International Balkans Conference on Challenges of Civil Engineering, BCCCE,
19-21 May 2011, EPOKA University, Tirana, ALBANIA.

Investigation of Self-Compacting Concrete by Using Fracture Mechanics Methods

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ABSTRACT

Over a century, concrete has been used as a construction material all over the world, and its application areas increases and becomes commonplace each day. SCC is a special concrete type which places itself in densely-equipped narrow and deep sections with its own weight, tightens without any vibrations, has high resistance or durability characteristics and performances, and has a very fluid- consistency. Fracture Mechanics researches defects that increase stress concentration such as notch, crack and flaws in the material and the damages occurring in relation to these defects. Therefore, a cracked construction could be analyzed only by using fracture mechanics methods, that is, by determining fracture parameters realistically. Fracture parameters are among the most important characteristics of hardened concrete. In this study, SCC was investigated via the two-parameter fracture model which needs two fracture parameters namely: the critical stress intensity factor K_{Ic}^{s} and the critical crack mouth opening displacement $CTOD_c$ to characterize failure of concrete structures. In SCC mix, silica fume, fly ash and marble powder were used as powder materials. Since physical characteristics of the powder materials used are different, fresh concrete characteristics of the series display differences. Water curing was applied to all the concrete specimens. Although concrete mix ratio and storage conditions of all series are the same, powder admixture type affected concrete compressive strength. It is known that there is a close relation between concrete compressive strength and fracture parameters. Based on maximum loads of SCC specimens produced with different powder materials, critical stress intensity factor K_{Ic}^{s} and critical crack tip opening displacement $CTOD_c$, fracture parameters were determined. Consequently, it was observed that concrete compressive strength and powder admixture type are effective on fracture parameters of concrete.

Keywords: *Fracture mechanics; Two-parameter model; Self-compacting concrete; Fly ash; Marble powder*

INTRODUCTION

SCC is a special concrete type which places itself in densely-equipped narrow and deep sections with its own weight, tightens without any vibrations, has high resistance or durability characteristics and performances, and has a very fluid- consistency [1]. Its most important difference from conventional concrete is that powder materials and super plasticizer are used in its compound. Although SCC is denser than the conventional concrete, it includes such defects as cavity and fracture as it has [2].

Fracture Mechanics Science searches for defects like notch, fracture and cavity available in the material increases strain mass and the damage caused by these. These damages are also valid for concrete and reinforced concrete constructions. As concrete has a heterogenic structure, it has been determined that it could not be analyzed by Linear Elastic Fracture Mechanics (LEFM) Principles. Therefore, researchers have developed nonlinear fracture mechanics models that attend to fracture process zone. It is possible to classify these models as Cohesive Crack Models (Work-of-fracture Method, Size Effect Model [3] and Variable-Notch One-Size Specimen Method [4] and Effective Crack Models; Two-Parameter Model [5], Peak-load Method [6] and Effective Crack Model. In this study, self-compacting concretes which have different compounds has been obtained by using marble powder, silica fume, fly ash. Self-compacting concrete beams produced as notched were subjected to three-point bending tests. With the aid of sample maximum loads obtained, by using Two-parameter Fracture Model K_{Ic}^{s} and $CTOD_c$ fracture parameters were determined. When the results of the tests were evaluated, it was seen that powder material types (puzolanic or inert) are effective on SCC's fracture parameters.

SELF-COMPACTING CONCRETE

Self-compacting concrete (SCC) can be placed and consolidating under its own-weight without any mechanical vibration, and is at the same time cohesive enough to be handled with acceptable segregation or bleeding. SCC has many advantages over conventional concrete: (a) eliminating the need for vibration; (b) decreasing the construction time and labor cost; (c) improving the filling capacity of highly congested structural members; (d) decreasing the permeability and improving durability of concrete, and (e) facilitating constructability and ensuring good structural performance. SCC has been attracting more and more attention world-widely since its introduction in the late 1980's. New applications for SCC are being increasingly explored because of its many advantages over conventional concrete [7].

