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Experimental study on tensile strength development of concrete with manufactured sand

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HIGHLIGHTS

- Tensile strength development of concrete with manufactured sand (MSC) was tested.
- Effect of stone powder content on tensile strength development of MSC was examined.
- Statistical relation of tensile strength to compressive strength at any curing time.
- Formulas predicting long-term tensile strength of MSC are proposed.

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ABSTRACT

Concrete with manufactured sand (MSC) is a potential environmental friendly building material. As the limited study on tensile strength development of MSC, the findings of research work are presented in this paper. The MSC cubes were tested by the splitting tensile method, the influences that the water-cement ratio and the stone powder content have on the tensile strength development of MSC were analyzed. Test results showed that manufactured sand with no more than 13% stone powder content was beneficial to the long-term tensile strength of MSC. Forecast models are suggested for the prediction of long-term tensile strength of MSC.

1. Introduction

With the widespread awareness of the environmental friendly construction and the sustainability of urbanization development, the supply of natural sand in China is limited by the governmental protection of farmland and river course. Manufactured sand crushed from stone or gravel, also known as machine-made sand, artificial sand or crushed-stone sand, has been used as a substitute of natural sand in concrete [1–3]. This is also becoming a global trend to produce concrete by using manufactured sand in the safeguarding of limited natural sand resources [4–7]. Therefore, concrete with manufactured sand (MSC) has gradually become an essential and green building material.

However, many studies discovered the special morphology features of manufactured sand differed from the natural sand such as a rough surface, irregular particle shape, angular edges and a distinguish characteristics of the stone powder contained [3,8,9]. This features causes manufactured sand to have possible effects on the mix proportion and workability of fresh MSC [10–14], and the basic mechanical properties, the volume stability and the durability of hardened MSC [13–21]. It has also been reported the influence that the manufactured sand replacing natural sand has on bond property between steel bar and MSC [22,23]. Relative to the studies that mainly focused on long-term compressive strength of MSC, a limited number of studies have investigated on the long-term tensile strength of MSC [20,24–26]. While it is widely accepted that tensile strength is related to compressive strength, increasing compressive strength by using manufactured sand has been found to improve the tensile strength of MSC [20], but the conversion from compressive strength to tensile strength was lack of determination. As the significance of steady long-term tensile strength harmonized with compressive strength of MSC to the

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reliable cracking resistance and serviceable crack development, and the load-carrying capacities of reinforced concrete structures under flexure, shear, torsion, punching, fatigue and impaction, the further studies on the determination of long-term tensile strength of MSC is still necessary.

Currently, two methods named as direct tensile test and splitting tensile test are adopted to measure the tensile strength of concrete. The direct tensile strength is inclined to be used in specifications and guides as it is more realistic to reflect the tensile properties of concrete, however the test is difficult to ensure axial tension [27,28]. The splitting tensile strength is more popular in research and engineering application as the test is simpler and more reliable with lower variation comparing with the direct tensile test [29]. What is more, cylindrical and cubical specimens are always used for splitting tensile test [30,31]. There is no distinct difference between test results of a cylindrical specimen (300 mm × 150 mm diameter) and a cubical specimen (dimension of 150 mm) [31,32]. Power function of compressive strength has always been used to forecast tensile strength of concrete, in which compressive strength of concrete could be the cubic compressive strength, f_{cu}, or the cylindrical compressive strength, f_c, according to the type of specimens. It should be noted that a conversion factor, λ, is defined as the ratio of cylindrical compressive strength to cubic compressive strength, $\lambda = 0.79 \sim 0.81$ and $\lambda = 0.8 \sim 0.89$ for ordinary concrete with cubic compressive strength less than 80 MPa in China Code [28] and CEB-FIB Code [33], respectively. Nihal et al. [29] counted test data of ordinary concrete to calculate integral absolute errors and adjust parameters of the relationships between splitting tensile strength and cylinder compressive strength. Parra et al. [34] studied the splitting tensile strength and cylinder compressive strength of self-compacting concrete with four different water-binder ratio, W/B, compared with vibrated concrete, and suggested that the splitting tensile strength of self-compacting concrete should be modified by about 15% less than normally vibrated concrete. Behnood et al. [35] applied four methods of non-linear regression analysis, artificial neural network, support vector machine and M50 model tree techniques to predict the splitting tensile strength of concrete. All of these studies provide the beneficial references for the research of tensile strength of MSC.

