

Critical Crack-Tip Opening Displacement of SCLC



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Abstract The aim of this study is to consider the effects of water/binder ratio on fracture behavior of self-compacting lightweight concrete (SCLC). To do so, four mixes with constant nominal size of aggregate ($d_a = 12.5$ mm) have been prepared such that the weight of aggregate and portion of coarse aggregate to fine aggregate were designed to be constant. Forty-eight notched beam specimens were tested under displacement-controlled condition to achieve the maximum tolerable loads of beams under three-point bending configuration. Afterwards, the results were analyzed according to size effect method to realize the influences regarding water/binder ratio. Test results showed that as the water/binder ratio increased from 0.35 to 0.50, the fracture energy and toughness decreased by 65.8 and 54.5%. Moreover, the water/binder ratio had apparent influences on the values of critical crack-tip opening displacement.

Keywords Self-compacting lightweight concrete • Fracture energy
Fracture toughness • Material properties • Water to binder ratio
Crack-tip opening displacement

1 Introduction

In recent years, more attention has been paid to develop a generation of concrete, which has the ability to fill the formworks without external vibration, bleeding, and segregation, as well as having a low density [1, 2]. This demarche is the integration of technical knowledge, economy, and environmental protection, since this category of mix compositions could reduce the waste demolish and self-weight of

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structures along with the air CO_2 , which is a byproduct of cement industry. SCLC is a good example of these types of concrete, which usually consists of lightweight coarse aggregate and normal weight river sand. The use of lightweight aggregate (LWA) is reported to have the ability to reduce the autogenous shrinkage [3] due to internal curing [4, 5]. With recent trend toward using lightweight aggregate in concrete, some researches have been conducted all over the world to reveal the advantages and disadvantages of LWA. For instance, it is reported that the use of LWA could reduce the water permeability since its internal structure is not inter-connected and holds water [6]. The porous structure of LWA leads to lower ion concentration and besides the decrease of chloride penetration [7, 8], it could decrease the influences of water expansion due to freezing, and consequently, could enhance the freeze and thaw resistance [9]. Instead, lower modulus of elasticity in comparison to normal weight concrete (NC), increases the risk of creep [10].

Even before cracking, concrete exhibits nonlinear response [11] and fracture parameters are the means that should be used to explain the behavior of cracked concrete members [12]. Although the knowledge about the fracture behavior of NC is sufficient, there are still debates on the issue of fracture behavior of SCLC due to use of high amounts of ultra-fine particles and LWA as a coarse aggregate. Therefore, structural application of SCLC necessitates an understanding of the material fracture behavior. In this regard, this study considers the effects of water to binder ratio on fracture energy (G_f), toughness (K_{IC}), and critical crack-tip opening displacement (CTOD_C) of SCLC.

2 Introduction

The literature introduces some approaches for determination of fracture parameters of concrete. Work-of-fracture method (WFM) is one of the most popular methods, which has been introduced in RILEM 50-FMC [13]. The method uses three-point bending test on notched beam specimens to determine the fracture energy of the concrete. However, it is proved that the method has the drawback of size dependency [14, 15]. Based on WFM, the size dependent fracture energy (G_F) could be obtained as [13]:

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

where W_F is the area under load displacement curve, b is the beam width, d is the depth of the beam, and a_0 is the notch length. Apart from the size dependency, which is mainly attributed to weight of specimen [16], conducting a stable test is too hard and needs special conditions such as very stiff universal testing machine.

The other method is boundary effect model (BEM), which is based on local fracture energy definition, and has been originally proposed by Duan et al. [17–19].

According to this concept, one could determine the size-dependent fracture energy as [19, 20]:

$$G_F\left(\frac{a}{d}\right) = \frac{1}{d-a} \int_0^{d-a} g_f(x) dx \tag{2}$$

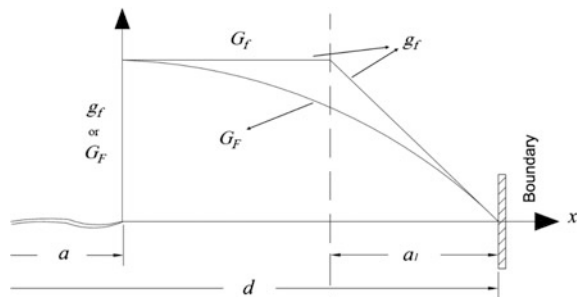
in which a is crack length and g_f is the local fracture energy. The variation of local fracture energy along the crack path was described by a bilinear approximation proposed by Hu and Wittman [21] (see Fig. 1). Accordingly, by defining the intersection of these two asymptotes as a transition ligament size (a_1), the Eq. (2) has been solved to determine the size independent fracture energy (G_f) as

$$G_F = \begin{cases} G_f \left(1 - 0.5 \frac{\frac{a_1}{d}}{1 - \frac{a}{d}}\right) & 1 - \frac{a}{d} > \frac{a_1}{d} \\ G_f \left(0.5 \frac{1 - \frac{a}{d}}{\frac{a_1}{d}}\right) & 1 - \frac{a}{d} \leq \frac{a_1}{d} \end{cases} \tag{3}$$

In this method, for each concrete mix, two series of specimens, having pre-cracks with a/d ratios of 0.1 and 0.6, should be tested using work-of-fracture method to determine the values of G_F and a_1 [21, 22]. Afterwards, by using Eq. (3), one determines the size-independent fracture energy of the composition. Although this method looks simple, it has some drawbacks such as a need to special testing equipment. Besides, this method is not introduced in any guidelines. Therefore, the Bazant’s size effect method (SEM) is preferable.

Bazant and Pfeiffer proposed a model [23] which subsequently became a basis for size effect method. According to this model, RILEM published a guideline to introduce SEM to researchers and practitioners [24]. In this method, geometrically similar specimens are tested to determine the peak loads. Subsequently, by extrapolating these peak loads to a specimen with infinite dimension, along with using the Bazant’s size effect law (SEL), the fracture parameters could be determined. The SEL is a nonlinear fracture mechanics’ relation between the depth of specimen and nominal failure stress σ_N as

Fig. 1 Bilinear model for local fracture energy



$$\sigma_N = B(1 + \beta)^{-0.5}, \quad (4)$$

where β is brittleness number and B is an empirical parameter.

The brittleness number, introduced by Bazant and Kazemi [25], is a tool for ductility assessment of the concrete using fracture mechanics. Besides, it indicates the design criterion of the structure. In other words, when $\beta > 10$, the behavior of specimen approaches brittle behavior and should be designed according to linear elastic fracture mechanics' constitutive relations [25]. Instead, the plastic limit criterion should be used for specimens with $\beta \leq 0.1$. For $0.1 \leq \beta \leq 10$, nonlinear fracture mechanics' constitutive relations should be used [2]. The brittleness number could be calculated as

$$\beta = d/d_0 \quad (5)$$

in which d is the beam depth and d_0 is an empirical constant to be found from the experiments.

The SEM uses linear regression for extrapolation as

$$Y = AX + C, \quad (6)$$

where A and C are the slope and intercept of the fitted line, respectively. X and Y are the abscissae and ordinates of a coordinate system as

$$\begin{cases} X = d \\ Y = \frac{1}{\sigma_N^2} \end{cases} \quad (7)$$

The SEM recommends the least size range ratio of 1:4 to avoid data scattering. In addition, based on the LEFM theory, the size-independent fracture energy could be found as [1, 2]

$$G_f = g\left(\frac{a_0}{d}\right)E^{-1}A^{-1} \quad (8)$$

Generally, in order to avoid scattering data, the size range of the test specimens is chosen to have at least the scale ratio of 1:4. Besides, since the fracture of the specimen with infinite size follows the LEFM theory, the fracture energy and the effective length of fracture process zone can be determined as

$$C_f = \frac{Cg_f(\alpha_0)}{Ag_f'(\alpha_0)} \quad (9)$$

in which $g(a_0/d)$ is non-dimensional energy release rate, which could be found in many references such as [26, 27], A is the angular coefficient of the fitted line, and

E is the modulus of elasticity. Since the method uses extrapolation method to determine the fracture energy in an infinitely large specimen, the LEFM governs. Hence, the other fracture parameters of interests could also be found as [24]:

$$K_{IC} = d_0^{0.5} B \sqrt{g \left(\frac{a_0}{d} \right)} \quad (10)$$

$$CTOD_C = 3.19 \frac{K_{IC}}{E} \sqrt{c_f}, \quad (11)$$

where c_f is the effective length of fracture process zone and could be found on RILEM FMT-89.

