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# Development of ultra-high performance engineered cementitious composites using polyethylene (PE) fibers

Ke-Quan Yu [a,b], Jiang-Tao Yu [a], Jian-Guo Dai [b,*], Zhou-Dao Lu [c], Surendra P. Shah [d]

[a] Department of Civil Engineering, Tongji University, China
[b] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, China
[c] Department of Civil and Environmental Engineering, Tongji University, China
[d] Walter P. Murohy Professor of Civil Engineering (emeritus), Northwestern University, USA

## HIGHLIGHTS

- The tensile, compressive and flexural behaviors of UHP-ECC were systematically investigated.
- UHP-ECC combines the strain-hardening and multiple crack characteristics and the high strength of mortar matrix.
- Ultra-high-molecular-weight polyethylene (PE) fibers with a high aspect ratio were deployed.
- The digital image correlation (DIC) technique was utilized to monitor the crack patterns during the tests.
- Scanning electron microscope (SEM) analysis was conducted to understand the microstructure of UHP-ECC.

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## ABSTRACT

Ultra-high performance engineered cementitious composites (UHP-ECC), which combines the strain-hardening and multiple crack characteristics and the high strength of mortar matrix, was investigated in this study. The tensile strength and elongation of the UHP-ECC achieved were 20 MPa and 8.7%, respectively. For the production of UHP-ECC, ultra-high-molecular-weight polyethylene (PE) fibers were deployed to reinforce the ultra-high strength mortar while special attention was paid to the mix process to ensure satisfactory fiber dispersion. The tensile stress-strain curves, the compressive strength and elastic modulus, and the flexural behavior of UHP-ECC were investigated to understand its mechanical performance. The digital image correlation (DIC) technique was utilized to monitor the crack patterns of UHP-ECC during the tensile and flexural tests. In addition, Scanning electron microscope (SEM) analysis was conducted to achieve an in-depth understanding of the microstructure of UHP-ECC.



## 1. Introduction

Strength, ductility and durability are crucial properties for development of modern concrete technology. High-strength concrete facilitates the design of size-efficient structural members and provides additional strength safety margins (particularly in compression) for structures. High ductility concrete prevents catastrophic structural collapse by absorbing massive amounts of energy during extreme load/displacement events-such as earthquakes and blasts, while the use of highly durable concrete extends the service life of concrete infrastructure, reduces the life-time maintenance cost and improves the infrastructure sustainability.

Ultra-high performance concrete (UHPC) with a high compressive strength up to 200–800 MPa [1–5] have been studied worldwide. In general, the cement dosage of UHPC is over 800 kg/m$^3$ and the water/binder ratio is lower than 0.20 while high-range water-reducing admixture (HRWR) is required for use to achieve the high compressive strength. Furthermore, the UHPC is composed of very fine powders, such as crushed quartzite and silica fume. The basic composition for the production of UHPC was well explained in Richard and Cheyrezy (1995) [1]. In the report published by Federal Highway Administration (FHWA 2013) [6], UHPC is defined for those cementitious-based composites materials with discontinuous fiber reinforcement, compressive strengths over 150 MPa, pre- and post-cracking tensile strengths above 5 MPa. No particular requirement is imposed on the ductility of UHPC although in the report an idealized uniaxial tensile mechanical response of UHPC is recommended [6]. In contrast, strain

* Corresponding author.
*E-mail address:* cejgdai@polyu.edu.hk (J.-G. Dai).

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hardening fiber cementitious composite (i.e., engineered cementitious composites, ECC) featuring with excellent ductility and multiple instances of micro-cracking with self-controlled widths [7–13] with the addition of Polyvinyl Alcohol (PVA) fibers at a volume fraction of 2%, can achieve a tensile strain capacity up to 3–5%. The micro-crack width characteristic is appreciated because it improves the durability of concrete and entitles the fiber composites with self-healing effects [7,14].

Recently researchers have spent significant efforts in developing ultra-high performance fiber-reinforced concrete (UHPFRC) with strain hardening properties [15–25]. Fig. 1a and b presents a summary of the compressive strength, tensile strength and tensile strain capacity of the UHPFRCs found in existing literature. It is seen that, in most cases, the achieved tensile strain capacity was around 0.6% based on the tests of dumbbell specimens under direct tension, while the tensile and compressive strengths range from 10 to 18 MPa and 80 to 220 MPa, respectively. It should be noted that the nature of materials and methods of reinforcement may affect the compressive and tensile strength. Therefore the data presented in Fig. 1 mainly reflect that there is a lack of good combination of strength and ductility in existing UHPFRCs. It may not provide an accurate quantitative comparison of the material performance of these UHPFRCs developed by different research groups. In particular, the tensile and flexural behaviors of ultra-high-performance fiber reinforced cement composites, such as UHPFRC, UHP-ECC. are strongly influenced by the fiber orientation and dispersion [26–29] as well as the size effect [30–31]. Nevertheless, it is worth mentioning that Ranade (2013) developed successfully a UHPFRC with the 28 days compressive strength of 150 MPa, tensile strength of around 15 MPa and a tensile strain capacity of 3.3% [32,33]. This development truly combined the high strength of mortar matrix and high tensile ductility. However, saturated cracks could not be developed in their direct tensile tests and the observed residual crack width was much wider than often desirable for improved durability.

