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A strain-hardening cementitious composites with the tensile capacity up to 8%

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HIGHLIGHTS

- The ultra-high ductile cementitious composites (UHDCC) has the averaged tensile strain ranging 8% to 12% corresponding to the peak stress.
- The compressive strength of UHDCC cubes ranges from 45.9 MPa to 121.5 MP, while the cylinder strength ranges from 20 MPa to 90 MPa.
- In some cases, the compressive strain hardening behaviors was observed.
- The ultra-high ductility of UHDCC originates from the ultra-high crack bridging capacity.

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ABSTRACT

Fiber reinforced concrete (FRC) has advantage in tensile ductility over the normal concrete. Among the family of FRC, engineered cementitious composites (ECCs) are known for their strain-hardening behavior and high tensile capacity. However, even the ductility of normal ECC is not sufficient to support it to be a solo structural material. To improve the tensile capacity of ECC to a higher level, a new cementitious material, ultra-high ductile cementitious composites (UHDCCs), is developed with the specially selected polyethylene (PE) fibers. The present paper introduces the mixture process and a series of mechanical tests on UHDCC with 3 different mixtures. Uniaxial tension test indicated the outstanding strain hardening and saturated multiple cracking properties of UHDCC. At ultimate state, the crack spacing of UHDCC was generally less than 2 mm with the residual crack widths less than 100 μm. The tested UHDCC exhibited the averaged tensile strain at peak stress over 8% with some mixture even exceeding 12%. UHDCC had the compressive strength ranging from 45.9 MPa to 121.5 MPa. The strain hardening behaviors were observed in the compression test of UHDCC-1 and UHDCC-2. To figure out the formation of tensile capacity, comparative studies were conducted on the pseudo-strain hardening (PSH) indexes of UHDCC. The test results demonstrated that the ultra-high ductility of UHDCC originates from the ultra-high crack bridging capacity. It implies that with sufficient bridging provided by fibers, UHDCC can maintain the tensile ductility at an amazing level, despite the high fracture toughness of matrix. Additionally, analysis demonstrates that the classic PSH criterion is still valid for quantifying the tensile capacity of UHDCC.

1. Introduction

In modern concrete technology, two superior mechanical properties are extensively concerned by researchers. One is the ultra-high strength, for example, ultra-high-performance concrete [6,10,39]. To achieve the ultra-high compressive strength, fine powders, such as quartz flour, silica fume and glass powder are used in mixture to ensure a highly dense matrix. Generally, the cement dosage of UHPC is more than 800 kg/m^3 with water/binder ratio less than 0.20. Literature indicates UHPC has the compressive strength of 200–800 MPa [30,4,47,44,45,48]. The high-compressive strength of concrete promises the construction of size-efficient structural members and more strength margins in structural safety. However, concrete with higher strength generally has a more brittle nature [7]. Hence in UHPC production, short steel fibers, usually at 1–4% volume fraction, are utilized to reduce the brittleness of matrix [29]. Nevertheless, the fiber reinforced UHPC always featured by a tension-softening property after peak stress or a low strain-hardening property with the tensile capacity at about 0.5% [31,40,27,1,24–26,34]. Due to the insufficient ductility,

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the tensile strength of UHPC can be hardly considered as a part of structural capacity at ultimate state.

Another category of high performance concrete is the pseudo-strain hardening (PSH) cementitious composites, e.g., the engineered cementitious composite (ECC) [17,19] and the strain-hardening cement composites (SHCC) [13,35,36]. ECC is a special class of high-tensile-ductility concretes. Based on the micromechanics design theory, ECC possesses the tensile capacity of more than 3%, while keeping the fiber volume fraction no more than 2% [20,21]. The ductility (tensile strain capacity) of ECC is about two orders of magnitude higher than that of normal concrete. In addition, ECC exhibits multiple cracking during strain-hardening process with micro-crack width less than 100 μm [22], making it a highly durable material in a wide variety of environmental exposure conditions. Due to its high tensile ductility and durability, ECC is attractive in a variety of civil engineering applications, such as road pavement, high-rise building and structural repair and retrofit [28,18]. Nevertheless, there are still some limitations in the mechanical property of ECC, which hinders it from wider engineering applications. Particularly, to guarantee the stability of strain-hardening and high tensile capacity, engineers have to control the fracture toughness of matrix. In some cases, special aggregates, like polypropylene beads or crumb rubbers, are added as artificial flaws to reduce the fracture toughness [37,50,51,49]. As an adverse effect, the compressive strength and cracking strength of normal ECC are relatively lower than that of high-strength concrete.

