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Relationship between fracture area and tensile strength of cement paste with supplementary cementitious materials

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HIGHLIGHTS

- The axial tensile strength and ultimate strain of cement paste with SCMs is studied.
- The relationship between tensile strength and fracture area with SCMs is analyzed.
- Increasing dosage of BFS, FA, and SF improves the ultimate strain.
- The total fracture area is relatively large, as the tensile strength is small.

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ABSTRACT

Fly ash (FA), silica fume (SF), and blast furnace slag (BFS) were used as the supplementary cementitious materials (SCMs) in cement paste. The axial tensile strength, ultimate strain and the area of fracture surface of cement paste with SCMs were experimentally investigated in this study, and the relationship between tensile strength and fracture area of specimens were analyzed. The test results show that the tensile strength of the specimens decreases with the increasing addition of SCM. Except for SF, there is a negative correlation between the tensile strengths of specimens and W/B ratio. The increasing dosage of BFS, FA, and SF improves the ultimate strain. The fracture area of cement paste decreases with an increase in water-binder (W/B) ratio. The total fracture area is relatively large, as the tensile strength value is relatively low.

1. Introduction

The axial tensile properties of cementitious materials are important parameters which have great effects on crack resistance and safety of concrete. However, previous research has not paid much attention to the tensile strength properties, particularly axial tensile strength properties [1]. Engineers working with reinforced concrete have simply ignored the tensile strength of the concrete because of its low value and placed steel to pick up the entire tension. Concrete has several drawbacks: brittleness, easy to crack, and low tensile strength [2]. Hence, it is difficult to conduct axial tensile properties experimentation due to various drawbacks, such as eccentric load and uneven stress distribution. Moreover, there has been no reliable method to conduct the experimentation which focuses on tensile strength of cementitious materials. There has been various indirect methods to test the tensile and fracture properties of cement concrete, the majority of them are based on indirect tension tests, such as splitting tension test, beam with third-point loading, and compact tension specimen method [3–6]. These methods cannot accurately measure the tensile strength of cement-based materials. Raphael et al. [7], after examining a large number of tensile test results, postulated that the direct tensile strength is about 10% of its compressive strength; splitting tensile strength is about the same as the direct tensile strength; and flexural strength is about 15% of compressive strength. Popovics [8,9] and Khaliq et al. [10] concluded that the splitting tensile strength is usually 5–12% greater than the direct tensile strength, whereas it is 40–50% lower than the flexure tensile strength. Zheng et al. [11], reviewing works of several researchers, have reported that flexural tensile strength is generally 35% higher than splitting tensile strength. Swamy et al. [12] studied the tensile strengths of paste, mortar and concrete, and the tensile strength of concrete was invariably higher than that of the corresponding mortar matrix. Toutanji et al. [13] revealed that the partial replacement of

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Portland cement by silica fume decreases the tensile strength of both paste and mortar. The reduction in the strength of cement paste was greater than the reduction in the strength of mortar.

Previous research which focuses on the tensile strength of plain concrete includes: (1) Material composition: Bennett et al. [14] reported that the tensile compressive strength of the aggregate had less influence on the strength of the corresponding concrete. Zielinski et al. [15] investigated the influence of maximum aggregate size, water-cement ratio and cement content upon uniaxial impact tensile strength, and the cement type and quality were found not to affect the impact tensile strength of concrete. Khan et al. [16] showed that the tensile strength of concrete decreased with an increase in w/b ratio, and there was a gradual decrease in tensile strength with an increase in w/b ratio. Bhanja et al. [17] indicated that, other mix design parameters remaining constant, silica fume incorporation in concrete results in significant improvements in the tensile strengths of concrete. (2) Environmental conditions: Thomas [18] discussed the effects of moisture content of specimen during testing, and water-cement ratio on tensile strength of paste, mortar, and concrete. Khaliq et al. [10] pointed out that temperature has a significant effect on the tensile strength properties of concrete. (3) Testing apparatus: the following modes of gripping the specimens for direct tension test have been adopted by many researchers. They are by means of (1) rings on truncated cones [19], (2) embedded steel bars [20–23], (3) gluing [11,24–29] and (4) lateral gripping [30,31]. (4) Estimated value: the tensile strength is estimated from the compressive strength using empirical correlation equations [17,18,32–34]. The literature reveals the drawbacks of axis tensile test. (1) Decentration. Because of the error of the specimens and the unevenness of inner micro-crack distribution, it is difficult to achieve the physical alignment of specimens. With the development of cracks under loading, the physical centre of the specimen changes. (2) Low success rate. Because of the brittleness and stress concentration of cementitious materials, the tensile fracture position usually is out of the range of strain gage [11].

Based on the above research work, it can be found that: (1) few studies have investigated the axial tensile strength of cement paste or cementitious materials. The studies of the stress–strain relationship of various cementitious materials are insufficient. (2) There has been no study based on the relationship between fracture area and tensile strength of cementitious materials. Based upon these phenomena, this paper carries on the discussion on the above issues, the main content is as follows.

