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Investigation of Fracture Parameters of Self-Compacting Concrete Produced with Marble Powder by Peak-Load Method

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ABSTRACT

Fracture parameters are among the most important characteristics of hardened concrete. In this study, SCC was investigated via the two-parameter fracture model (peak-load method) 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, different marble powders were used as powder materials. Marble powder is a new material for concrete. Marble powder is a limestone origin waste material. Samples 150x150x150 mm and 150x150x450 mm in size were produced. It is known that there is a close relation between concrete compressive strength and fracture parameters. 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 are effective on fracture parameters of SCC.

Keywords. Self-Compacting Concrete, Fracture Parameters, Peak Load Method, Marble Powder

INTRODUCTION

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 (Okamura and Ouchi, 1999).

The possibility of casting concrete relying only on gravity and thus avoiding vibration compaction is one of the most significant recent breakthrough developments in the construction sector in this century. The Self-Compacting Concrete technology has rapidly developed from the stage of exploration in research laboratories to routine use in many parts of the world that is from Japan to USA. The concrete material design concept is modified, the concreting process is radically changed and several implications are seen in architectural as well as structural design. Overall increased productivity give rise to cost cuts, improved quality assurance and improved durability reducing service life costs (Skarendahl, 2005).

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 analysed 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 (Bazant et al., 1986) and Variable-Notch One-Size Specimen Method) (Tang et al., 1996) and Effective Crack Models (Two-Parameter Model (Jeng and Shah, 1985), Peak-load Method (Yang et al., 1997) and Effective Crack Model).

Powder admixture type plays very important role in concrete (Youjun et al, 2005). With the need of high performance for concrete, properties of powder admixtures gradually become a main factor during concrete design. Marble powder is a new material for concrete (Alyamaç, 2008). It is well known that marble powder as filler material (mineral powder admixtures) in SCC shows quite good performance (Topçu et al., 2009). Marble powder is very important for sustainable concrete (Alyamaç and Ince, 2009).

Based on above considerations, in present paper, self-compacting concretes which have same compounds has been obtained by using different marble powders. Self-compacting concrete beams produced as notched were subjected to three-point bending tests. With the aid of sample maximum loads obtained, by using Peak-Load Method, the critical stress intensity factor K_{IC}^{s} and the critical crack mouth opening displacement $CTOD_c$ fracture parameters were determined. Consequently, it was observed that powder admixture is effective on fracture parameters of SCC.

EXPERIMENTAL PROGRAM

Materials. According to EN 197-1, 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 cm^2/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 is shown in Table 1. The aggregate and sand were air-dried prior to mixing. The superplasticizer viscoCrete-3075 was used in order to produce SCC for all mixes. Three types of marble powder were utilized to obtain SCC mixes.

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

Marble Powder (MP). All natural stones that industrially can be processed as cut to size, polished, used for decorative purposes and economically valuable are called as marble. USA, Belgium, France, Spain, Sweden, Italy, Egypt, Portugal and Greece are among the countries with considerable marble reserve (Onargan et all., 2006). Turkey has the 40 percent of total marble reserve in the world. 7.000.000 tons of marble have been produced in Turkey annually and 75 percent of these production have been processed in nearly 5000 processing plants. It can be apparently seen that the waste materials of these plants reach millions of tons. Stocking of these waste materials is impossible.

In marble quarries, the stones are being cut as blocks via different methods. These blocks are being moved to processing plants. In these plants, the blocks with 15-20 tons weight are being cut to size as decorative tiles and being polished. During the cutting process, the dust of the marble and water mixes together and become waste marble mud. The material that become dry mud after being refined within the refinement facilities are too big for stocking and becoming harmful for the environment day by day (Fig. 1). During the cutting process 20% - 30% of the marble block become dust.

Figure 1. Marble powder (MP) waste

These type solid waste materials should be inactivated properly without polluting the environment. The most suitable inactivating method nowadays is recycling. Recycling provides with some advantaged such as protecting the natural resources, energy saving, contributing to economy, decreasing the waste materials and investing for the future (Kaseva and Gupta, 1996). The self-compacting concrete technology has a big potential for this type solid waste materials (Uysal and Sumer, 2011). Their physical and chemical properties are given in Table 2. Microstructure of powder admixtures can be seen from Fig 2.

Table 2. Physical and chemical properties of marble powders used

Properties	Cherry	White	Gold
Specific gravity	2.71	2.71	2.71
Specific surface area (cm^2/g)	3924	4372	5106
CaO (%)	40.45	54.55	49.53
SiO_2 (%)	28.35	0.14	1.25
Fe_2O_3 (%)	9.70	0.32	0.32
MgO (%)	16.25	4.17	0.40

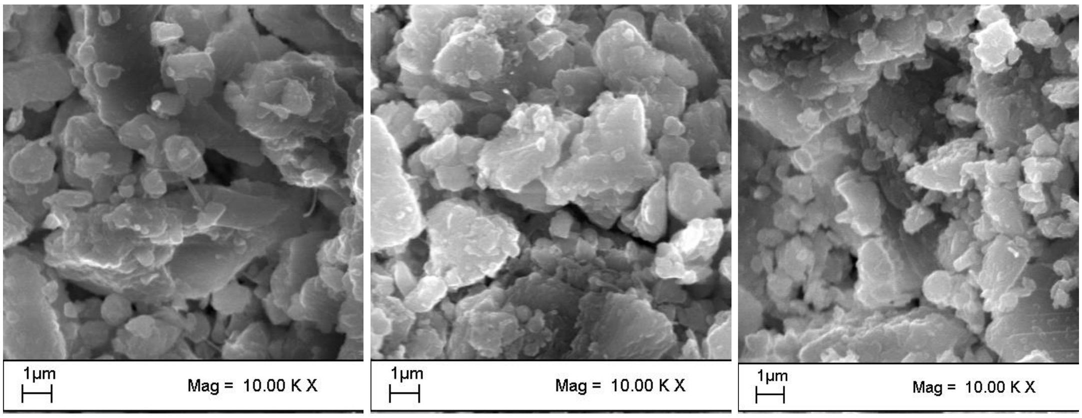

Figure 2. SEM of marble powders: Cherry, White and Gold, respectively.

Table 3. Mix Proportions

Mixture no.	MP-C	MP-W	MP-G	MP-CWG	REF
Cement (kg/m^3)	350	350	350	350	350
Name of marble powder	Cherry	White	Gold	Mixed	--
Marble powder (kg/m^3)	150	150	150	150	--
Sand (kg/m^3)	791	791	791	791	838
Coarse aggregate (kg/m^3)	791	791	791	791	838
W/C	0.57	0.57	0.57	0.57	0.57
Superplasticizer (l/m^3)	7	7	7	7	7

Mix Proportions. The concrete mixture proportions were reported in Table 3. Five mixture proportions were made (Fig. 3). All series were prepared same ratio of sand to cement. SCC mixes prepared with different marble powder named cherry, white and gold. Concrete mixes were made in power-driven revolving type drum mixers.

Preparation of Test Specimens. Self-consolidation characteristics are related to the workability properties: filling ability, passing ability and, the resistance to segregation. Filling ability is the capability of completely filling all spaces without vibration. Passing ability is the aptitude to flow through reinforcement bars without any blocking. Resistance to segregation is to remain homogeneity of concrete without separating of grout from the mix. Although several methods have been used for self-compacting concrete in order to characterize the fresh state of the resulting concrete, there is no single test that can adequately measure for workability properties. On the other hand, there is no unique standard test method measuring the workability properties of SCC. In this study, the standard test methods used according to (EFNARC 2005) are given: slump-flow, T50 time, v-funnel, L-box and sieve segregation resistance tests.

To determine mechanical properties of hardened concrete, compressive strength tests was applied at 28 days. The test specimens were used as 150 mm cubes. Samples for determine fracture parameters 150x150x450 mm in size notched beams were produced (Fig. 3). Specimens in each series were cast in plastic moulds. Specimens were removed from the mold after 1 day and subsequently, the ones with test age of 28 days were cured 95% relative humidity and temperature of about 23 ^{o}C. All the specimens were tested in a testing machine with the capacity of 2000 kN.

