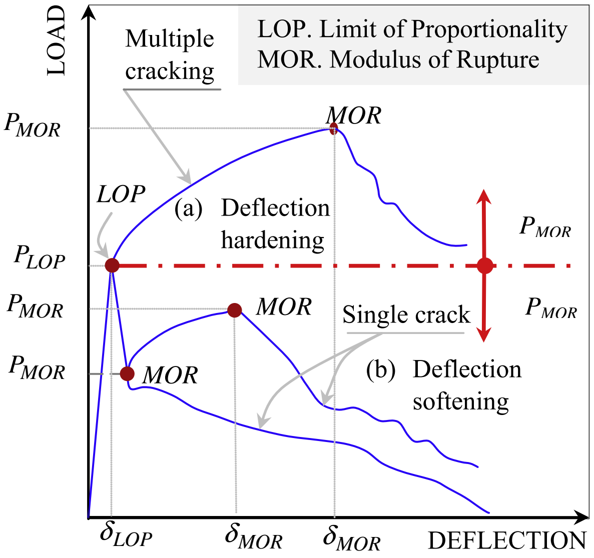

Fig. 2. Typical load–deflection response curves of FRC (Kim et al., 2008).

The main advantages of synthetic fibers are high tensile strength, elasticity modulus, ultimate strain and low specific gravity. Synthetic fibers are proved durable under many normal and harsh conditions with good bonding with cement and no health problem. The main disadvantages represented by low fire resistance, negative effect on workability and no improvement on compressive strength. All advantages and disadvantages are reported by many researchers record. Table 1 presents the reported advantages and disadvantages of using synthetic fibers in a cementitious composite.

In the last decades, approximately 100,000 m^3 per annum of fiber-reinforced cementitious composites (FRC) have been produced. Approximately 60% of this quantity was used in slabs on grade, 25% was used in fiber shotcrete, 5% was used in precast members, and 10% was employed in miscellaneous applications. The majority of the advances in FRC concern the utilization of ordinary Portland cement. However, gypsum, high alumina and various special cements have also been used. The goal of the use of this type of cement is to improve the durability of the composite or to minimize the chemical interactions between the fibers and the matrix. In addition, recent research innovate uniquely developed mortar and cementitious composites having optimized particle-size distributions (Kobayashi and Cho, 1982). As shown in Fig. 2, the flexural performance of FRC may be characterized as 1) deflection-softening or 2) deflection-hardening (Soroushian et al., 1992). FRC with a deflection-hardening performance produces a greater ultimate load after the initial crack compared with normal cementitious composite or FRC with a deflection-softening behavior. Regarding the tensile behavior, the FRC exhibits two different behaviors, namely, 1) tensile strain softening or 2) tensile strain hardening, as shown in Fig. 2. It should be noted that Eq. (1) is essential to assess the strain-hardening performance of FRC.

$$\frac{\sigma_{pc}}{\sigma_{cc}} \geqslant 1 \qquad (1)$$

where

σ_{pc} = The post-cracking strength at point B (Fig. 3), which is determined by the fiber bridging capacity.