The size effect method is a globally accepted method, which is to be implemented in this study. However, it should be noted that this method is not suitable for specimens, which are not geometrically similar. Recently, Hu and Duan claimed that their model (BEM) could circumvent this drawback [28]. While, Hoover and Bazant experimentally proved that this model does not fit the results [29].

3 Materials and Testing Method

3.1 Materials

In this study, ordinary Portland cement, provided from Tehran cement factory, has been used. The coarse aggregate was lightweight expanded clay aggregate (LECA), whose specific gravity was about 583 kg/m³. For all compositions, same river sand was provided whose fineness modulus was about three. According to ASTM C494 specifications [30], type G poly carboxylate-based super plasticiser was used to reach the desired workability. Moreover, limestone powder had a role of viscosity modifying agent.

Four composition with water/binder ratios of 0.35, 0.4, 0.45, and 0.5 have been prepared in which LECA/sand ratio has been kept constant at 0.294. The total weigh of aggregate was constant and equal to 1100 kg/m³. The detailed mix design parameters and fresh state test results could be found in [2]. Moreover, the maximum nominal size of coarse aggregate was 12.5 mm for all mixes.

3.2 Curing and Casting of Notched Beam Specimens

For each mix, 12 specimens with four different sizes of 38.1 × 38.1 × 102 mm³, 38.1 × 76.2 × 203 mm³, 38.1 × 152.4 × 407 mm³ and 38.1 × 304.8 × 814 mm³, were casted according RILEM recommendations [24]. For each specimen, a pre-crack with a_0/d ratio of 0.2 was made during the casting by using 3 mm acrylic plate. All specimens have been demolded after 1 day and cured under water at 20 ± 20C.

3.3 Test Method

In order to reach the desired accuracy, a closed-loop servo-electro-controlled testing machine with the highest capacity of 150 kN, provided from Zwick/Roell, was used. All tests have been carried out under displacement-controlled condition such that the peak loads were achieved in about 1 min. Afterwards, the peak loads were recorded and the effects of specimen weights were compensated according to RILEM recommendations. The test setup configuration could be found in [1, 2].

4 Results and Discussions

RILEM FMT-89 proposed a method for weight compensation in which the effect of weight are being excluded from the analysis by RILEM FMT-89 [24]:

$$P_0 = P + \frac{2S_n - L_n}{2S_n} mg, \quad (12)$$

where P_0 is corrected peak load, P is recorded maximum load of specimen, S_n is the span of the specimen and is considered to be $S_n = 2.5d$, L_n is length of the beam specimen and based on RILEM recommendations is equal to $2.67d$, m is mass of specimen, and g is gravitational acceleration, which is assumed to be about 9.81 m/s^2 . Figure 2 shows the corrected peak loads versus specimens' depth.

As stated previously, the results of each series should be extrapolated to a specimen with infinite dimensions. In this regards, the procedure has been carried out for all compositions. To illustrate the method, Fig. 3 shows the fitted line for W50.

