Construction and Building Materials 52 (2014) 137–145

Contents lists available at ScienceDirect

Construction and Building Materials

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

Effect of coarse aggregate volume on fracture behavior of self compacting concrete

I.M. Nikbin [a,*], M.H.A. Beygi [a,1], M.T. Kazemi [b,2], J. Vaseghi Amiri [a,1], E. Rahmani [a,1], S. Rabbanifar [a,1], M. Eslami [c,1]

[a] Department of Civil Engineering, Babol University of Technology, Iran
[b] Department of Civil Engineering, Sharif University of Technology, P.O. Box: 11155-9313, Iran
[c] Department of Civil Engineering, Andishmand Institute of Higher Education, Iran

HIGHLIGHTS

- Fracture parameters of SCC were obtained using two different methods.
- With increase of coarse aggregate volume, 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 volume.

ARTICLE INFO

Article history:
Received 1 October 2013
Received in revised form 1 November 2013
Accepted 12 November 2013
Available online 4 December 2013

Keywords:
Fracture energy
Aggregate volume
Self compacting concrete
Size effect

ABSTRACT

This paper presents the effect of volume of coarse aggregate on fracture characteristics of self- compacting concrete (SCC). Based on an experimental programme, a series of three point bending tests were carried out on 58 notched beams. SCC was prepared with coarse aggregate in varying percentages of 30%, 40%, 50% and 60% (as the percentage of the total aggregate volume). For all mixes, the fracture parameters were analyzed by the work-of- fracture method (WFM) and by the size effect method (SEM) to obtain a suitable correlation between these methods which is used to calibrate fracture numerical models. The results showed that with decrease of volume of coarse aggregate from 60% to 30% in SCC, (a): fracture energies of G_F in WFM and G_f in SEM strongly decrease which may be explained by the change in fractal dimensions, (b); based on size effect plot, behavior SCC specimens approaches linear elastic fracture mechanic (LEFM) criterion, (c): SCC ductility, measured by means of characteristic length (L_{ch}) in WFM and fracture process zone length (C_f) in SEM, significantly decreases, (d): the brittleness number is approximately tripled.

1. Introduction

During the past four decades, self-compacting concrete (SCC) has undergone remarkable development. SCC shows significant advantages in terms of both working environment and technology, such as eliminating special problems associated with the vibration task and casting process including inadequate or excessive compaction [1]. It has high workability while preventing bleeding and segregation during casting. Obviously, it has environmental, technical and economical benefits over normal vibrated concrete (NVC) such as increasing the speed of construction, reduction of labor resources and improved durability [2]. Apart from research interests, applications of SCC in building industry have also increased due to this successful evolution in the concrete technology.

There are significant concerns among researchers that SCC may have different behavior compared to NVC and this is due to the presence of comparatively higher amounts of fine particles and paste volume in order to avoid segregation in fresh mix [3]. These differences in mix composition can lead to change in the pore structure and result in modified mechanical properties, especially fracture behavior, and consequently different cracking mechanisms in SCC as compared to NVC. Fracture behavior of concrete as a quasi-brittle material is an important aspect to be considered for analysis and design of engineering structures especially

---

* Corresponding author. Tel.: +98 (112) 5280914.
E-mail addresses: nikbin@iaurasht.ac.ir (I.M. Nikbin), M.beygi@nit.ac.ir (M.H.A. Beygi), Kazemi@sharif.edu (M.T. Kazemi), Vaseghi@nit.ac.ir (J. Vaseghi Amiri), Ebrahim.rahmani84@gmail.com (E. Rahmani), Saeed.rabbanifar@yahoo.com (S. Rabbanifar), mona_eslami84@yahoo.com (M. Eslami).
[1] Tel.: +98 (112) 5280914.
[2] Tel.: +98 (21) 6616 4237.