2. Materials and mix design

2.1. Materials

The cement used in this study was type I/II Portland cement with specific surface area was 369.6 m^2/kg. Its 3 days and 28 days compressive strengths were 34.3 MPa and 60.5 MPa respectively, and its 3 days and 28 days flexural strengths were 6.3 MPa and 8.7 MPa respectively. The chemical composition and physical properties of raw materials are given in Table 1.

2.2. Mix design

The mix designs of testing specimens were divided into four groups (A/B/C/D) according to different combinations of SCM and water/binder ratios. The detailed mix design was shown in Table 2.

Table 2
Mix designs of cement paste with mineral admixtures.

Code	Dosage	W/B	C (g)	W (g)	FA (g)	BFS (g)	SF (g)
A-1	Control	0.3	2400	720	0	0	0
B-1-1	15% FA	0.3	2040	720	360	0	0
B-1-2	30% FA	0.3	1680	720	720	0	0
C-1-1	25% BSF	0.3	1800	720	0	600	0
C-1-2	50% BSF	0.3	1200	720	0	1200	0
D-1-1	5% SF	0.3	2280	720	0	0	120
D-1-2	10% SF	0.3	2160	720	0	0	240
A-2	Control	0.35	2400	840	0	0	0
B-2-1	15% FA	0.35	2040	840	360	0	0
B-2-2	30% FA	0.35	1680	840	720	0	0
C-2-1	25% BSF	0.35	1800	840	0	600	0
C-2-2	50% BSF	0.35	1200	840	0	1200	0
D-2-1	5% SF	0.35	2280	840	0	0	120
D-2-2	10% SF	0.35	2160	840	0	0	240

2.3. Test procedure

2.3.1. Axis tensile strength test

Author et al. [34] proposed a testing apparatus which can measure uniaxial tensile strength properties. Fig. 1 shows the 40 mm × 40 mm × 160 mm molds used for the steel restricted crack test and the axis tensile strength test. Two screws were embedded into the ends of the mold. The total length of one screw was 8 cm and the embedded screw length in the mold was 5 cm. There were two notches in both sides of the mold for fixing two steel slices that were used to make two notches in the hardened cement paste.

Before casting of the fresh cement paste, two steel slices were set in both notches. When the cast cement paste reached the final setting time, the two steel slices were removed carefully, forming two notches on both sides of the hardened specimens. The size of the notches in the hardened cement paste is 0.1 mm wide, 0.8 mm deep, and 40 mm long. The specimens were demolded 1 day after casting and cured for 28 days in a standard curing box. After 28 days of curing, the fiber-reinforced plastic (FRP) was wrapped around the ends of the specimens where cracks were intensive. The wrapped FRP formed a ring and its length was 5 cm from the end of the specimens. The FRP was used to reinforce cracked specimens at the ends and ensure the specimens were failed at the notches when the tensile strength tests were carried out.

The measuring instrument of axis tensile strength was the MTS 810 material test system shown in Fig. 2. Two screws out of the specimens were fixed with two ball joints that connected to the loading equipment. The introduced universal hinge can eliminate or diminish the effect of decentration between the tensions. Strain gauges were glued on the surfaces of the specimens to examine the stress–strain relationship.

2.3.2. Calculation of fracture surface area

The fracture surface of a specimen which was snapped is shown in Fig. 3. The contactless observation of appearance and unevenness of surface came true by means of three-dimensional ultra-large scene depth microscope system (optical microscope system). By utilizing the three-dimensional microscope, the appearance of fracture surface was observed, as shown in Fig. 4. Because the total area of fracture surface was relatively large, while the roughness of the fracture surface was relatively small, the fracture area of each specimen was divided into multiple subareas. The effective area of corresponding subarea of fracture surface was calculated by means of integral principle. The sum of the area of all subareas was the effective area of the corresponding fracture surface.

Fig. 4 shows the three-dimensional fracture surface, which was processed by specific software. Apart from clear appearance of the fracture surface, the software determines the height of every point on the surface, and the color contours of the surface are delineated as well.

The fracture surface of $A1$ is used to demonstrate the calculation methods of fracture area. The $A1$ surface is divided into several subareas, as shown in Fig. 5. After scanning for each subarea, 3D image are obtained by software processing, as shown in Fig. 4. Then the 3D image is divided by n color contour, from its top to bottom. The length of arbitrary curve is tested and calculated as S mm. The height

Table 1
Chemical composition and physical properties of raw materials.

Raw materials	CaO (%)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MgO (%)	SO_3 (%)	R_2O (%)	Cl (%)	D (kg/m^3)	BS (m^2/kg)
C	62.6	21.3	4.67	3.31	3.05	2.11	0.75	0.007	3200	381
FA	4.77	54.88	26.89	6.49	1.31	1.16	1.93	0.001	2600	454
SF	1.72	92	0.78	0.79	2.71	1.16	–	0.018	2200	22,205
BFS	34.54	28.15	16	1.1	6	0.32	0.91	0.005	2900	416

Notes: C: cement; FA: fly ash; SF: silica fume; BFS: slag; D: density; BS: blaine surface; R_2O: $K_2O + Na_2O$.