Construction and Building Materials 150 (2017) 252–259

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Experimental investigation of the effects of aggregate size distribution on the fracture behaviour of high strength concrete

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HIGHLIGHTS

- Aggregate size distribution affects the fracture behaviour of high strength concrete.
- Strong dependence of fracture energy upon aggregate size distribution.
- Limited dependence of stress intensity factor upon aggregate size distribution.
- Water to binder ratio alters stress intensity factor but fracture energy is relatively insensitive to it.
- Maximum fracture energy for high strength concrete is limited by strength of aggregates.

ARTICLE INFO

Article history:
Received 8 August 2016
Received in revised form 8 May 2017
Accepted 15 May 2017

Keywords:
Aggregate size distribution
Aggregate grading
Fracture energy
Stress intensity factors
Size effect

ABSTRACT

This paper examines the influence of different aggregate size distributions on the fracture behaviour of high strength concrete. Three-point bend test was performed on 63 notched beams casted using three aggregate size distributions and two water to binder ratios. The total fracture energy, G_F, and critical stress intensity factor, K_{IC}, were used to determine the fracture characteristic of concrete. The results show that the values of G_F decrease substantially with increasing coarseness of aggregate grain structure, λ. Values of K_{IC} also decreased but demonstrated only limited dependence on λ. In contrast, reducing the total w/b ratio substantially increases the value of K_{IC} but had no measurable effect on G_F.

1. Introduction

Concrete is widely used in the construction of buildings, bridges and other infrastructure around the world. Its use is driven by its flexibility of form, the relative simplicity of manufacture and the widespread availability of both binder materials, such as Portland cement, and inert, graded, granular aggregates. As a particulate composite material, the physical and mechanical properties of hardened concrete are strongly influenced by both its constituent materials and the proportions in which they are combined. The aggregate typically occupies more than 70% of the volume of a concrete mix and plays an important role in determining the physical properties and mechanical behaviour of both the fresh and hardened material [5]. The interactions that occur at the interface between the aggregate particles and the cement paste which surrounds and binds them influences many of the properties of hardened concrete, including strength, stiffness and fracture toughness. Historically, normal strength concrete, with a compressive strength of less than 50 MPa, has been used in the construction of plain, reinforced and prestressed concrete structures [7]. However, over the past 30 years, there has been increasing use of, and reliance on, so-called high-strength concrete for the creation of ultra-high-rise buildings and long-span bridges [25,3]. High-strength concretes routinely have compressive strengths in the range 60–90 MPa although much higher values can be achieved. This requires good mix design, the appropriate selection of constituent materials combined with the use of specialised admixtures. As a consequence, there is significant interest in understanding the mechanisms that govern the failure behaviour of such high-strength ceramic composites.

Whilst the fracture resistance of Portland cement concrete is known to be dependent on its compressive strength and water/

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http://dx.doi.org/10.1016/j.conbuildmat.2017.05.142

binder ratio, w/b, other parameters such as the size, shape, surface texture, and volume fraction of the aggregate have also been found to influence the fracture mechanics parameters of hardened concrete [10,25–27,18,30,8,12,16]. In normal strength concrete both the fracture toughness, i.e. the critical stress intensity factor, K_{IC}, and the fracture energy, G_F, of concrete have been found to increase with the compressive strength of the concrete [12], and the maximum aggregate size [10,25,18]) and volume fraction of the aggregate [2]. Similar behaviour have also been reported for the self compacted concrete [14]. However, aggregate type, and associated particle shape and surface texture has been found to have little effect on the facture energy of normal strength concrete [26,27].

The compressive strength of high strength concrete also affects the measured values of both K_{IC} and G_F [26,27], which increases as the maximum aggregate size increases [5]. Unlike normal strength concrete, the values of G_F for high-strength concrete have been found to be sensitive to the aggregate type [30,27]. Other results for high–strength concrete show that K_{IC} increases as the w/b ratio decreases [12]. Thus, the w/b ratio and properties of the aggregate both control the compressive strength and influence the fracture behaviour of high-strength concrete. Hence, for simplicity, compressive strength is widely used as an input parameter for calculating G_F along with the maximum aggregate diameter [6,4]. However, the results of Chen and Liu [5], and Ackay et al. [1], indicate that both K_{IC} and G_F of normal and high-strength concretes are influenced by the volume fraction of coarse aggregate. This is because the dissipated fracture energy is dependent on the physical characteristics of the crack path through the concrete. A tortuous crack path, with associated micro-cracking, crack-bridging and aggregate interlocking will result in the absorption of more energy than a smooth crack path. The path of a crack during fracture will be influenced by the coarseness of internal random grain structure of the concrete, λ, which is itself dictated by aggregate grading [2]. This suggests that aggregate grading can influence the fracture behaviour of concrete.

