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Evaluation of the effect of maximum aggregate size on fracture behavior of self compacting concrete

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HIGHLIGHTS

- Fracture properties of SCC were obtained using two different methods.
- With increase of coarse aggregate size, fracture toughness increases.
- Size effect method can predict the peak load with a good precision for SCC beams.
- SCC ductility increases with increase of coarse aggregate size.

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ABSTRACT

This paper presents and discusses the effect of maximum size of coarse aggregate on fracture characteristics and brittleness of self-compacting concrete (SCC). Based on an experimental program, a series of three point bending tests were carried out on 86 notched beams, as recommended by RILEM. For all mixes, the parameters were analyzed by the work-of-fracture method (WFM) and by the size effect method (SEM) and consequently a correlation between these methods was obtained which is used to calibrate cracking numerical models. Test results showed that with increase of size of coarse aggregate, (a): fracture energies of G_F in WFM and G_f in SEM increase which may be explained by the change in fractal dimensions, (b); based on size effect plot, behavior SCC specimens approaches strength criterion, (c): SCC ductility, measured by means of characteristic length (L_{ch}) in WFM and fracture process zone length (C_f) in SEM, increases. In addition, the correlation between G_F and G_f values showed that the ratio G_F/G_f is approximately equal to 2.94.

1. Introduction

During the past four decades, self-compacting concrete (SCC), as a new generation of high-performance concrete, has been known as a successful event in concrete technology and consequently has been proposed as the subject of extensive research studies [1,2]. SCC may be defined as concrete with the capacity to spread into formwork and to flow through obstacles which fills the complex shapes with restricted areas and highly congested reinforcements, compacting only under its own weight without the need for mechanical vibration during the casting process and without showing segregation or bleeding [3–5]. SCC can be pumped to a great high and enhances the speed of construction [6,7]. SCC suggests a safer construction process. SCC also offers significant environmental, technical and economical advantages such as reduced noise emissions and construction time [8,9]. Apart from relevant research interests, applications of SCC in building industry have also increased remarkably due to the successful evolution it has brought about in the precast concrete applications in recent years [10]. There are serious concerns among researchers that SCC may have different behavior compared to normal vibrated concrete (NVC) and this is mainly due to the presence of comparatively higher amounts of ultra-fine particles, paste content and very powerful superplasticizers and lower coarse aggregate in order to provide a unique rheology in fresh mix [11]. These differences in mix composition can lead to change in the pore structure and result in modified mechanical behavior and especially fracture properties and consequently different cracking behavior in SCC compared to NVC. Fracture behavior of concrete as a quasi-brittle material is

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an important aspect to be considered for analysis and design of engineering structures especially dams, nuclear power plants, tunnels and bridges [12]. It has been proved that increase of the paste volume in concrete may lead to decrease in aggregate bridging and interlocking across the crack resulting in the reduction of energy absorption [13,14]. On the other hand, Craeye et al. [15] indicated that SCC mixes containing limestone powder as a mineral additive have a large autogenous shrinkage and consequently higher cracking tendency [15]. Nevertheless, many researchers have reported that use of ultra-fine particles such as limestone powder increases compactness of the SCC matrix and consequently may reduce the porosity of interface transition zone (ITZ) between aggregate and paste [16,17]. Strength, quality and volume fraction of ITZ are of significant importance when fracture behavior of concrete is considered. On the other hand, the property of ITZ is greatly affected by properties of the aggregates such as size, volume, shape, surface texture [18]. In NVC, Shah and Chandra [19] reported that a reduction in ITZ strength leads to significant increase of fracture energy (G_F). It is also generally proved that differences of drying shrinkage and modulus of elasticity between aggregate and the paste are responsible the stress concentration in the ITZ and consequently early age cracking [18,20,21]. In NVC, Akcaoglu et al. [18] showed that increasing maximum aggregate size (d_{max}), the properties of ITZ becomes critical. Many investigations have been conducted by several researchers on fracture behavior of NVC by taking into account various mixture parameters such as water content, aggregate size and volume [22,23]. It has been proved by many researchers that in concrete, as a specific type of composite material, fracture behavior is significantly related to the properties of matrix and inclusions [24]. Accordingly, many researchers was previously studied The effect of aggregate size, type and volume on fracture parameters of NVC [24,25]. In NVC, Hillerborg [23] based on the experimental results obtained from about 700 beam tests, analyzed the effect of d_{max} on the G_F and indicated that G_F tends to increase while d_{max} increases from 8 mm to 20 mm. The same trend was reported by Mihashi et al. [25], Walsh [26], Bazant and Oh [27] and zhao et al. [28]. Trunk and wittmann [29] and Ghaemmaghami and Ghaemian [30] indicated that the highest value of fracture energy is obtained in dam concrete with highest d_{max}. They introduced a power function between G_F and d_{max}. Issa et al. [14] observed that G_F increases monotonically with increase of d_{max}. They also found that the rate of G_F growth with d_{max} is higher in small d_{max} e.g. in 9.5 mm than for 38 mm. Zhou et al. [31] conducted systematic testing of the effect of various d_{max} on the fracture properties of high strength concrete and reported that G_F increases with increase of $d_{max.}$ However, some researchers have reported the opposite tendency. Bar et al. [32] and wolinski et al. [33] concluded that there is no monotonic effect of d_{max} on fracture toughness values for mixes with d_{max} from 5 mm to 20 mm and 8 mm to 32 mm. Petersson [22] reported that the G_F does not seem to depend on d_{max} but with an increase of the d_{max}, L_{ch}, as a ductility index in fracture mechanic, increases. Moseley et al. [34] stated that aggregates play two paramount leading roles in cracking process. First, by increasing stress concentration, it acts as a critical point for the initiation of cracks and second, by creating a point of arresting of a crack. Their experimental results indicated that, as the aggregate size increases, NVC shows dramatically ductile behavior. Yan et al. [35] reported that the fractal dimension of NVC greatly enhances with increasing d_{max}. Mihashi et al. [25] showed that the fracture process zone (FPZ) is mostly influenced by the aggregate size. In view of the above, these experimental studies proved that, for NVC, there is a remarkable relationship between coarse aggregate size with fracture parameters. Since few investigations have been carried out on this subject for SCC, the use of all the assumptions and relations that are valid for NVC might be somehow risky for SCC due to lack of adequate knowledge on the fracture behavior.