The functional requirements on a fresh SCC are different from those on a vibrated fresh concrete. Filling of formwork with a liquid suspension requires workability performance which is recommended to be described as follows: (a) filling ability: Complete filling of formwork and encapsulation of reinforcement and inserts horizontal and vertical flow of the concrete within the formwork with maintained homogeneity. (b) Passing ability, passing of obstacles such as narrow sections of the formwork, closely spaced reinforcement etc. without blocking caused by interlocking of aggregate particles. (c) Resistance to segregation: Maintaining of homogeneity throughout mixing and during transportation and casting. The dynamic stability refers to the resistance to segregation during placement. The static stability refers to resistance to bleeding, segregation and surface settlement after casting [8].

Although SCC is regularly used in applications every day, the technology still has a very large potential for refinement and further development. SCC will develop to be even more cost effective and thus increase its competitiveness on the market. There are a number of areas having high priority in the further development [9].

TWO-PARAMETER FRACTURE MODEL (TPM)

To analyze a concrete structure according to fracture mechanics, fracture parameters of the cementitious material must be determined at first. The studies on determining the fracture parameters of concrete were initiated by Kaplan [10]. He used the principles of classical linear elastic fracture mechanics (LEFM), which proposes a unique parameter (the critical stress intensity factor K_{Ic} for concrete fracture). However, the subsequent experiments revealed that

LEFM is not valid for concrete since K_{Ic} depends on size and geometry. The inapplicability of LEFM is because of the existence of an inelastic zone named fracture process zone (FPZ) in front of the crack in concrete. For this reason, several non-linear fracture mechanics models have been developed to characterize FPZ (Figure 1).

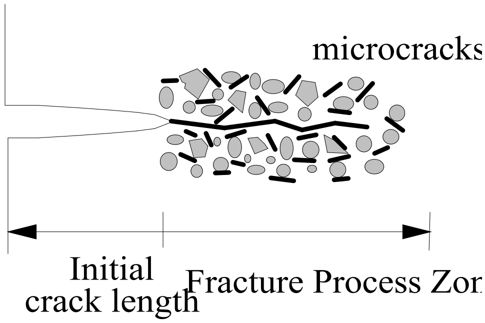

Figure 1 Fracture process zone

These models can be classified as the cohesive crack models (the fictitious crack model by Hillerborg [11] and the crack band model by Bazant [12]) and the effective crack models (the two parameters model (TPM) by Jenq and Shah [5], the effective crack model by Nallathambi and Karihaloo [13] and the size effect model by Bazant and Kazemi [14]). The cohesive crack models simulate FPZ by a closing pressure, which diminishes near the crack tip while the effective crack models simulate FPZ by an effective crack length. The primary aim of these approaches is to determine the critical crack extension (size of FPZ) at the peak load $\Delta a = a_e - a_0$, in which a_c and a_0 are the critical crack length at the peak load and the initial crack length respectively. Nevertheless, a_c depends on the structural size, because it decreases as the size increases. Consequently, the non-linear fracture approaches propose that at least two fracture parameters are required for concrete fracture. However, the results of any fracture model can be easily adapted to the other fracture models of concrete.

A concrete structure fails, according to TPM, when the stress intensity factor K_I and the crack opening displacement CTOD reach their critical values,   and $CTOD_c$. These fracture parameters can be calculated by means of the following LEFM equations:

$$K_{Ic}^{s} = \sigma_{Nc}\sqrt{\pi a_c}\, f_1(\alpha_c) \tag{1}$$

$$CTOD_c = \frac{4\sigma_{Nc} a_c}{E_c} f_2(\alpha_c) f_3(\alpha_c, \beta) \tag{2}$$

in which σ_{Nc} is the nominal failure stress, d is the structure size, E_c is the Young's modulus, $\alpha_c = a_c/d$, $\beta = a_c/a_0$ and f_1, f_2, f_3 are the dimensionless functions, which depend on the geometry of the structure and on the load type.

In this approach, the fracture parameters may be deduced from one of two different experimental methods: namely the compliance proposed by RILEM [2], and the peak load methos [4]. The peak-load method is a more simple method than the one introduced by RILEM in determining the fracture parameters of TPM because it requires uncomplicated testing equipment. However, it necessitates three or more distinct specimens due to the randomness of concrete properties. This is true for both methods. These specimens may be identical in size but different in initial crack length or have initial cracks of the same length but different sizes. For each of the tested specimen, the following equations can be written according to TPM:

$$K_I^i\left(\sigma_{Nc}^i, a_c^i\right) = K_{Ic}^s \qquad , i = 1,2$$
$$CTOD^i\left(\sigma_{Nc}^i, a_c^i\right) = CTOD_c \tag{3}$$

in which i denotes the ith specimen. Consequently, with this method at least two tests must be performed instead of one since the K_{Ic}^s is determined which causes the smallest standard deviation in the $CTOD_C$. In order to obtain this statistical adequacy, totally six specimens, with three different initial crack length and two specimens from each initial crack length, are sufficient in practice [15].

Nevertheless, TPM, the effective crack model by Nallathambi and Karihaloo[6] and the size effect model by Bazant and Kazemi[7] give essentially equivalent results. The experimental studies revealed that the parameter of the critical stress intensity factor (K_{Ic}) is reasonably well correlated both in TPM and in the effective crack model[17]. In addition, value of K_{Ic}^s obtained by TPM can be transformed to the fracture energy in size effect model according to the well-known LEFM relation:

$$G_f = \left(K_{Ic}^s\right)^2 / E_c' \tag{4}$$

in which for plain strain $E_c' = E_c / \left(1 - \nu^2\right)$ for plain stress $E_c' = E_c$, ν = Poisson ratio. Similarly, $CTOD_c$ parameter can be transformed to the effective fracture process zone length (c_f) in size effect model parameter as given by Eq. (5)[12]:

$$c_f = \frac{\pi E_c'}{32 G_f} CTOD_c^2 \tag{5}$$

The fracture energy parameter G_F determined by the fictitious crack model corresponds to the area under the entire stress-separation curve. This parameter is not identical to G_f in the size effect model. Statistical investigations by Bazant and Becq-Giraudon [16] have shown that the ratio G_F/G_f is about 2.5.

ENPERIMENTAL STUDIES

According to EN 197-1 [17] CEM I 42.5 N was used in all mixes. Its specific gravity, specific surface area by Blain, and 28 days compressive strength were 3.09, 3490 cm2/g and 49.1 MPa respectively. The maximum aggregate size was 16 mm (density of 2.66). The maximum sand grain size was 4 mm (density of 2.61). Mineralogically, the aggregate consisted of river. The grading of the aggregate mixture are shown in Table 1. The aggregate and sand were air-dried prior to mixing. The super-plasticizer viscoCrete-3075 was used in order to produce SCC for all mixes. Three types of powder, silica fume, fly ash [18] and marble powder [19-20], were utilized to obtain SCC mixes. Their physical and chemical properties are given in Table 2.

Table 1 The grading of aggregate (Cumulative percentage passing %)

Sieve size (mm)	16	8	4	2	1	0.5	0.25
Aggregate mixture	100	72	56	42	27	13	4

Table 2 Physical properties of mineral admixtures

Özellikler	Silica fume	Fly ash	Marble powder
SiO2 (%)	91	58.82	0.94
Al2O3 (%)	0.58	19.65	--
Fe2O3 (%)	0.24	10.67	0.46
CaO (%) (CaCO3)	0.71	2.18	(97.35)
MgO (%)	0.33	3.92	--
SO3 (%)	-	0.48	--
Density	2.04	2.25	2.71
Blaine (cm2/g)	--	3812	4372
45µm geçen	%98 < 45µm	--	--

Mix proportions are given in Table 3. Concrete mixes were made in power-driven revolving type drum mixers. Four mixture proportions were made (Fig. 2) [21]. First was control mix (without silica fume, fly ash and marble powder), and other three mixes contained just one type of powder.