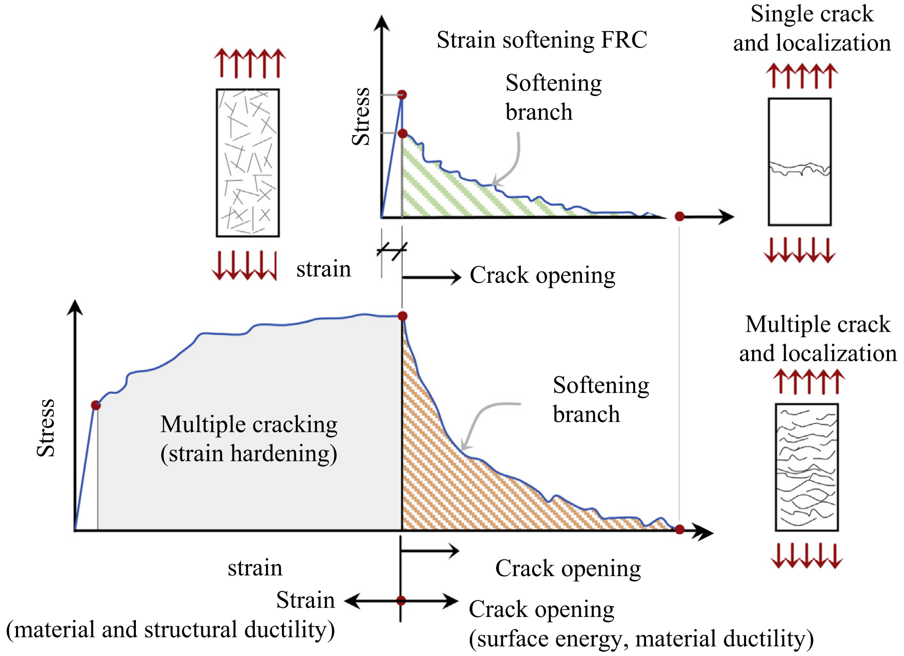

Fig. 3. Typical tensile strain softening and hardening behavior of FRC, HPFRCC and UHPFRCC (Park et al., 2012).

σ_{cc} = The first cracking strength at point A (Fig. 3), which is influenced by the tensile strength of the matrix.

3. Ultra-high performance cementitious composites

The incorporation of fibrous materials in HPCC and UHPCC materials has several advantages. Fibers work as bridges over which the internal strains/stresses can be transferred along the composite systems. Therefore, these fibers stop the concentration of pressures and control the propagation of sizable cracks. UHPCC (also known as "reactive powder concrete") is a combination of HPCC and fibers. Because the ultimate strain of a cementitious composite decreases as its compressive strength increase, the use of fiber is crucial in UHPCC. Improving the microstructure and using the particle-packing mix design method have enabled the production of this superior material. It worth noting that in this mix design method, materials of similar sizes are mixed to enhance the permeability of the cementitious composite. UHPCC exhibits superior strength and durability characteristics with compressive strengths between 150 and 800 MPa and fracture energy levels between 1200 and 40,000 J/m^2. The main differences between UHPCC and HPC are as follows: 1) high content of cement (usually 800–1000 kg/m^3), 2) high content of superplasticizer (usually polycarboxylate-based), 3) high content of silica fume (approximately 25% of the cement) and, 4) low concentration of water (water-to-binder ratio is usually less than 0.2). In addition, the size of coarse aggregate usually ranges from 0.5 to 5 mm (Chan and Chu, 2004; Habel et al., 2006; Garas et al., 2009; Abu-Lebdeh et al., 2010). Note that some researchers limit the particle size of aggregate to 0.5 mm and exclude the use of coarse aggregate to produce superior ultrahigh performance cementitious composites (Richard and Cheyrezy, 1995; Lee et al., 2010; Abu-Lebdeh et al., 2011).

Recently, researchers have indicated that UHPCC (with a strength greater than 200 MPa with standard curing) can be fabricated using a high concentration of mineral admixtures (ground granulated blast furnace slag, fly ash and silica fume that constitutes 25–60% of the total cementitious content) (Yazici, 2007; Yazıcı et al., 2009). The strength gain of these materials begin 32 h after mixing with water and yields insignificant development in strength after 90 days (Habel et al., 2006). Note that some waste materials, such as rice husk ash, recycled glass cullet and local natural sands, were employed as cement supplementary materials to produce an economical UHPCC. A successful attempt to design UHPCC (with a compressive strength of 150 MPa) with a low cement concentration (approximately 650 kg/m^3) was achieved using the Andreasen & Andersen particle packing model (Yu et al., 2014).