In view of the importance of tensile strength of MSC applied in reinforced concrete structures and the limited study on the tensile strength development of MSC, this paper presents the test results of splitting tensile strength of MSC with different water-binder ratio and stone powder content for a curing time up to 388 days. Based on the statistical analyses of test data of this study and collected from other researches, forecast models of long-term tensile strength of MSC conversed from the cubic compressive strength or tensile strength at 28 days considering curing time are proposed. Finally, on the basis of a parallel study of long-term compressive strength of MSC, formula for predicting long-term tensile strength of MSC directly from the cement's compressive strength and density, water-cement ratio and curing time are suggested.

2. Experiment

2.1. Raw materials

Grade 42.5 ordinary silicate cement, crushed limestone in continuous grading 5–31.5 mm, and manufactured sand made of limestone with approximately 0–4.75 mm particle size were used in this test. The stone powder content, in mass of manufactured sand, was adjusted to 5%, 9% and 13%, where stone powder defined as particle size less than 0.075 mm. Tap water and high-performance water reducer FDN-1 with a water-reducing rate of 19% were also used in all mixes.

The physical, chemical and mechanical properties as well as particle size distributions of cement, stone powder, manufactured sand and coarse aggregate have been presented in a parallel study paper for the long-term compressive strength of MSC [26].

2.2. Mix proportions of MSC

Proper content of stone powder in manufactured sand has been verified to improve mixture workability of MSC with the same mix proportion [10,11]. This is because of the increasing consistency due to higher water absorption of stone powder and the larger volume of paste composited with stone powder as pulverized material. Considering the effects of manufactured sand on mixture workability and compressive strength of MSC, the mix proportion design of MSC was adjusted based on the specification in China Standard JGJ 55 [10,26,36]. The water absorbed by stone powder was added as part of the initial mixing water, the sand ratio was increased about 2% on the basis of concrete with natural sand, and reduced 1–2% with every 2–3% increment of stone powder in manufactured sand [3,26].

Three series of mixture proportions were designed with constant water-cement ratio (m_w/m_c) of 0.56 (Series C), 0.45 (Series D) and 0.40 (Series E), respectively. Each series had three stone powder content of 5%, 9% and 13%, successively marked as 1, 2 and 3 behind the series code. Detailed mix proportions are presented in Table 1.

2.3. Test method

Testing for slump of fresh MSC by the slump cone was in accordance with the specifications of China Standard GB/T50080 [37] and the identical British Standards BS EN 12350–2:2009 [38]. Tests for cubic compressive strength and tensile splitting strength of MSC were in accordance with the specifications of China Standard GB/T50081 [30] and the identical British Standard BS EN12390-3:2009 [39] and BS EN12390-6:2009 [31]. Cubic specimens in dimension of 150 mm were cast and compacted in moulds on a vibrating table, and covered with polyethylene sheets on cast surfaces for 24 h. Specimens were then removed from the moulds and cured under water at temperature 20 ± 2 °C in standard curing tanks till immediately before testing. Details of curing times for tests are listed in Table 2.

2.4. Test results

Details of workability and unit weight of fresh MSC, and compressive strength of hardened MSC at 28 days are also presented in Table 1. Generally, when stone powder in manufactured sand was less than 13%, it had positive effects on the workability and compressive strength of MSC. 9% stone powder content was the best beneficial to workability and unit weight of fresh MSC for every mix proportion.

Fig. 1 shows the splitting tensile strength of MSC in groups of different m_w/m_c against the curing time, where $f_{st,t}$ is the tensile strength at t days. With the increase of compressive strength, the tensile strength grew rapidly within 3 days to 28 days and slowed down after 28 days. This is because of the beneficial effects of stone powder has, as reported that the crystal nuclei effect on cement hydration [8,21,40,41] and the enhancement effect on interface of aggregate to set cement [3,11,21,40]. The former could improve the hydration degree of cement around the grains of stone powder, improve the crystal rate of calcium hydroxide and C–H–S gel, and form a secondary hydrate-calcium carbo-aluminate hydrate ($C_3A{\cdot}CaCO_3{\cdot}11H_2O$) to prevent ettringite to be single-sulfur