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Mixing design and microstructure of ultra high strength concrete with manufactured sand

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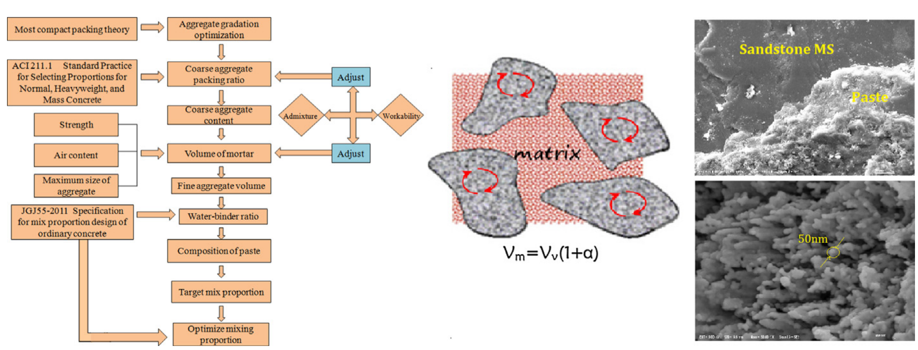
HIGHLIGHTS

- Invented a mix design method based on gradation optimization and volume analysis.
- C120 manufactured sand UHSC is prepared with this novel method.
- The hydration products in UHSC is much finer than that in ordinary concrete.

GRAPHICAL ABSTRACT



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ABSTRACT

Preparation of ultra high strength concrete with manufactured sand is an effective approach to reduce the natural resource depletion and environmental impact of cement concrete industry. In this paper, a new proportion design method was put forward to design ultra high strength concrete with manufactured sand and the microstructure of manufactured sand ultra high strength concrete was observed. Results indicate that the novel method can be applied to design concrete with C120 degree. Ultra high strength concretes prepared with sandstone manufactured sands can have higher strength than those made with river sands. The microstructure of manufactured sand ultra high strength concrete is very dense and the sizes of the hydration products e.g. ettringite, calcium hydroxide and monosulfate Calcium sulfoaluminate hydrates and C-S-H gel become much finer than those in the ordinary concrete. Energy Dispersive Spectrometer result shows that there is no obvious element enrichment at the micro scale of the ultra high strength concrete paste and the hydration products distributes homogeneously. Densely packed and homogenously distributed hydration products with smaller size contribute to the strength of ultra high strength concrete.

1. Introduction

The cement concrete is the largest manufactured product by human society and the basic ingredient for the construction

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industry. However, the cement industry is a high energy consuming, natural resource depleting and carbon-intensive industry [1], by increasing the concrete strength of structures is substantial to reduce the materials especially cement consumption [2]. Therefore, preparing Ultra high strength concrete (UHSC) with manufactured sand (MS) is an approach to improve natural resource efficiency [3] and reduce the environmental impact of the life cycle of concrete [2]. In the past two decades, the infrastructure construction in China kept increasing with average rate more than 10% annually. In 2014, China has built nearly 6.5 billion m^3 of concretes, consumed 2.41 billion tons (nearly 60% of the global) of cements [4], and more than 4.5 billion tons of fine aggregates, mainly river sand (RS) was used in concrete. As a sort of no-renewable natural resource, the river sand has been excessively exploited for decades. Although the share of manufactured sand (MS) keeps increasing rapidly, MS is mostly treated as a low quality sand and just used in middle and low strength degree concretes. To increase the utilization level of the MS, the MS concrete is extensively studied recently in China [5–7]. Shen et al. [8] studied the characterization of MS e.g. particle shape, surface texture and behavior in concrete. Li et al. [5,6] studied the influence of the MS's characteristics (e.g. rock micro fine content, surface roughness, crushing value and rock type) on the strength and abrasion resistance of pavement cement concrete prepared with MS, and the effect of limestone fines content in MS on durability of low- and high-strength concretes. Those studies indicated that MS was not necessarily worse than river sand, and a certain stone powder (micro fine) content in the sand contributes to the strength development, abrasion resistance and durability of the concrete; Ji et al. [7] put forward a mix proportion method of MS concrete based on a theory: minimum paste theory. Nanthagopalan et al. [9] prepared low and medium strength (25–60 MPa) self-compacting concretes (SCC) with MS, and studied the properties of fresh and hardened MS SCC. Cortes et al. [10] studied the rheological and mechanical properties of mortars prepared with natural sand and MS. University of Illinois at Urbana Champaign studied the differences between the MS and RS e.g. shape, micro-morphology and surface [11]. Kim et al. [12] experimentally investigated the fracture characteristics of crushed limestone sand concrete through a Wedge Splitting test, and the results were compared with those of crushed granite sand concrete and river sand concrete. Menadi et al. [13] studied the strength and durability (permeability) of concrete incorporating crushed limestone sand. Most research works indicated that the properties of MS or crushed sand concretes had equal or even better properties than RS concrete in some respects [14–18].

