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# The effect of water to cement ratio on fracture parameters and brittleness of self-compacting concrete

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ABSTRACT

The paper describes an experimental research on fracture characteristics of self-compacting concrete (SCC). Three point bending tests conducted on 154 notched beams with different water to cement (w/c) ratios. The specimens were made from mixes with various w/c ratios from 0.7 to 0.35. For all mixes, common fracture parameters were determined using two different methods, the work-of-fracture method (WFM) and the size effect method (SEM). Test results showed that with decrease of w/c ratio from 0.7 to 0.35 in SCC: (a) the fracture toughness increases linearly: (b) the brittleness number is approximately doubled: (c) the effective size of the process zone $c_f$ in SEM and the characteristic length ($l_{ch}$) in WFM decrease which may be explained by the change in structural porosity of the aggregate–paste transition zone; and (d) the fracture surface of concrete is roughly smoother, which can be attributed to the improved bond strength between the aggregates and the paste. Also, the results showed that there is a correlation between the fracture energy measured by WFM ($G_F$) and the value measured through SEM ($G_f$) ($G_F \cong 2.92G_f$).



## 1. Introduction

Self-compacting concrete (SCC) is able to flow and compact under its own weight, filling the molds even in the presence of congested reinforcement and restricted area while maintaining its uniformity for a long time without any bleeding or segregation due to excessive vibration [1]. It can be pumped to a great height and through long distances [2]. SCC may provide a safer and more productive construction process. The necessity of SCC was originally proved by Prof. Okamura at the University of Tokyo, Japan [3]. The use of SCC has spread at a fast pace all over the world, and consequently research interest in the field of SCC has increased in recent decades. This interest is due to the increase of the frequency of application of SCC in construction of many structures such as bridges, tunnels and high-rise buildings and also the importance of durability of such structures [1]. SCC as a quasi-brittle material in structures needs more concentration from researchers in order to assess the better utilization of this material in construction. In the past few years, the mechanical properties of SCC with inclusion of two ingredients, admixtures and additives, in its heterogeneous structure have been studied from different points of view. Among the properties of hardened concrete, fracture behavior is a fundamental phenomenon in design and safety assessment of structures especially large-scale structures [4].

The fracture behavior in concrete profoundly depends on the properties of the particular components in the mixture. Since SCC and normal vibrated concrete (NVC) have different mix compositions, it is expected that this difference affects fracture parameters. As a matter of fact, researchers have generally accepted that the use of higher powder content and decreasing the share of aggregate in SCC leads to better particle packing and less bleeding [5–7]. Furthermore, because of the absence of mechanical compaction, reduction of the content of water around aggregates and consequently having a different pore structure, the interfacial transition zone (ITZ), as the main weak zone in concrete that forms around the aggregates, is denser in SCC [6,8]. Moreover, the use of mineral admixtures such as limestone powder in SCC increases the heat of hydration and consequently thermal stress [5]. This can change pre- and post-cracking behavior and energy absorption. On the other hand, earlier researchers reported that increasing the volume of paste in SCC as opposed to NVC increases the risk of cracking associated with drying shrinkage and it might be expected that SCC would exhibit different brittle behavior from NVC [9]. Craeye et al. [10] confirmed that the presence of mineral powders in SCC mixes increases autogenous shrinkage and leads to formation of internal stresses and consequently concrete cracking. However, Fava et al. [11] observed similar fracture behavior in similar strength (50 MPa) in the SCC and NVC notched specimens. Zhao

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et al. [12] conducted an experimental investigation to evaluate the toughness and fracture toughness of SCC mixes with different compressive strengths, using wedge splitting tests. The results of this investigation showed that toughness values for SCC are lower than the typical values for NVC, given in the recommended codes. Therefore, it is important to ensure that all the design provisions established for NVC are also valid for SCC.

Despite the recent efforts, few studies are available, concerning the fracture behavior of SCC, specially no significant experimental data exist on the effect of different w/c ratios on fracture behavior of SCC. w/c Ratio plays a critical role in compressive strength and fracture behavior of concrete [13]. According to several studies carried out on the fracture behavior of NVC, the structure of porosity of the ITZ is closely related to w/c ratio [13]. Petersson [14] reported that when w/c ratio exceeds 0.4, fracture energy decreases. Nallathambi et al. [15] reported that crack growth in mixes with high w/c ratio is faster and thus the fracture toughness of NVC decreases with increase of w/c ratio. The results reported by Mindess et al. [16] indicated that the fracture energy did not vary with w/c ratio. Phillips and Binsheng [17] concluded that there were similar patterns between fracture energy and brittleness with w/c ratio. Ince and Alyamac [18] demonstrated that, according to Abrams' law, there are certain relations between the fracture parameters and w/c ratio in NVC. Jo and Tae [19] claimed that reduction of w/c ratio causes fracture energy and brittleness to increase in NVC. Prokopski and Langier [13] found that as the content of water in the NVC mixes increases, the stress intensity factor $K_{IC}$ remarkably drops. Carpinteri and Brighenti [20] conducted a systematic test on the effect of different w/c ratios on fracture energy of NVC. They showed that for both too high and too low w/c ratios, the fracture energy decreases. However, Zhao et al. [21] stated that there was no systematic relation between water to binder ratio and fracture energy in NVC.

The main purpose of the present research is to experimentally investigate the effect of w/c ratio on the fracture parameters of SCC. The tests were carried out on 154-notched specimens subjected to three-point bending using closed-loop servo-controlled testing system. The fracture parameters are studied using two main methods, the work-of-fracture method (WFM) and by the size effect method (SEM), according to RILEM recommendations [22,23]. For all mixes, the fracture energy, as a fundamental fracture parameter, was determined by the two methods, predicting a quite accurate relation between the energy values, determined based on the two methods, and to use it in calibration of numerical fracture models for realistic design criteria in structures designed with SCC.

## 2. Fracture parameters evaluation

The results of the three-point bend tests on notched beams can be used to determine fracture energy, using the two methods. In the first method, recommended by the technical committee RILEM 50-FMC [22], the fracture energy is expressed as the work needed to create one unit area of a crack. As the beam is broken in two parts, the fracture energy can be computed dividing the total dissipated energy by the initial ligament area:

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

where the term $W_F$ is the total amount of work of fracture in the test, $b$ is the width, $d$ is the depth and $a_0$ is the initial notch depth of the beam cross section. It is worth noting that this method in fracture mechanic texts is also known as WFM or Hillerborg's method. Many researchers indicated that the $G_F$ value, determined according to this method is size-dependent and an increase of $G_F$ occurs with increase of beam size. A detailed description of this method with possible sources of experimental errors is presented in the book of Bazant and Planas [4]. Many experimental investigations indicated that the weight of the specimen plays a noticeable role in the load distribution and may lead to remarkable errors. Researchers suggested that in order to take into account the effect of specimen weight, we can use the weight compensation procedure as found in the book of Bazant and Planas [4]. In practice, it is not possible to fully compensate the weight and it is recommended that a slight overcompensation to be implemented. As a result, a residual load, $P_0$, is detected at the end of the tail of the load–displacement curve as shown in Fig. 1.

Usually the last recorded point of the test is point B. Under this condition, the total work ($W_F$) is given as:

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

where $W_m$ is the measured work which equals the area AMBA and $A$ is a constant that, as explained by Elices et al. [24], can be easily obtained by least square fitting to the data as:

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

Moreover, to describe the brittleness of a material in WFM, the characteristic length which is related to the fracture process zone length has been introduced by Hillerborg et al. [25] as:

$$l_{ch} = EG_F/f_t^2 \tag{4}$$

where $E$ is Young's modulus and $f_t$ is the tensile strength. The lower the value of $l_{ch}$, the more brittle the material.

The first method suffers from drawbacks the most important of which is its dependency on size of specimens. Therefore, a second method, which is based on the size effect law, was recommended by RILEM TC89-FMC [23] to complement the first method. This method was originally proposed by Bazant and Kazemi [26] and indicates that the fracture energy is independent of the size of the specimens. According to this method, If specimens of similar geometries are tested and the maximum loads are extrapolated to a specimen of infinite dimensions, a ductile–brittle transition of the fracture mode occurs and the fracture energy is expected to have one unique value, regardless of the type, size or shape of the specimen. This method is known as the size effect method (SEM). SEM suggested a nonlinear fracture mechanics relation between the nominal failure stress $\sigma_N$ and the characteristic dimension of the specimen (d) for geometrically similar specimens as follows:

$$\sigma_N = \frac{B}{\sqrt{1 + \beta}} \tag{5}$$

where $B$ is an empirical parameter and $\beta$ is the brittleness number. The maximum nominal stress of two-dimensional similar structures also is determined from the experimental tests as:

$$\sigma_N = C_n \frac{P_u}{bd} \tag{6}$$

where $P_u$ is the peak load, $C_n$ is a constant coefficient introduced for convenience, $b$ is the width and $d$ is the reference dimension (usually beam depth).

In SEM, the brittleness number indicates the adjacency of the structural failure mode to ideal brittle linear fracture mechanics (LEFMs). The following equation for the brittleness number is suggested by Bazant and Kazemi [26] as:

$$\beta = \frac{d}{d_0} \tag{7}$$