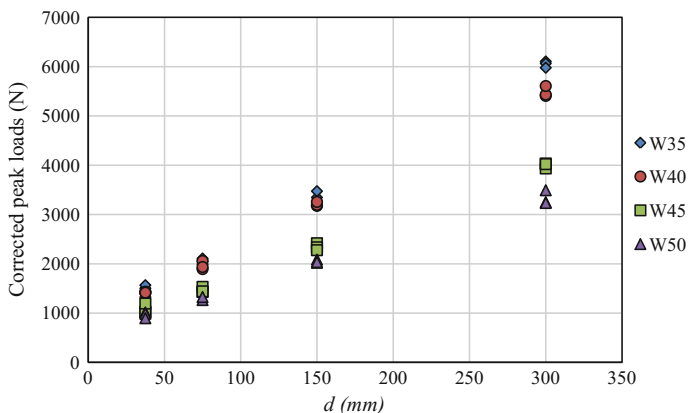


Fig. 2 Corrected peak loads of each mix versus depth of specimens

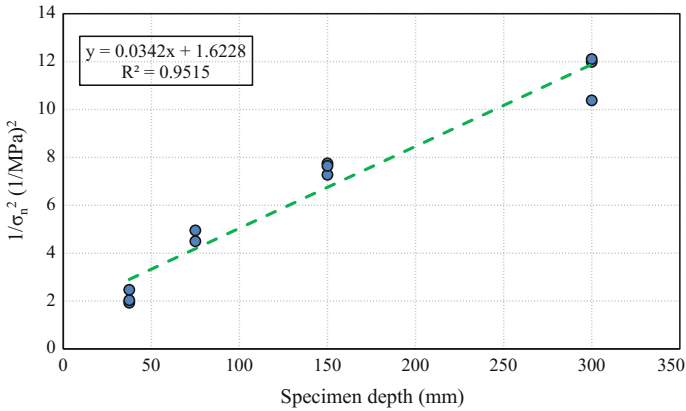


Fig. 3 Fitting a line for W50 mix

As can be seen, the values of slope and intercept of the fitted line are $0.0342 \text{ mm}^{-1} \text{ MPa}^{-2}$ and 1.6228 MPa^{-2} , respectively. Subsequently, in order to determine the fracture parameters Eqs. (8)–(10) were used. Figure 4 shows the variation of fracture energy and toughness versus water/binder ratio. It is apparent that by increasing the value of water/binder both values of fracture energy and toughness decrease. These findings could be attributed to probable increase in porosity of paste and interfacial zone. In addition, the critical crack-tip opening displacement has been affected by water/binder ratio (see Fig. 5). As can be seen, 27.4% variation in water/binder ratio caused 49.3% variation of fracture toughness along with 47.7% variation of fracture energy, and 3.2% of CTOD_c.

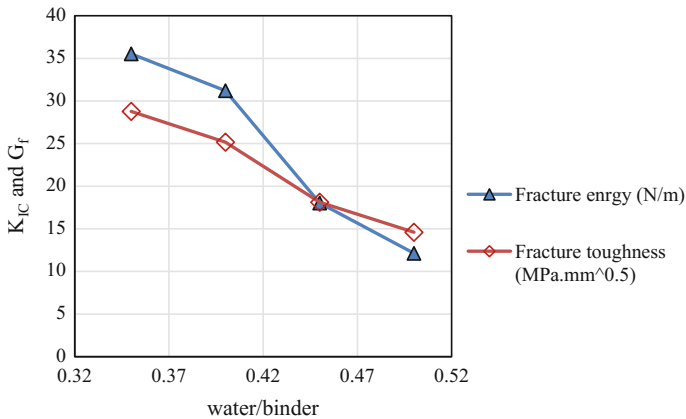


Fig. 4 Fracture energy and Fracture toughness versus water/binder ratio

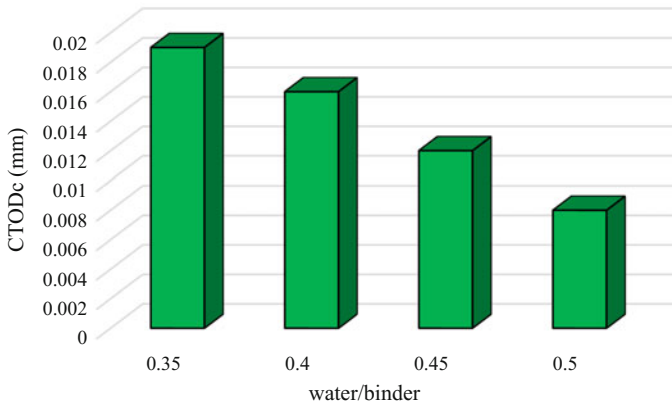


Fig. 5 Variations of critical crack-tip opening displacement versus water/binder ratio

5 Conclusions

The following conclusions could be drawn from the study:

1. The fracture energy has been influenced by water/binder ratio. In other words, as the water/binder ratio decreased, the fracture energy increased.
2. The decrease of water/binder ratio increased the fracture toughness of self-compacting lightweight concrete.
3. As the water/binder ratio increased, the critical crack-tip opening displacement decreased.

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