Table 3 Mixture proportions

Series	Cement (kg/m^3)	Silica Fume (kg/m^3)	Fly Ash (kg/m^3)	Marble Powder (kg/m^3)	Sand (kg/m^3)	Coarse (kg/m^3)	W/C	Super Plasticizer (%)
SF	298	52	0	0	852	852	0.67	2
FA	298	0	52	0	856	856	0.67	2
MP	298	0	0	52	861	861	0.67	2
REF	350	0	0	0	864	824	0.67	2

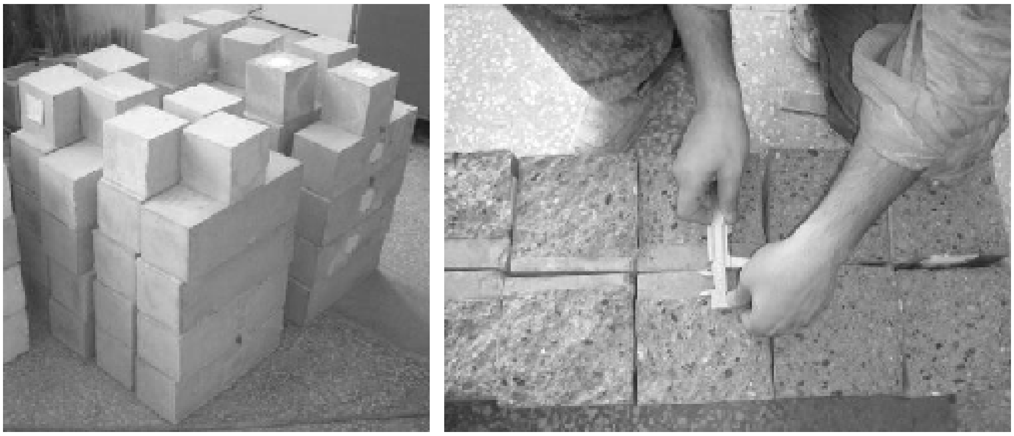

Figure 2 Test specimens

The 150 mm concrete cubes were cast for compressive strength. Specimens 150×150×450 mm (span length = 380 mm) were cast in steel moulds for fracture model. The specimens were cast as the notch face is at the bottom. The eight beam specimens were classified into three groups of according to the relative initial crack length a_0/d = 0.1, 0.2 and 0.25. All the test specimens were demounted after 24 h, and were put into a water-curing tank during 28 days.

ENPERIMENTAL RESULTS

Fresh concrete properties were determined. Slump-flow, T50 time, V-funnel test, L-box (h1/h2), test and sieve segregation resistance measured, as shown in Table 4. The cube and beam specimens were tested and determined peak loads. Three-point bend beams have been widely used to measure fracture properties of concrete. When the Two-parameter Method (TPM) used to determine of fracture parameters of concrete, K_{Ic}^{s}, $CTOD_c$, G_F and c_f was results.

Table 4 Physical properties of mineral admixtures

Series	T_{50} (s)	Flow (cm)	SG (%)	h_1/h_2 (%)	T_v (s)	f_c (MPa)	K_{Ic}^{s} (MPa√m)	$CTOD_c$ (mm)	G_f (N/m)	c_f (mm)	G_F (N/m)
SF	1	65	0	0.89	5.3	45.7	1.101	0.0177	36.4	27.1	90.9
FA	1.1	70	4	0.86	6.6	41.8	1.136	0.0191	40.5	27.1	101.2
MP	0.8	69	4	0.86	7.2	35.9	1.089	0.0232	40.1	37.3	100.3
REF	-	[15]	-	-	-	31.9	1.334	0.0259	63.9	27.6	159.7

The K_{Ic}^{s} - $CTOD_c$ relationship were determined for each group by utilizing the Equations 1 to 3, for instance for the batch FA and REF as shown in Figure 3.