3.1. Use of mono- fibers in UHPCC

Short steel fibers of various aspect ratios and strengths were usually incorporated in UHPCC with various contents (more than or equal 2%) to achieve multi-cracking behaviors and increase strain the capacity (up to 1%) (Habel et al., 2006; Garas et al., 2009; Yazıcı et al., 2009). UHPCC can be grouped into the following four levels based on their behavior under loading as described in Fig. 4 where σ_{cc} is the cracking stress, ε_{cc} is the cracking strain, E_{cc} is the elastic modulus and σ_{pc} is the post cracking strength.

A number of studies have utilized a low concentration of steel fibers ($\leq$1.0%) to achieve high performance self-compacted cementitious composite and material with a maximum post-cracking tensile strength of 37 MPa with a minimum energy absorption capacity of 50 kJ/m^3 (Level 4 in Fig. 4) (Deeb et al., 2012; Wille et al., 2014). However, the achievement of high-energy absorbing material was not confirmed at this level. Previous studies have suggested discrepancies in the properties of UHPCC composed of smooth, hooked and twisted steel fibers (Wille et al., 2014). This is due to the high fiber-matrix bond strength. The majority of applications of smooth steel fibers have been utilized to develop UHPCC with tensile strength that is comparable to composites composed of deformed fibers. Regarding the mix design of HPC, which incorporates mono-fibers, substantial efforts have primarily involved steel fibers. Different mix-design methods had been employed, such as the re-proportioning method (Nataraja et al., 2005), the stiff mixtures method (Dvorkin et al., 2011) and the modified Andreasen & Andersen particle packing method (Yu et al., 2014). In the re-proportioning method, several trial mixes are prepared to evaluate the water-to-binder and aggregate-to-binder ratios via optimization of the workability, 28-day strength, and durability properties. Due to the superior mechanical and durability performance of UHPCC, information on the mix design of UHPCC is available. Note that few studies have attempted to optimize the fiber content and length to achieve a single goal (such as to prevent spalling) (Bilodeau et al., 2004). In addition, a material numerical model for UHPCC has not been developed and few fuzzy-genetic models for HPCC are available (Altun et al., 2013).

An UHPCC with superior ductility was developed using engineered cementitious composites (ECC). These composites typically contain approximately 2% volume of fibers. Using a micromechanics-based approach to the mix design, which involves careful matching of the matrix strength and the fiber pullout strength, maximum tensile strain capacity values in the range of 3–7% are possible, as shown in Fig. 5. This material can be placed using many approaches, such as ordinary casting techniques, placement as a self-consolidating cementitious composite, and shotcreting. However, the initial cost of this material is substantial, which can increase sustainability and the service life of structures, because they produce better durability with minimal cracking in harsh environmental conditions (Mindess, 2014). Instead of brittle fracture, experimental investigations have demonstrated that the plain ECC exhibits plastic yield behavior. It should be noted that the ECC has been investigated for structures rehabilitation and retrofitting to tolerate impact loads (Mehta and Monteiro, 2006).

DUCTAL® is a commercial example of a UHPCC that is composed of steel fibers or PP fibers. The compressive and flexural strength of DUCTAL® reinforced with steel fibers are 150–180 MPa and 32 MPa, respectively. However, the same material has a compressive strength and flexural strength of 110–135 MPa and 24 MPa, respectively, when reinforced with PP fibers. Typical mix proportions of these materials are listed in Table 2. Another commercial example of mono-fiber UHPCC is BSI®-CERACEM, which has achieved a compressive strength of 165 MPa and a tensile strength of 8.8 MPa. Recently, this material was used to build the toll gate rooftops for the new Millau viaduct in the south of France. This self-consolidating material was reinforced with 2.5% steel fibers. In addition, UHPCC reinforced with mono-fiber, which is known as "reactive powder cementitious composite (RPC)", has been developed by a group of researchers in France using different curing techniques. It worth noting that few studies have investigated the effect of mono-fiber with different sizes (i.e., blending micro-fiber and macro-fibers with the matrix) (Kim et al., 2011). Enhanced structural properties have been achieved by increasing the concentration of micro-fibers.