This paper describes an experimental investigation on the influence of coarse aggregate size on fracture parameters of SCC. In this study, the fracture parameters are examined using two different methods, namely work of fracture method (WFM) and, size effect method (SEM). The tests have been carried out on 86 notched beams in a servo controlled testing system subjected to three-point bending according to RILEM recommendations [36,37].

2. Fracture parameters evaluation

2.1. Work of fracture method (WFM)

Different methods have been proposed by international standards in order to determine the fracture parameters. One of the simplest methods to determine the fracture energy, as the most important fracture parameter of concrete, is work of fracture method introduced by the technical committee RILEM 50-FMC [36]. In this method, using three-point bending test on notched beams and determining the work needed to create a crack with unit surface area projected in a plane parallel to the crack direction, as the beam is broken in two parts, the specific fracture energy is determined as:

$$G_F = \frac{W_F}{b(d - a_0)} \tag{1}$$

where W_F is the total amount of work of fracture in the test when the beam is halved which is equal to the area under load–displacement curve, b is the beam width, d is the beam height and a_0 is the notch depth.

Since this method was originally established for concrete by Hillerborg et al. [38], it is also known as Hillerborg method in many Ref. [12]. Though simple, this method suffers the drawback of being dependent on specimen size which has been reported by many researchers and has been further explained by Bazant and Planas's book [12]. Extensive researches have been done by researchers on the reasons of the fracture energy's dependency on the specimen size and the major sources of error have been found to be attributed to the specimen weight and practical difficulties in recording the tail part of load–displacement plot [39]. In order to obtain a size-independent value of G_F, many researchers have proposed innovative methods. One of the methods to eliminate the major sources of error in RILEM method is proposed by Elices et al. [39] which is adopted in this study in which weight compensation method is used. In fact, it is not feasible to compensate for the weight precisely. Thus, it is recommended that a slight over compensation to be implemented. Consequently, a residual load, P_0, is detected at the end of the tail of the load–displacement curve as shown in Fig. 1. As it can be seen in Fig. 1, the test is usually stopped at B, before the specimen is fully broken. Considering that the area under the ideal curve is intended and the effect of P_0 must be eliminated, Elices et al. [39] proposed the following expression to calculate the area under the ideal load–displacement curve as:

$$W_F = W_m + 2\left(\frac{A}{u_B - u_A}\right) \tag{2}$$

where W_m is the area under the load–displacement curve which is corresponding to the surface area AMBA and A is a coefficient introduced by Elices et al. [39] which can be easily achieved by fitting a straight line to the far end of experimental data in a load (P) versus Δu^{-2} plot. This is done by the standard least square fitting as: