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The influences of matrix and steel fibre tensile strengths on the fracture energy of high-strength concrete

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ABSTRACT

This research discusses the effects of both steel fibre and matrix strengths on fracture energy of high-strength concrete. The variables of experimental study were water/cement ratio, steel fibre strength and steel fibre volume fraction. The water/cement ratios of 0.35, 0.45 and 0.55, and steel fibres with a tensile strengths of 1100 and 2000 MPa were used and volume fractions of steel fibre were 0.33%, 0.67% and 1%. Mechanical properties, fracture energy and characteristic length of concretes were investigated.

Significant influences of matrix and fibre tensile strengths on the fracture energy and the characteristic length are noted.

1. Introduction

It is well-known that the addition of steel fibres into concrete at a certain volume fraction improves the ductility of concrete [1–4]. The major effect of steel fibres randomly distributed in matrix can be seen after matrix cracking. Steel fibres bridge gap between adjacent surfaces of existing micro-crack, delay crack formation and limit crack propagation by reducing the crack tip opening displacement [5,6]. This mechanism is known as *bridging mechanism*. In addition to effect of crack bridging, steel fibre–matrix bond strength also contribute to the increasing fracture toughness of the steel fibre reinforced concrete (SFRC). Other factors such as fibre type and orientation of fibres in matrix, aspect ratio (length/diameter), volume fraction and tensile strength of fibre as well as matrix strength influence the performance of SFRC [7–9].

Fracture energy of concrete is one of the most important parameter in understanding the properties of concrete and determining the design criteria of large concrete structures. The fracture energy (G_f) is defined as the area under the load–deflection curve per unit fractured surface area. The most widely used fracture mechanics models for analyzing concrete structures is the fictitious crack model (FCM) proposed by Hillerborg et al. [10–12]. RILEM [13,14] and Petersson [15] recommended a method for the determination of G_f using simple three-point bending test. The fracture energies of high-strength steel fibre reinforced concretes (HSFRCs), tested in this experimental study, were evaluated using the equation given by RILEM, in which toughness was calculated from the load–deflection curves obtained by performing a third-point test on notched beam in accordance with EN14651 [16].

The main objective in this research is to determine the effects of both matrix and fibre tensile strengths on fracture energy and mechanical properties of HSFRCs and emphasize the importance and dependency of tensile strength of steel fibre to the matrix strength. The opening and propagation of the crack are controlled by the steel fibres along the fracture plane. In many studies, it is pointed out that fibres, during the crack propagation after matrix cracking, are broken or pulled-out of the matrix due to the bond strength between steel fibre and matrix [17–20]. Both matrix and fibre tensile strengths play an important role on this bond strength or pull-out resistance of steel fibre from matrix. In the case of a mechanical mismatch between steel fibres and concrete, the performance expected from HSFRCs, especially improvement in fracture energy, may not be obtained. However, optimum solutions by selecting proper fibre type, considering its tensile strength, and water/cement ratio provide an economical advantage if the fracture energy is a criteria in the mix design of concrete.

2. Experimental study

2.1. Materials and mix proportions

CEM I 42.5R Portland Cement and silica fume with 81.35% SiO_2 were used for the program. Crushed limestone fines (0–4 mm) and crushed limestone

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(4–12 mm and 12–19 mm) were used as fine size and coarse size aggregate, respectively. Specific gravity of fine and coarse aggregates were 2.71 and 2.74, respectively. High-range water reducing admixture was used to observe the effects of steel fibre in workability of fresh concrete. Cold drawn steel fibres with low and high carbon, with hooked-ends, were used and their properties are given in Table 1.

The water/cement (W/C) ratios of 0.35, 0.45 and 0.55 were used and volume fractions (V_f) of steel fibre in concrete were 0.33%, 0.67% and 1%. Vebe time of control concretes (no fibre addition) for each water/cement ratio was kept constant as 4 s by changing the amount of water reducer. A total of 21 concrete mixtures including control groups were produced in this experimental research. The mix proportions of concrete series are given in Table 2.

2.2. Test specimens: preparation and testing

For a uniform mixture, cement, silica fume and all aggregates were blended first and then, the mixture of water and high-range water reducing admixture was added to the mixture. Finally, steel fibres were carefully scattered to the mixture to provide a uniform distribution of fibres in the mixture. The specimens were cast in steel moulds and compacted on a vibration table. All the specimens were demoulded after about 24 h and exposed to 28 days standard water curing.