3.2. Use of hybrid of fibers in UHPCC

The recent advances in materials science and engineering and the associated technology have facilitated the development of hybrid cementitious materials with superior strength and durability properties. These materials have very low water-to-binder ratio

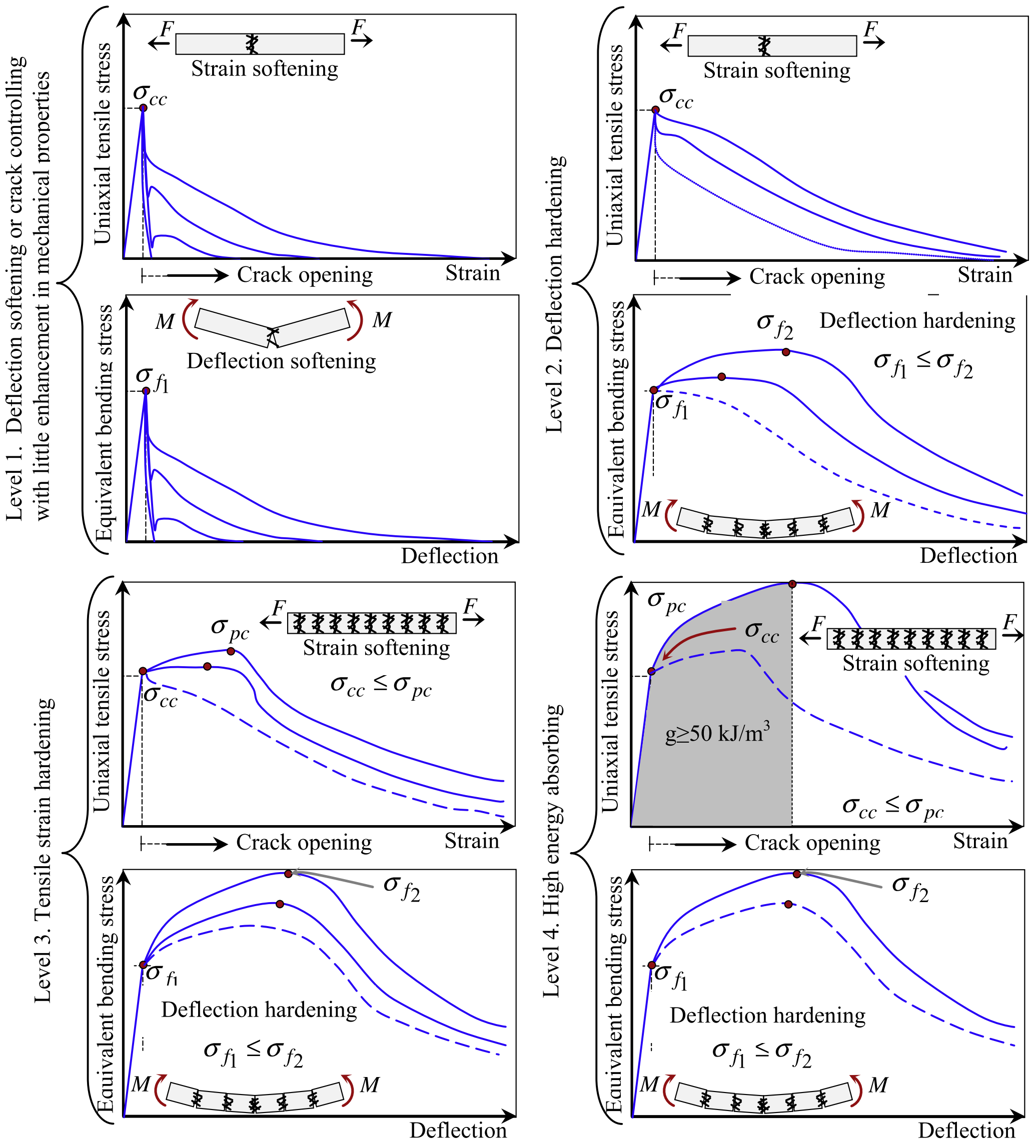

Fig. 4. Performance levels of UHPCC (Wille et al., 2014).