In China, there are more than 87% of the global high-rises under construction, high-rise buildings have to be constructed using high strength concrete or ultra high strength concrete. The ultra high strength concrete refers to the concrete with the strength higher than 100 MPa according to the standard of China [19]. Shi et al. [20,21] studied the hydration and microstructure of an ultra high-strength concrete with cement–silica fume–slag binder, written a thorough review on the raw materials, mixture design, hydration, microstructure and properties of ultra high performance concrete. Tuan et al. [22] studied the hydration and microstructure of ultra high performance concrete incorporating rice husk ash. Schröfl et al. [23] studied the preferential adsorption of polycarboxylate superplasticizers on cement and silica fume in ultra-high performance concrete (UHPC). Yu et al. [24] addressed a mix design of Ultra-High Performance Fibred Reinforced Concrete (UHPFRC) to achieve a densely compacted cementitious matrix. The mix design of concrete is a reminiscent topic of concrete materials science, various kinds of concrete design methods are put forward in the past century [25,26], because the density of MS has a wider variation and mostly higher than RS, so the sand ratio design is much different than ever. The ordinary concrete mix design standard method [19] cannot be applied to the mix proportion of MS concrete directly, so a novel mix design method is a very significant issue to the utilization of MS concrete [7]. Mostly the refined quartz sand is used to prepare UHPC or UHSC with high cementitious materials content and low water demand [20], generally the MS is forbidden to be used in high strength concrete because of the misunderstanding.

In this paper, we use a new method to design the mix proportion of UHSC with MS as well as RS and ordinary coarse aggregates (the maximum normal size in 20 mm). The trial and error method has been used to optimize the mixing proportion of the concrete. The microstructure of this concrete is studied with a field emission scanning electron microscopy, and the elements distribution is observed with an Energy Dispersive Spectrometer (EDS). This paper presented a novel mixing proportion method to prepare UHSC with MS, and verified its possibility and interpreted its mechanism.

2. Materials and methods

2.1. Materials

A commercial Portland Ordinary cement (P.O 52.5) produced in Huaxin Cement Company was used in this investigation. Its properties and chemical compositions are shown in Tables 1 and 2 respectively.

The fly ash, GGBS and silica fume were used as supplement cementitious material in this investigation. The fly ash has a specific surface area of 376 m^2/kg, and the 0.045 mm screen residue of the fly ash was 4.7%. The GGBS meet the S-5 grade with a specific surface area of 403 m^2/kg. The silica fume has SiO_2 content of more than 95%. Table 2 shows the chemical compositions of those materials.

Crushed limestone with two particle size grades, i.e. 10–20 mm and 5–10 mm were used. The particle size distribution is listed in Table 3, its index of crushing is 18.6%, and the apparent density is 2710 kg/m^3. The composite coarse aggregate is a mixture of those two types of crushed stone with proportion of 1:1.

Four kinds of fine aggregates were used in this experimental investigation, i.e. a river sand (RS), a granite MS (MS-G), a limestone MS (MS-L) and a sandstone MS (MS-S). MSs are products from stone broken with a vertical impact crusher. The stone dust is controlled by a water washing process with a wheel type sand washing machine. Their physical properties and size distributions are listed in Tables 4 and 5 respectively.

A polycarboxylate superplasticizer with a trade name as SP-CR8 was used in this investigations, its water-reducing ratio is 28.5%.

2.2. Experimental methods

The ultra high strength concrete was prepared in the laboratory with a testing forced mixer. The mixing times of each mixture are 4 min. The slump of the fresh concretes was controlled at the range of 180–220 mm by adjusting the dosage of water reducer. The cubic concrete specimens were formed in 100 mm × 100 mm × 100 mm mold, then each group of molds was vibrated for 40 ~ 75 s till the concretes became consolidated. After being demoulded at 24 h later, cubic specimens were cured in a chamber with 100% relative humidity and a temperature of 20 ± 2 °C. At the age of 7, 28 and 90 days, then concrete specimens were tested for compressive strength.

The microstructure testing sample was obtained from concrete specimen S-6 at 28 days. The sample contained a sandstone MS particle bonded with a paste bulk. The testing sample was dried by a vacuum dryer and coated with a thin layer of carbon before observation. The microstructure was obtained by a field emission scanning electron microscope (FESEM, Zeiss Ultra Plus). X-ray energy dispersion spectroscopy (EDS) and an elemental mapping analysis system attached to the SEM were utilized to measure the elements map of the fracture surface of the concrete.

Table 1
The physical properties of cements.

Cement Sort	PO 42.5
Normal consistency %	27.2
Initial Setting time Min	130
Final Setting time Min	195
3d Strength (flexural/compressive) MPa	6.9/27.4
28d Strength (flexural/compressive) MPa	9.4/52.6