Vebe time test to observe the chances in workability due to the use of steel fibre and unit weight test were made on fresh concretes.

Three cylinders, 150 mm in diameter and 300 mm in height, were used for compressive strength and modulus of elasticity tests. The splitting tensile strength test was performed on three disc specimens with a diameter of 100 mm and a thickness of 60 mm. The flexural tensile strength test was performed on 150 × 150 × 700 mm^3 prismatic notched-specimens by using the beam method according to EN14651 standard at which load is applied at one third points of the specimen [16]. Two prismatic notched-specimens, with an effective span of 500 mm, were tested by using a closed loop deflection-controlled loading frame of 250 kN capacity and loading rate was 0.2 mm/min. Central notches, with a depth of 25 mm and width of 3 mm were made using a diamond saw. Test setup is given in Fig. 1. The load and the mid-span deflection of the beams were simultaneously recorded and also, load–deflection curves for each specimen was also obtained graphically during the test.

Table 1
Properties of hooked-end steel fibres used.

Type	Length l (mm)	Diameter, d (mm)	Aspect ratio (l/d)	Density (g/cm^3)	Tensile strength, f_{su} (N/mm^2)
Dramix RC 80/60 BN (with low carbon)	60	0.75	80	7.85	1050
Dramix RC 80/60 BP (with high carbon)	60	0.71	85	7.85	2000

Table 2
Mix proportions of concrete series.

Water/cement	Tensile strength of steel fibre (N/mm^2)	Cement (kg/m^3)	Water (kg/m^3)	Super plasticizer (kg/m^3)	Steel fibre (%)	Silica fume (kg/m^3)	Sand (kg/m^3)	Coarse aggregate (kg/m^3)
0.55	–	325	179	0.9	0	0	891	965
	1050	325	179	0.9	0.33	0	891	965
		325	179	0.9	0.67	0	891	965
		325	179	0.9	1.00	0	891	965
	2000	325	179	0.9	0.33	0	891	965
		325	179	0.9	0.67	0	891	965
		325	179	0.9	1.00	0	891	965
0.45	–	396	178	1.35	0	19.8	842	913
	1050	396	178	1.35	0.33	19.8	842	913
		396	178	1.35	0.67	19.8	842	913
		396	178	1.35	1.00	19.8	842	913
	2000	396	178	1.35	0.33	19.8	842	913
		396	178	1.35	0.67	19.8	842	913
		396	178	1.35	1.00	19.8	842	913
0.35	–	487	170	1.8	0	48.7	785	850
	1050	487	170	1.8	0.33	48.7	785	850
		487	170	1.8	0.67	48.7	785	850
		487	170	1.8	1.00	48.7	785	850
	2000	487	170	1.8	0.33	48.7	785	850
		487	170	1.8	0.67	48.7	785	850
		487	170	1.8	1.00	48.7	785	850

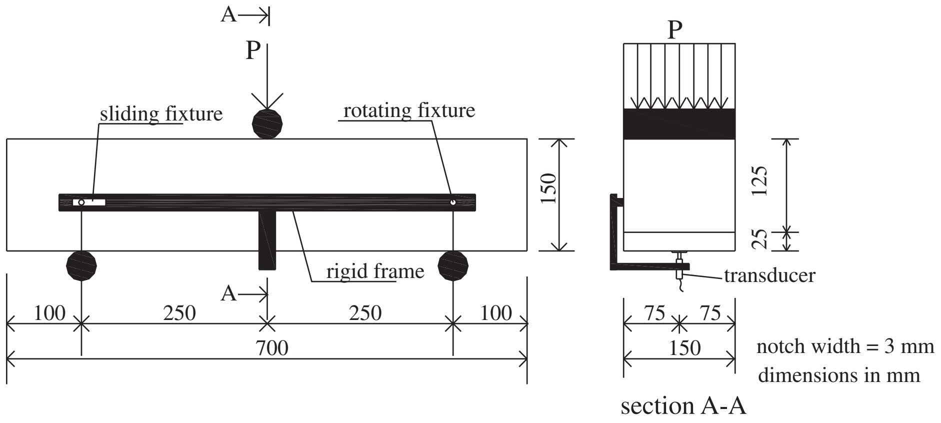

Fig. 1. Flexural test setup.