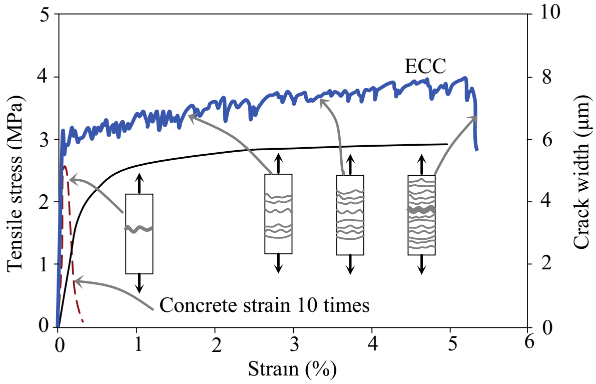

Fig. 5. Tensile strain hardening performance of ECC (Mehta and Monteiro, 2006).

and high contents of silica fume, fibers and superplasticizer. Moreover, their design involve using particle packing density method and exclusion of large particles (>2 mm). However the high cost

Table 2
Content of constituent materials for commercial UHPCC in kg/m^3(Mindess, 2014).

	DUCTAL®	CEMTEC multi-scale®
Portland cement	710	1050.1
Silica fume	230	268.1
Crushed quartz	210	
Sand	1020	514.3
Water	140	180.3
Fibers	40–160(1)	858 (2)
Superplasticizer	10	44

(1) Either steel or PP fibers (13 mm × 0.2 mm).
(2) A combination of three different geometries of steel fibers.

of a UHPCC, it can tolerate high and impact loading with least repairs cost. The use of fiber-hybridization is becoming potent system for designing a UHPCC. The aim of using hybrid combinations is to generate synergetic interaction between fibers that may boost the advantages those can be achieved by mono-fiber. Pioneer researchers classify synergy into the following categories (Mindess, 2014).

3.2.1. Binary combination of fibers in UHPCC

The hybrid combination of fibers is advanced system of composite reinforcement that contains two or more fibers. The goal of this fiber hybridization is to achieve better performance of the cementitious composite compared with the performance with individual fibers. The majority of the produced hybrid fiber-reinforced cementitious composites contain metallic and synthetic fibers. Numerous researchers have suggested that the use of hybrid fibers improves the mechanical properties of cementitious composite (Soroushian et al., 1993; Yao et al., 2003; Chen and Liu, 2005; Sivakumar and Santhanam, 2007a,b; Topcu and Canbaz, 2007). These properties include 1) the compressive strength, 2) the splitting tensile strength, and 3) the flexural strength and flexural toughness. The predominant combination was steel-PP because it has demonstrated improved performance of cementitious composite in its fresh and hardened states. Hybridization of steel-PP increases the capability to resist the initiation and propagation of cracks (Banthia and Nandakumar, 2003). With respect to mono-fiber composites, those containing hybrid system of fibers have more compressive strength, splitting tensile strength, and tensile strain capacity with strain-hardening performance (Ahmed and Maalej, 2009; Funke et al., 2013; Chi et al., 2014). Moreover, composites with hybrid fibers are characterised by their elevated flexural strength/toughness (Sivakumar and Santhanam, 2007a,b; Stähli and Van Mier, 2007). These enhancements may ascribed to the result that the inclusion of fibers enhances both pre- and post-fracture properties of HyFCC flexural specimens, as shown in Fig. 6. An investigation of the micro-crack pattern of cementitious composite reinforced with nonmetallic fibers is needed.