In recent years, a group of PSH cementitious composites with high strength were developed. The mechanical property of ultra-high-performance strain-hardening cementitious composites (UHP-SHCC) was reported in the previous research [15,16]. The best performing UHP-SHCC has an average compressive strength of 96 MPa and a tensile ductility of 3.3% after 14 days curing Kamal et al. [15]. Ranade et al. [32,33] developed the high-strength, high-ductility concrete (HSHDC) with the compressive strength exceeding 150 MPa, direct tensile strength of around 15 MPa and tensile strain about 3–4%. This material combines the high strength and high ductility for the first time. However, the cracks of HSHDC were not fully triggered under the uniaxial tension, and the residual crack width was much wider than the polyvinyl alcohol (PVA) ECC specimens [19].

Some of the aforementioned materials have impressive ductility, but their tensile capacities are still insufficient to make themselves the solo structural materials, especially at extreme condition. In civil engineering, to ensure the reliability at the extreme condition, both the strength and ductility of structural material are highly concerned in structural design. A variety of standards and codes set mandatory requirements to the elongation of steel reinforcement, of which the minimum elongation is no less than 9%, see Table 1. Moreover, Chinese code [9] requires the strain at peak stress in steel used in seismic building no less than 9% and the elongation up to 20%. To date, no cementitious material, including the most ductile ECC, can meet such a high-level requirement. Therefore, although some of the high performance concretes did act as the secondary reinforcement in structure, it is still too early to say they could replace steel bar and make themselves the real reinforcement at the extreme condition.

The present study aims to develop an unprecedented cementitious material. Besides high tensile strength, the material should have the tensile capacity up to 8%, approaching the ductility level of steel. Meanwhile, all the mechanical characteristics of ECC, like the strain hardening property, the saturated multiple cracks, etc., should be maintained to ensure the durability of material in extraordinary environment. The ultra-high ductile cementitious composites, in short UHDCC, has the prospect of becoming a solo structural material for the future advanced engineering, like steel-free structure and 3D construction printing, etc.

The present paper introduces the development of UHDCC mixture and a series of tests on the macro-mechanical properties of UHDCC, including tensile behavior, compressive behavior and cracking pattern. Additionally, single-crack tension tests and matrix fracture toughness tests were conducted to explain the phenomenon of high tensile ductility in UHDCC.

2. Materials and experimental methods

2.1. Material and specimen preparation

The materials and mix proportions adopted in the present study are listed in Table 2. PII. 525 Portland cement was used in all 3 mixtures, named UHDCC-1, UHDCC-2 and UHDCC-3, respectively. Class F fly ash was used as one of the main binders for UHDCC-1 and UHDCC-2. For UHDCC-3, more reactive powders, i.e., the ground granulated blast furnace slag (GGBFS) and the silica fume (SF) were adopted to achieve the high strength and high toughness of matrix. The particle size and chemical properties of ingredients are listed in Fig. 1 and Table 3. For comparison, the mixture proportions of UHDCC-1 are identical to the widely adopted M45 in PVA-ECC mixture [38], except for fiber type and the dosage of polycarboxylic high-range water reducer (HRWR).

Polyethylene (PE) fiber with high-molecular and high strength was used as reinforcement for cementitious matrix. The geometric

Table 1
Various standards and codes of steel reinforcement.

Standard	Grade	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)
GB1499.2-2007	HRB335/335E	335	455	17
	HRB400/400E	400	540	17
ASTM A615&A615M-04a	GRADE40	280	420	12
(2004)	GRADE60	420	620	9
JIS G3112-(2004)	SD295A	⩾295	440–600	17
	SD295B	295–390	⩾440	17

Table 2
Mixture proportion of UHDCC (kg/m^3).

Mixture ID	Sand	Cement	Fly ash	GGBFS	SF	Water	HRWR	Fiber
UHDCC-1	474.4	593.0	711.6	–	–	313.1	4.0	19.0
UHDCC-2	601.1	936.7	201.4	–	–	361.3	4.2	19.0
UHDCC-3	700.0	500.0	–	650	150	230.0	25.0	19.0