In high-strength concrete, the propagation of cracks, whether passing round or through the aggregates, is dominated by the quality and distribution of the various size of aggregates [13]. When using high-quality aggregates, the aggregate grading (and associated particle-size distribution) is a significant factor in controlling the coarseness of the internal random grain structure of concrete and influences the crack path that develops during the fracture process. Chen and Liu [5], and Ackay et al. [1] have noted that whilst the volume fraction of coarse aggregate is thought to influence both K_{IC} and G_F of concrete there remains a lack of experimental evidence in this area. Since the volume fraction of coarse aggregate reflects the aggregate size distribution, understanding the fracture behaviour of concrete based on its aggregate size distribution is important. Therefore, the objectives of this study were to investigate the role of aggregate size distribution and w/b ratio on the fracture behaviour of high-strength concrete and resulting values of K_{IC} and G_F.

2. Experimental setup

2.1. Materials

Flinty river gravel from the Thames Valley river was used for coarse aggregate with sizes in the range of 5 mm to 16 mm. The fine aggregate was a natural river gravel of size ranging from 4 mm down to 0.30 mm. A CEM Type I with a specific surface area of 338 m^2/kg was employed in the mix combining additional Pulverized Fuel Ash (Fly Ash) conforming to BS EN450-S category B. A slurry-based silica fume was also involved in some of the concrete mixes. A super-plasticiser was employed to allow appropriate workability of the fresh concrete.

The concrete mix proportions of each material used are shown in Table 1. A total of six different concrete mixes were produced employing three aggregate grading curves, designated as 'A', 'B' and 'C', see Fig. 1. To achieve the appropriate grading a batch of the as-received aggregate was sieved into its component fractions and the required amount of each fraction was then recombined. Two total water to binder (w/b) ratios of 0.20 (equivalent to a free w/b ratio of 0.17 ± 0.02) and 0.30 (equivalent to a free water/binder ratio of 0.23 ± 0.01) were used, and were designated as '1' and '2'' respectively, see Table 1. Thus, mix 'A1' indicates a mix with aggregate grading type 'A' and a total w/b ratio of 0.20.

It is well established that the workability of fresh concrete, as measured by its consistence, has a profound effect on the ease of compaction of the material and that incomplete compaction can adversely affect the properties of the resulting hardened concrete [19]. As a consequence, the consistence of all the mixes used in this study was kept constant, the target slump value for all the mixes was 120 ± 20 mm (equivalent to a consistence class S3 as prescribed by ENV 206, Part 1: 2000). This was achieved by varying the quantity of super-plasticiser in each mix, Table 1. Since the aggregate to binder ratio is also known to affect the concrete properties, it is kept constant for all mixes used in this study.

2.2. Specimens and test setup

At least nine 100 × 100 × 100 mm cubes were tested to determine the average compressive strength of the hardened concrete, following BS EN 12390: Part 3 (2000). The fracture behaviour of the hardened concrete was determined using 100 × 100 × 850 mm beam specimens tested in three-point bend (TPB) following RILEM TC 50-FCM (1985). All of the specimens were de-moulded approximately 24 h after casting and cured under water at 22 ± 2 °C for 30 days prior to testing.

Fig. 2 shows the dimension of the notched beam specimen for the associated three-point bend test arrangement. The depth (d), the width (t) and the total length (L) of the beam was 100, 100, and 850 mm respectively with a support span (S) of

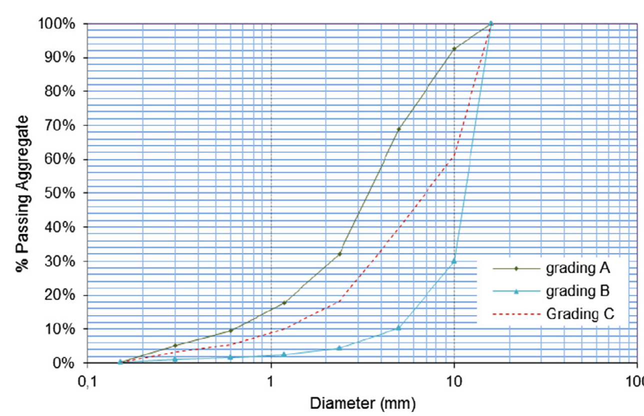

Fig. 1. Aggregate grading curves for types 'A', 'B', and 'C'.

Table 1
Mix proportions of the six concrete mixes tested.

Mix	w/b*	Unit weight (kg/m3)						
		Aggregate		Cement	PFA	Silica fume	Water	Super-plasticiser
		Coarse	Fine					
A1	0.20	1108	499	547.7	76.7	54.7	135.9	2.64
A2	0.30	1108	499	679	-	-	203.7	1.61
B1	0.20	1552	54	547.7	76.7	54.7	135.9	2.01
B2	0.30	1552	54	679	-	-	203.7	1.42
C1	0.20	1322	284	547.7	76.7	54.7	135.9	2.27
C2	0.30	1322	284	679	-	-	203.7	1.50

* Total water/binder ratio.