In addition to the material mechanical properties, the research has investigated the performance of structural elements fabricated with hybrid fiber UHPCC. In this regard, the following structural characteristics of HyFCC have been investigated: 1) Flexural strength/toughness of hybrid fiber UHPCC structural members (Ahmed et al., 2007; Banthia and Sappakittipakorn, 2007; Soulioti et al., 2009; Lau and Pam, 2010; Banthia et al., 2014; Rashiddadash et al., 2014; Yap et al., 2014), 2) shear toughness of hybrid fiber UHPCC structural members (Ding et al., 2010), 3) Impact resistance of hybrid fiber UHPCC structural members (Nataraja et al., 2005; Mohammadi et al., 2009; Soe et al., 2013; Mo et al., 2014), 4) Pullout behavior of hybrid fiber UHPCC structural members (Soe et al., 2013), and 5) Fatigue strength of hybrid fiber UHPCC structural members (Singh, 2011; Ganesan et al., 2014). It was reported that steel-PVA hybrid composites have higher flexural strength compared to steel-Polyethylene (PE) hybrid fiber UHPCC, which is attributed to the strong bond between PVA fibers and the matrix compared to PE fibers (Ahmed et al., 2007). However, as shown in Fig. 7, the steel-PE fibers composites are showing higher flexural tensile strain hardening capacity compared to steel-PVA fibers composites, which is due to higher tensile strength of steel-PE hybrid combination compared to steel-PVA hybrid combination. It should be noted that all combination of steel-PVA and steel-PE hybrid composites are exhibiting multiple cracking behavior under bending.

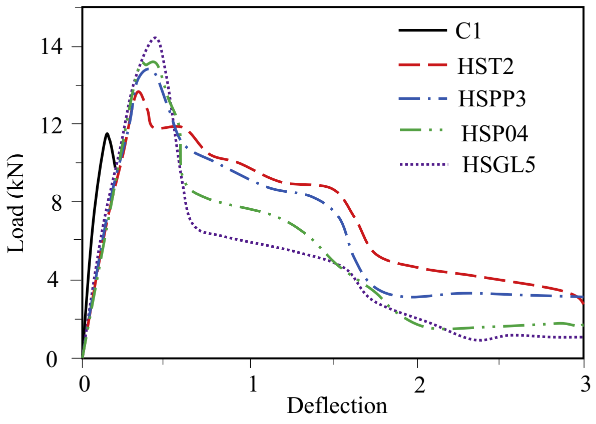

Fig. 6. Typical load–deflection plot for various hybrid fiber cementitious composites (Sivakumar and Santhanam, 2007a,b).

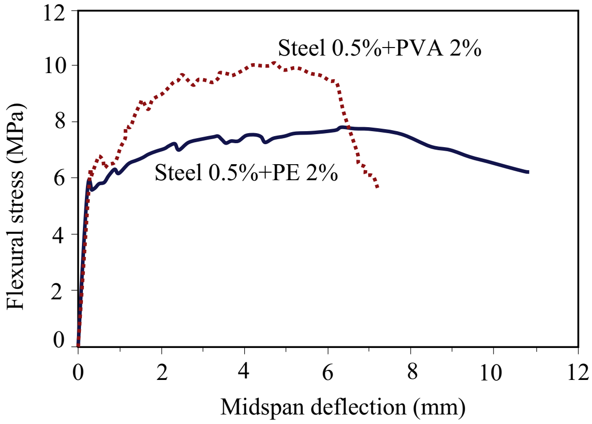

Fig. 7. Flexural stress–deflection curves for hybrid composites (Ahmed et al. 2007).

3.2.2. Ternary combination of fibers in UHPCC

Not only binary combination of steel fibers was used to develop hybrid UHPCC. But also, the ternary combination was attempted. Very limited studies were taken a combination of three different types in consideration (Pereira et al., 2012). However, most studies using this method of hybridization have been using one type of fibers with different geometries, such as the multi-level (micro- and macro-) steel fibers. A commercial example of such material is CEMTEC multiscale®. This material has high cement and fiber contents and has a very low permeability and achieving flexural strengths of 60 MPa. Typical mix proportions of CEMTEC multiscale® are given in Table 2.

