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Combined effect of coarse aggregate and fiber on tensile behavior of ultra-high performance concrete

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HIGHLIGHTS

- Tensile behavior of UHPC incorporating coarse aggregate is investigated.
- Coarse aggregate brings an impairment to utilization efficiency of fiber.
- Coarse aggregate can be successfully introduced into system of UHPC.
- Fiber type has almost no effect on strain hardening behavior of this UHPC.

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ABSTRACT

In this study, combined effect of coarse aggregate and fiber properties on tensile behavior of ultra-high performance concrete (UHPC) was investigated. Four replacement levels of coarse aggregates (0%, 15%, 25%, 35% by volume of mortar) and four types of steel fiber (three micro-fibers with a shape difference and one macro-fiber) were considered. Results showed that replacement level of coarse aggregate has a critical value of 25% and different fiber types act similarly in regard of compressive strength. Coarse aggregate brought impairment to bonding strength and utilization efficiency of fiber, especially for deformed ones. Furthermore, coarse aggregate could be successfully introduced into system of UHPC without impairing its tensile properties at a favorable replacement level ($\leqslant 25\%$). In addition, phenomenon of strain hardening behaviors of UHPC incorporating coarse aggregate could be triggered by further increasing fiber dosage to larger than 2.5%, however, it was independent of fiber type due to combined effect of coarse aggregate and fiber bridging.

1. Introduction

For the design of concrete structures with good long-term performance, insight into microstructure of concretes and its relationship with performance is of paramount importance [1–2]. As result, ultra-high performance concrete (UHPC) appeared, a new class of construction material with outstanding properties. UHPC has the remarkable mechanical properties and extremely low porosity, which was obtained through dense particle packing. Therefore, it implies that UHPC performs a high durability, improved resistance against various chemicals as well as higher penetration resistance [3–5]. Presently, there has been increasing interest in the use of UHPC as a vanguard product for industrial and structural applications in the past few years, such as coupling beams in high-rise buildings, precast members, infrastructure repairs and special facilities like nuclear waste storage containers [6–7].

Basic principles of developing UHPC have been established by Richard and Cheyrezy in 1995 [3]. Normally, UHPC is designed to be a super plasticized concrete by replacement of traditional coarse aggregates with fine sand [8]. In addition, thermal treatments of UHPC are mainly preferred in order to reduce curing time and increase mechanical strengths [9–10]. The well-chosen raw material and sophisticated technical procedures make it too costly to meet the demand of large-scale project engineering. To reduce its cost, natural sand has been employed successfully as a substitute for expensive quartz sand without impairing its mechanical strengths [6,11]. Specially, coarse aggregate is recently introduced into the system of UHPC to further reduce its cost and broaden its application [12–13]. Firstly, coarse aggregate is more economic efficiency than other raw materials used. Secondly, it makes UHPC possess a better shrinkage performance and lower hydration temperature rise [14], which is attributed to the decreased binder content and its strong restraint on shrinkage of UHPC. With the inclusion of coarse aggregates, UHPC can also easily possess a high compressive strength of 180 MPa as well as excellent workability

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[13]. Unfortunately, the interface around coarse aggregate would become more weak and more flaws are accompanied [15], resulting in a poor tensile performance of concrete, especially for that with a low water to binder (W/B) ratio, i.e., UHPC [16]. Therefore, for UHPC incorporating coarse aggregate, the optimal content of coarse aggregate should be investigated carefully in order to obtain better tensile properties.

In addition to the dense microstructure obtained by maximizing packing density with very fine minerals (silica fume, slag, fly ash, etc.) [8,17–20], superior performance of UHPC is also achieved by enhancing matrix toughness with optimal steel fiber reinforcement (smooth, twist, hook, hybrid etc.) [9,21–25]. Effects of steel fiber on the tensile behavior of UHPC without coarse aggregate have been widely reported in literatures [5,21,24,26–29]. It is accepted that the tensile behavior of UHPC is controlled by bond behavior between fiber and matrix, which is attributed to matrix properties (including particle size and mechanical properties), fiber properties (including geometry, length, diameter, volume content, and mechanical properties) and interfacial properties. Some researches show that UHPC produced from macro-fibers with deformed geometry (i.e. hooked, twist) provides the excellent performance with respect to post cracking strength, strain capacity and multiple cracking behavior, which is attributed to the high utilization efficiency [21,24]. However, utilization efficiency of smooth fiber can be improved by designing ultra-high strength matrix, which allows development of high tensile stress in the smooth fiber [26]. When coarse aggregates are introduced into UHPC, the matrix should be tailored carefully to obtain a high strength and a better bond condition. Besides, fiber distribution characteristic is another critical factor influencing post-cracking behavior of UHPC [29–31]. In addition to casting method, fiber properties (i.e. geometry, shape, volume content), fluidity and shape of forms, the existence of coarse aggregates have a strong effect on fiber distribution [31–32]. Consequently, pull-out behavior of varying steel fiber in concrete behaves differently compared with that without coarse aggregates. Therefore, to use UHPC incorporating coarse aggregate in civil infrastructure, combined effect of coarse aggregate and fiber on the tensile behavior of UHPC must be carefully investigated. However, to author's knowledge, there is little information available in literatures about the combined effect.