The present paper presents a further step development of the UHPFRC, which aims to retain high tensile strain, strain hardening and multiple microcracking characteristics, while achieving high tensile and compressive strengths. This UHPFRC is termed as UHP-ECC in this paper. The target values of its tensile strain capacity (6–10%), tensile strength (16–20 MPa), and compressive strength (>100 MPa) are indicated in Fig. 1. It has the intrinsic multiple microcracking behavior under tensile loading and its residual crack width should be no more than 100 μm.

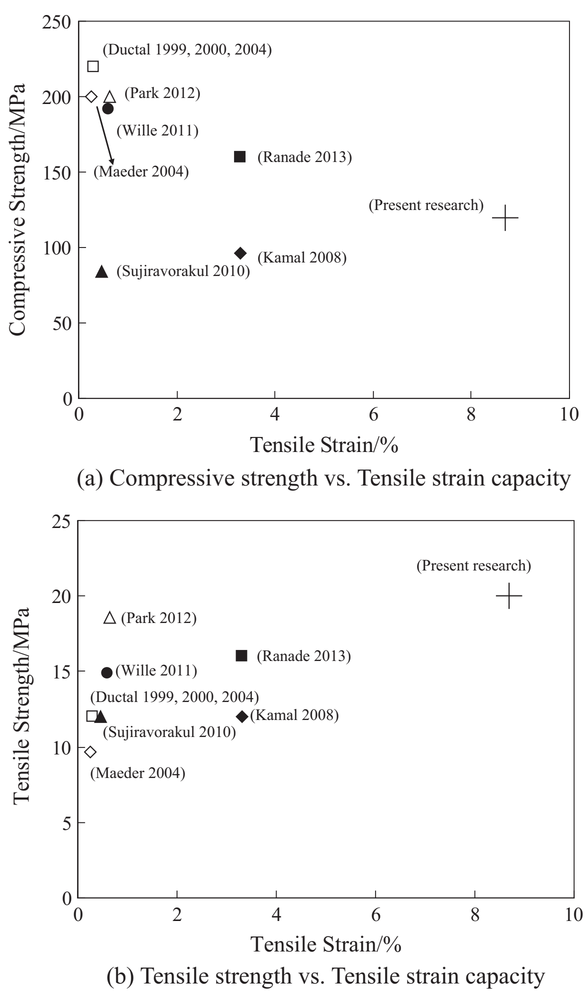


**Fig. 1.** A summary of the strength and ductility of UHPFRC in existing literature.

## 2. Theoretical background

The concept of ultra-high performance concrete (UHPC) was utilized to realize a densely packed homogenous cementitious matrix [2] to achieve a high compressive strength. While for achieving high tensile ductility micromechanics-based strain hardening criteria should be satisfied [8,32,33]. Hence, the design approach of UHP-ECC entailed integrating these two approaches into a single material by adapting the matrix features of UHPC in combination with a high-performance fiber with an aspect ratio and interfacial properties that satisfy the micromechanics-based tensile strain-hardening criteria.

In order to attain the multiple cracking states, two conditions should be satisfied [34,35]. The first condition is that the matrix tensile cracking strength $\sigma_c$ must not exceed the maximum fiber bridging strength $\sigma_0$.

$$\sigma_c < \sigma_0 \tag{1}$$

where $\sigma_c$ is determined by the matrix fracture toughness $K_{\mathrm{m}}$ and preexisting internal flaw size $a_0$.

The second condition is that the crack tip toughness $J_{\mathrm{tip}}$ to be less than the complementary energy $J'_{\mathrm{b}}$, which can be calculated from the bridging Stress $\sigma$ versus crack opening $\delta$ curve, as illustrated in Fig. 2 [34,35].

$$J_{tip} \leqslant \sigma_0\delta_0 - \int_0^{\delta_0} \sigma(\delta)d\delta \equiv J'_b \tag{2}$$

$$J_{tip} = \frac{K_m^2}{E_m} \tag{3}$$

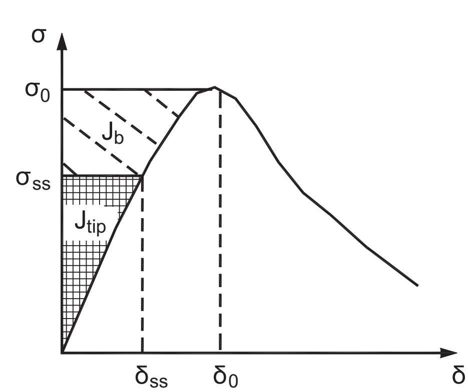


**Fig. 2.** Typical $\sigma$ ($\delta$) curve for tensile strain-hardening composite.