3.3. The potential use of UHPCC

Although the use of fiber-reinforced cementitious composite is not fully adopted in the building design codes of reinforced cemen-

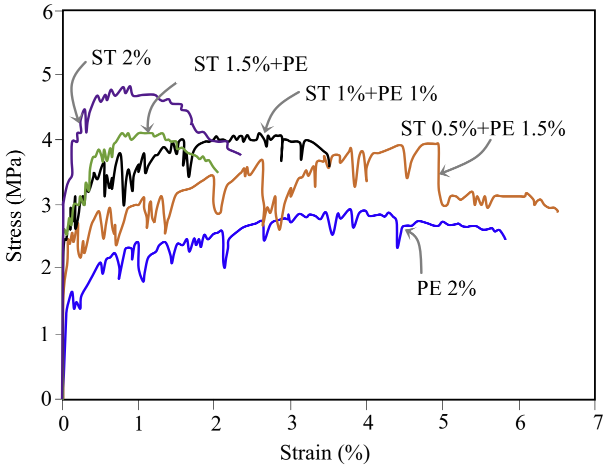

Fig. 8. Effect of hybrid reinforcement in the strain hardening behavior (Maalej et al., 2012).

titious composite, they can be used in many structural applications (Mindess, 2014). Hybrid fiber cementitious composites can be used in a number of structural applications in civil engineering, such as for 1) blast/impact resistant, 2) renovation of masonry works, 3) retrofitting of reinforced concrete, and 4) harsh environmental conditions. Hybrid fiber-reinforced cementitious composites have enhanced properties that satisfy the challenging requirements of these applications. In addition, ultra-high performance cementitious composite demonstrated efficiency for use in prestressed and precasted cementitious composite. Thus, they are appropriate materials for shielding structures with minimum permeability. However, the particle-size grading of the mixture and the curing conditions of these composites should be properly designed to achieve enhanced properties of UHPCC (Richard and Cheyrezy, 1995; Yazici, 2007; Garas et al., 2009; Yazıcı et al., 2009; Deeb et al., 2012; Yu et al., 2014). In these applications, hybrid fiber UHPCC is recommended because they are cost- effective and exhibit a strength comparable to the strength of mono-fiber composites and better strain capacity and crack bridging capacity at different scales, as shown in Fig. 8.

4. Conclusions

The conclusions of this state-of-art report are summarized as follows:

- The intrinsic drawbacks of cementitious composites are considerably minimized as consequences of using innovative constituent materials, getting better understanding of their mechanics and the involved technologies that escalate their demand.
- A cementitious composite with superior mechanical and durability properties must contains ultrafines such as silica fume, fly ash, slag, metakaolin,..etc.
- Still, no overall coincidence on the most favorable dosage of these fine materials; however, mix design application is essential to consider the inconsistency of the ingredient particles and the environmental situation.
- It is well-known that increasing the compressive strength for a cementitious composite does not involve enhancement of its all properties, especially tensile strength and strains. To overcome this drawback, a significant evolution is followed by the incorporation of short, discontinuous and randomly distributed fibers. In this regard, several synthetic fibers have been incorporated in a mono or hybrid states to enhance various properties such as tensile strength, strain capacity, modulus of elasticity, resistance to impact and abrasion, and dimension stability.
- Fiber hybridization have been implemented using various kinds of fibers or mono-fiber with different sizes. Numerous investigators show the favored usage of fiber hybridization compared to single fibers, which have been attributed to the synergetic interactions of hybrid fibers.
- In recent times, tons of fiber-based cementitious composites have been employed in slabs on grade, shotcrete, and precast members. The prospective structural implementation of UHPCC perhaps include: blast/impact resistant, renovation of masonry works, retrofitting of reinforced concrete, and harsh environmental conditions.

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