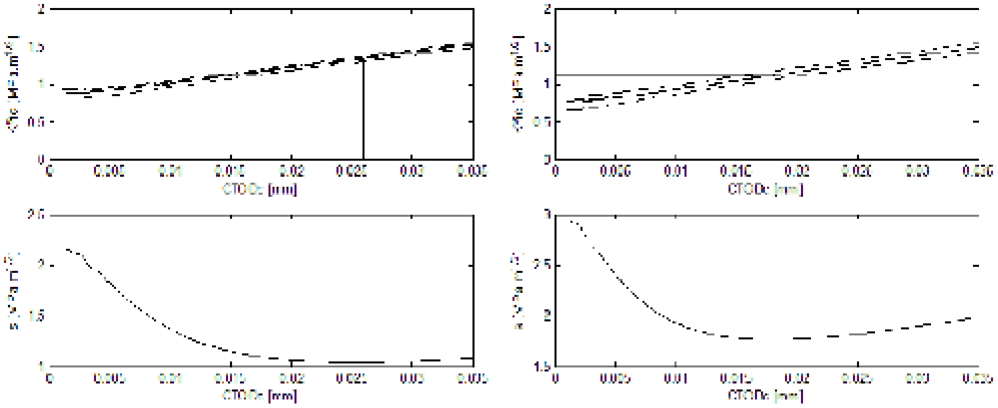

Figure 3 K_{Ic}^{s} versus $CTOD_c$ curve and s versus $CTOD_c$ curve for batch FA and REF

As expected, SCC with silica fume has the highest compressive strength and all SCCs compressive strength is higher than references SCC mix. All the specimen mixes were the same. But fracture parameters are different. Each powder material has the different microstructure, physical and chemical properties. Fracture parameters of SCC are compared and shown in Fig 4.

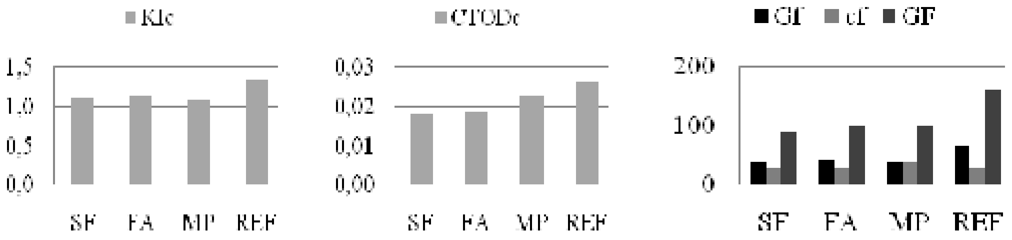

Figure 4 Fracture parameters of series

CONCLUSION

The conclusions of this study can be said as follows:

- When the properties of fresh SCC such as slump-flow, v-funnel time, segregation resistance and L-box are considered as a criterion to determine the optimum usage ratio of powder materials (silica fume, fly ash and marble powder) in SCC, it can be said that usage amount below %15 powder content is suitable for improving all these properties. Even the slump-flow values of SCC incorporating fly ash and marble powder are high. Therefore, the risk of segregation is increased. In the case of using silica fume, segregation risk is decreased. This section should state the most important conclusions of the paper.
- Fracture parameters of concrete, K_{Ic}^{s} and $CTOD_c$, obtained from three-point bend beams. K_{Ic}^{s} results is more suitable than the $CTOD_c$ results. Because of microstructure of powder materials, $CTOD_c$ results are different for each SCC series. Silica fume and fly ash are puzzolanic materials.
- Based on maximum loads of SCC specimens produced with different powder materials, critical stress intensity factor K_{Ic}^{s} and critical crack tip opening displacement $CTOD_c$, fracture parameters were determined. Consequently, it was observed that concrete compressive strength and powder admixture type are effective on fracture parameters of concrete.
- Fracture energy G_f (also G_F) and fracture process zone length c_f fracture parameters were also determined. Consequently, it was observed that concrete compressive strength is effective on G_f(also G_F), and powder admixture type is effective on.

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