Accordingly, in this paper, combined effect of coarse aggregate and fiber on tensile behavior of UHPC was studied. Three types of steel micro-fibers with varying geometry and one type of steel macro-fiber were applied as reinforcement. Tests had been done to obtain overall tensile stress-strain curves of UHPC. Bonding behavior between these fibers and matrix was also performed to analyses combined effect of coarse aggregates and fibers.

2. Experimental program

2.1. Raw materials

Portland cement, with a strength class of 52.5 conforming to the Chinese Standard GB 175-2007 [33], silica fume, ultra-fine slag and fly ash were used as cementitious materials. Their specific gravities were 3.15 g/cm^3, 1.87 g/cm^3, 2.84 g/cm^3 and 2.33 g/cm^3 respectively, and their chemical properties, determined by X-ray fluorescence (XRF) (ThermoFisher Scientific ARL QUANTX), are illustrated in Table 1. Moreover, their particle size distributions (PSD) determined by nitrogen sorption isothermal measurement (Coulter ONLNISORP 100 CX) are given in Fig. 1. River sand with an apparent density of 2.63 g/cm^3 and grain size below 5 mm was applied. Crushed basalt with an apparent density of 2.86 g/cm^3 and grain size between 5 mm and 20 mm was used as coarse aggregate. A polycarboxylate-based superplasticizer with solid content of 40% was adopted as water-reducer. To investigate effect of fiber on the tensile behavior of UHPC incorporating coarse aggregate, three types of steel micro-fibers and one type of steel macro-fiber were performed. Their properties are given in Table 2 and Fig. 2 shows images of each fiber type.

2.2. Mix proportion

Table 3 provides mix proportion of the UHPC series in which binder composition is invariable and water to binder ratio is fixed at 0.18 for all mixes. The optimized UHPC binder was made with 40% cement, 10% silica fume, 30% ultra-fine slag and 20% fly ash. Single fiber pullout tests were performed on the control specimen without coarse aggregate for avoiding the effect of coarse aggregate on pullout behavior of fiber. In an attempt to optimize coarse aggregate content with respect to tensile behavior, the coarse aggregate was partially replaced in mortar at four replacement levels (0%, 15%, 25%, 35% by volume of mortar). It should be noted that the W/B ratio and superplasticizer dosage of UHPC was initially designed to be invariable for these mixes. However, as the coarse aggregate replacement level increases, a satisfied fluidity (slump >100 mm) of fresh mixture was needed to realize the well-dispersion of coarse aggregate and good homogeneity of matrix. Therefore, the superlasticizer dosage was adjusted for

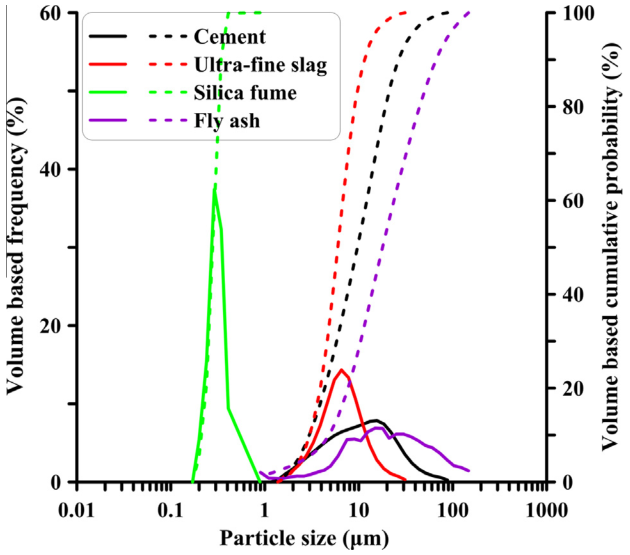

Fig. 1. Particle size distribution of cementitious materials.

Table 1
Chemical composition of cementitious materials.

Composition	Al_2O_3	CaO	SiO_2	Fe_2O_3	K_2O	MgO	Na_2O	SO_3	TiO_2	MnO	LOI
Cement	4.94	63.05	19.95	2.92	0.66	1.33	0.15	3.83	0.27	–	2.9
Silica fume	0.16	0.18	97.31	0.15	0.39	0.82	0.2	0.54	–	0.01	0.24
Ultra-fine slag	16.8	37.1	31.3	0.43	0.35	9.08	0.38	2.8	0.9	0.34	0.52
Fly ash	37.7	4.64	46.6	4.27	0.23	1.41	0.17	1.52	0.78	0.29	2.39