Figure 3. Test specimens

Peak-Load Method Based on TPM. In this study, notched beam specimens used in the two-parameter model. The cube and beam specimens were tested. . The results of the tests were analyzed in the two-parameter model (TPM) (Jeng and Shah, 1985) using the peak-load method (Tang et all., 1996). A concrete structure fails according to the TPM when the stress intensity factor K_I and the crack opening displacement *CTOD* reach their critical values, K_{IC}^{s} and $CTOD_c$, respectively. These fracture parameters can be determined with the following LEFM equations (1) and (2):

$$K_{Ic}^{s} = \sigma_{Nc}\sqrt{\pi a_c}\,Y(g,l) \tag{1}$$

$$CTOD_c = \frac{4\sigma_{Nc}a_c}{E'}V_1(g,l)M(g,l) \tag{2}$$

where σ_{Nc} is the nominal failure stress; $E' = E/(1-\nu^2)$ for plane strain; $E' = E$ for plane stress; E is Young's modulus; ν is the Poisson ratio; and Y, V_1, and M are dimensionless functions that depend on the geometry of the structure (g) and the load type (l). The parameter Y is also called the geometry factor. The function M is derived from the ratio of $COD(a_c)/CMOD_c$, where $CMOD_c$ is the critical crack mouth opening displacement. Because the Y, V_1, and M functions can be found in LEFM handbooks (Tada et al., 2000, Guinea et al., 1998), the TPM can easily be used in structural analysis. In this approach, the fracture parameters are deduced from one of two experimental methods: the compliance method, proposed by (RILEM, 1990), and the peak load method, proposed by (Tang et al., 1996). In the first method, the fracture parameters are determined from the relationship between the load and the crack mouth opening displacement (P-CMOD) of three point bending specimens with a central edge notch using closed-loop test equipment, as shown schematically in Fig. 4. The critical crack length a_c is calculated from two values taken from the P-CMOD curve: the initial compliance C_i and the unloading compliance C_u, measured at approximately 95% of the peak load (P_c) in the descending branch, as given by Eq. (3):

$$a_c = a_0\,\frac{C_u V_1(a_0/d)}{C_i V_1(a_c/d)} \tag{3}$$

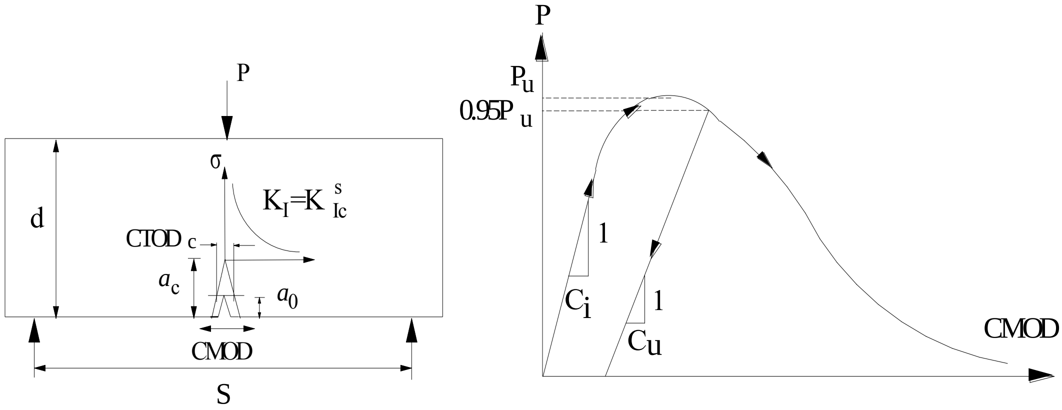

Figure 4. Fracture parameters of concrete according to the TPM

where *d* is the structure size. The Young's modulus of concrete *E* can also be calculated using the initial compliance C_i or the unloading compliance C_u.
Because it does not require complicated testing equipment, the peak-load method is simpler than the method introduced by RILEM to determine fracture parameters in the TPM. Nevertheless, it requires 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 their initial crack lengths may differ. Alternatively, the initial crack lengths may be equal, but the sizes of the specimens may differ. For the each specimen tested, the following equations (4) can be written according to the TPM:

$$K_I^i\left(\sigma_{Nc}^i, a_c^i\right) = K_{Ic}^s, \qquad CTOD^i\left(\sigma_{Nc}^i, a_c^i\right) = CTOD_c, \qquad i = 1, 2 \tag{4}$$

where *i* denotes the *i*th specimen. Consequently, the fracture parameters can be found by simultaneously solving four non-linear equations. However, three or more distinct specimens must be tested to ensure statistically valid results because random errors always exist in measured values of σ_{Nc}^1 and σ_{Nc}^2. In this study, a statistical procedure was used to calculate K_{Ic}^s and $CTOD_c$. In practice, it is possible to combine the fracture parameters K_{Ic}^s and $CTOD_c$, and the material parameter *E* into a single length parameter *Q*. This is referred to as the brittleness number by Jenq and Shah (1985) as given in Eq. 5:

$$Q = \left[\frac{E.CTOD_c}{K_{Ic}^s}\right]^2 \tag{5}$$

The experimental studies illustrated that the values of *Q* are ranging from 50-150 mm for mortar, and 150-450 mm for normal concrete. Smaller values of *Q* point out a more brittle material behavior.

TEST RESULTS AND DISCUSSION

Properties of Fresh Concrete. Fresh concrete properties were determined. Slump-flow, T_{50} time, v-funnel test (t_v), L-box (h_1/h_2) test and sieve segregation resistance measured, as shown in Table 4. In this study, different marble powder materials used to prepare for SCC mixes. Three powder types almost had same characteristics but they have different specific surface areas. Fresh concrete properties of SCC appear to be about the same. Type of marble powder on the properties of fresh concrete can be said about the same effect.

Table 4. Fresh SCC Properties

Mix	T_{50} (s)	Flow (cm)	Seg.Res. (%)	h_1/h_2 (%)	t_v (s)
MP-C	1.8	64	0	96	6.9
MP-W	2.1	61	0	93	7.5
MP-G	1.9	62	0	94	7.1
MP-CWG	2.0	62	0	95	7.0
REF	-	[13-15]	0	--	--

Properties of Hardened Concrete. The notched specimens were analysed according to the peak-load method based on the TPM. The specimens were designed with three different initial notch lengths and with the same specimen size. In the peak-load method, the fracture parameter K_{Ic}^{s} that causes the smallest standard deviation in the $CTOD_c$ is determined because at least two tests are required. However, as previously mentioned, at least three groups must be tested to obtain statistically valid results because random errors always exist in measured nominal strength values. The following statistical procedures were used to evaluate TPM, K_{Ic}^{s} and $CTOD_c$, according to this method (Ince, 2010a). Specimens were grouped with reference to their initial crack length a_0. Subsequently, the average K_{Ic}^{s} - $CTOD_c$ curve was obtained for these groups. The sample standard deviation of the groups was then calculated as follows:

$$s(CTOD_c) = \sqrt{\sum_{i=1}^{n}\left[\left(K_{Ic}^{s}\right)^{ave} - \left(K_{Ic}^{s}\right)^{i}\right]^2 \Big/ (n-1)} \qquad (6)$$

where n is the number of groups (n=3 in this study); $\left(K_{Ic}^{s}\right)^{ave}$ is the average value of K_{Ic}^{s} for all groups; and $(K_{Ic}^{s})^{i}$ is the value of K_{Ic}^{s} for the i^{th} group. The fracture parameter K_{Ic}^{s} was obtained by substituting this value of $CTOD_c$ into the average K_{Ic}^{s} - $CTOD_c$ curve. In this study, the Young's modulus of concrete in Eq. (7) was determined according to (ACI-318, 2002) as follows (in which E and f_c' are in MPa):

$$E = 4734\sqrt{f_c'} \qquad (7)$$

Table 5 shows the test data of the beams for all batches, respectively. In this table, the average failure loads P_{av} are summarized by grouping according to a_0 values. Figure 5 indicates the results of the peak-load method analysis for mixes with three different marble powders namely: cherry, white and gold, and references. In Table 5, the hardened concrete values based on two-parameter fracture model: $\alpha(= a_0/d)$, f_c', K_{Ic}^{s}, $CTOD_c$ and Q by using Equations 1-7 are also summarized for all batches. Figure 6 reveals the relations of the fracture parameters of TPM according to the Blaine surface area.

Table 5. Test Results

Mix	$P_{av}^{\alpha=0.1}$ (kN)	$P_{av}^{\alpha=0.2}$ (kN)	$P_{av}^{\alpha=0.25}$ (kN)	f_c (MPa)	K_{IC}^{s} $MPa\sqrt{m}$	$CTOD_c$ (mm)	Q (mm)
MP-C	17.1	14.4	13.2	40.08	1.0654	0.0228	411
MP-W	18.0	14.5	13.2	37.89	1.0472	0.0213	351
MP-G	18.1	14.6	13.7	42.42	1.0159	0.0192	340
MP-CWG	17.6	14.5	13.1	38.45	1.0800	0.0237	415
REF	15.2	13.4	11.9	33.02	0.9517	0.0219	392

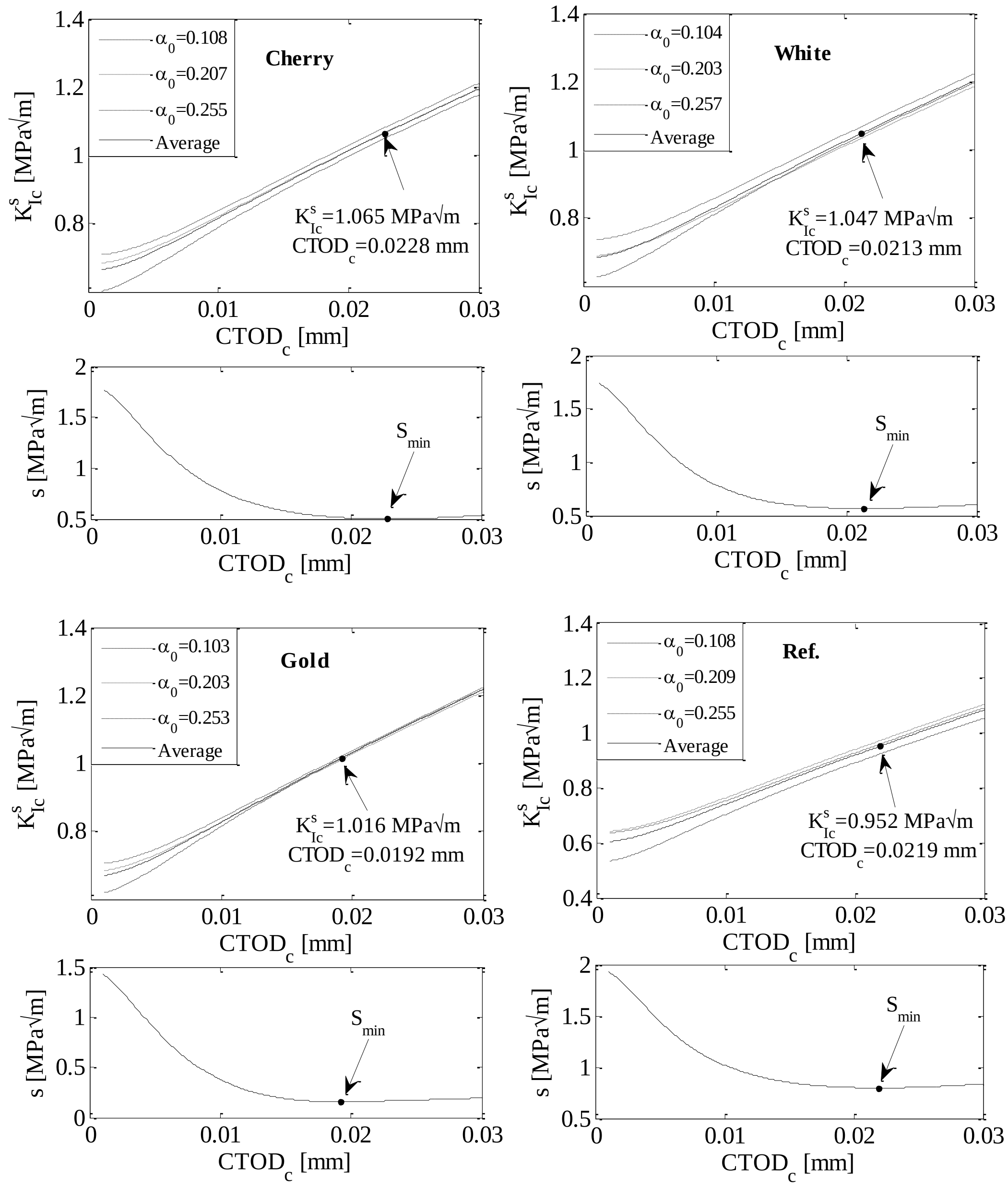

Figure 5. Peak-load method analysis for different SCC mixes and ref. concrete

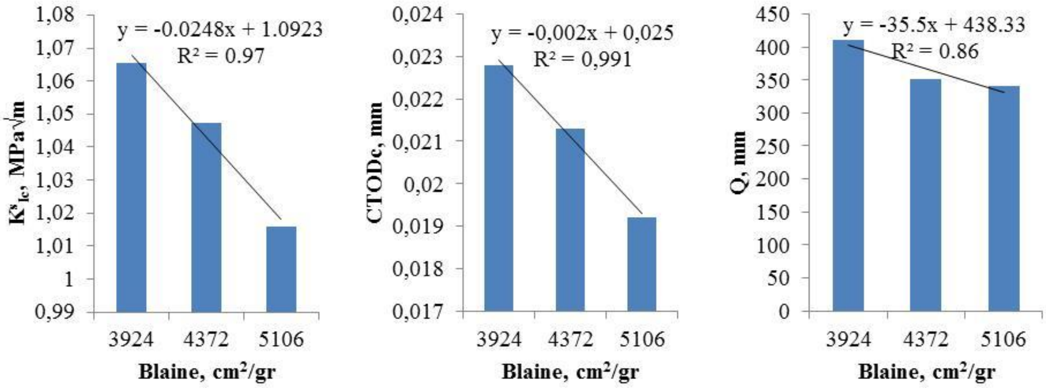

Figure 6. The relations between fracture parameters and Blaine values of MP

CONCLUSION

The experimental studies revealed that the fracture parameters of concrete are particularly influenced by four material parameters: compressive strength (f'_c), maximum aggregate size (d_{max}), water-cement ratio (*w/c*), and aggregate type. Bazant and Becq-Giraudon (2002) suggested relationships between the fracture parameters of the size effect model and these material parameters, based on the data of 238 sets available in the literature. It is well known that there is a strong correlation between f'_c and *w/c*. f'_c increases with reducing *w/c*. In addition, experimental studies indicate that *w/c* and d_{max} also affect the internal structure of the concrete. The total volume of voids in a given volume of concrete increases with increasing *w/c*, while it may decrease as d_{max} increases due to the fact that the context of cement paste decreases with increasing d_{max}. This also affects fracture the behavior of concrete. Ince (2004, 2010b) applied neural networks, which is a very powerful tool to solve many civil engineering problems, in order to predict the fracture parameters of TPM, K^s_{Ic} and $CTOD_c$, from *w/c*, d_{max} and f'_c . The results based on neural networks indicate that there is a very strong correlation between f'_c (or *w/c*) and K^s_{Ic} , whereas $CTOD_c$ is nearly independent. Moreover, it was concluded that both $CTOD_c$ and K^s_{Ic} increase with increasing d_{max}.

It was concluded from Figure 6 and considering above knowledge that the fracture parameters of concrete decrease as increasing the Blaine values of the powder. This effect is stronger at $CTOD_c$ than the other parameters. Moreover, it was observed that concrete compressive strength and the Blain values of powder are effective on fracture parameters of SCC.

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