0950-0618/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.conbuildmat.2013.11.041

large-scale members which consequently provides a basis for evaluation of the strength of cracked structures [4]. Researchers have reported that reduction of the aggregate content in concrete may lead to decrease in aggregate bridging and interlocking across the crack resulting in the reduction of energy absorption [5,6]. On the other hand, recent investigations indicated that SCC mixes containing limestone powder as a mineral additive have a large autogenous shrinkage and consequently higher cracking tendency [7]. Nevertheless, a number of studies have reported that use of extra-fine particles such as limestone powder increases compactness of the SCC matrix and consequently may improve interface transition zone (ITZ) between aggregate and paste [8,9]. Higher Strength and quality of ITZ are of significant importance when fracture behavior is considered. On the other hand, the properties of ITZ strongly depend on the properties of the aggregates such as size, volume, shape and surface texture [10]. Shah and Chandra [11] indicated that a reduction in ITZ strength leads to significant increase of fracture energy (G_F) as a fundamental fracture parameter in NVC. It is also generally found that the stress concentration in the ITZ and consequently early age cracking is due to differences of drying shrinkage and modulus of elasticity between aggregate and the paste [10,12,13]. Akcaoglu et al. [10] concluded that with increasing the maximum aggregate size ($d_{\max}$), the properties of ITZ becomes critical. Several investigations have been carried out by many authors on fracture behavior of NVC by taking into account various mixture parameters such as water to cement ratio, maximum aggregate size and volume [14,15]. It has been explored by many researchers that in concrete, as a specific type of composite material, fracture properties are actually related to the size, shape, surface texture and volume of aggregates [16,17]. Zampini et al. [18] reported that aggregate particle increase the toughness of the cement paste. Strange and Bryant [19] indicated that aggregate particles impede the extension of matrix crack. Moseley et al. [20] 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. This leads partly to decrease of fracture toughness and partly to increase of the tortuosity of fracture path and consequently ductility with increase of aggregate size. Gopalaratnam and Shah [21] indicated that the aggregate volume influences the fracture mechanics parameters of NVC. Feng et al. [22] concluded that the G_F increases monotonically with the addition of the volume of coarse aggregates. However, Evans and Marathe [23] reported the opposite tendency and concluded that with increasing coarse aggregate volume, G_F decreases. Chen and Liu [24] studied the effect of the coarse aggregate volume on fracture parameters of NVC and found that the coarse aggregate volume and size affected the fracture process zone (FPZ) of NVC. Some researchers [25] have indicated that larger aggregate size leads to a larger size of the FPZ. Amparano et al. [16] stated that with increasing volume of aggregate, the size of FPZ decreases. In view of the above, these experimental studies proved that, for NVC, there is a remarkable relationship between coarse aggregate volume 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 volume 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 58 notched beams in a servo controlled testing system subjected to three-point bending according to RILEM recommendations [26,27].

2. Determination of fracture parameters

2.1. Work of fracture method (WFM)

In order to determine the fracture parameters, different methods have been proposed by international standards. The simplest method to determine the fracture energy, as the most important fracture parameter of concrete, is work of fracture method introduced by RILEM 50-FMC [26]. In this method, conducting three-point bending test on notched beams and determining the energy needed to create a crack with unit surface area projected in a plane parallel to the crack direction, the specific fracture energy is obtained as:

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

where W_F is the total energy 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 proposed by Hillerborg et al. [28], it is also known as Hillerborg method in many references [4]. 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 [4]. 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 capturing the tail part of load–displacement curve [29]. 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. [29] 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. [29] 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. [29] 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:

$$P - P_B = A\left[\frac{1}{(u-u_A)^2} - \frac{1}{(u_B-u_A)}\right] \tag{3}$$

In order to determine size-independent fracture energy Hu and Wittman [30] have proposed another method. Hu and Wittman [30] demonstrated that the local specific energy varied during the propagation of a crack, and the variation becomes considerable as the crack approached the stress – free back face boundary of the specimen. The concept of free boundary effect extended by Karihaloo et al. [31], Abdalla and Karihaloo [32] and Karihaloo et al. [33] and is known as boundary effect method (BEM). They proved that the same size-independent specific fracture energy can be obtained by testing only two specimens of the same size but with notches which are well separated [31,32]. BEM significantly