Effects of the aggregate size and specimen dimensions on the brittle fracture of concrete

M.A. Issa & A. Chudnovsky
Department of Civil and Materials Engineering, University of Illinois at Chicago, Chicago, IL, USA

ABSTRACT: There is a large argument about the reported findings in literature with respect the effect of the concrete-specimen size and maximum aggregate size on the fracture properties of concrete. This argument was the direct motivation for the National Science Foundation (NSF) to initiate a research program objecting at providing a reasonable understanding of the effects of the specimen size and aggregate size on the fracture properties of concrete. The authors have conducted an extensive experimental program over the past 15 years and published a series of novel papers that discussed their results and compared them with results of other reliable studies. Herein, the authors summarize major findings and clarify critical factors, with a dominant goal of making valuable information available for interested researchers. The relationships between the size effects and main fracture parameters such as crack length and trajectories, critical energy release rate, and fracture roughness and toughness were explored.

1 INTRODUCTION

Numerous studies have revealed that inevitably micro and sub-micro defects and resulting highly localized stress concentrations are responsible for brittle fractures often occur while the applied stresses are substantially lower than the yield strength of the material. Consequently, fracture behavior depends not only on the applied load and environment, but also on the nature of the defects sizes, orientations, and locations. Cementitious-based materials like concretes are highly heterogeneous by design. The stress-strain relationship of concrete, exhibits a nonlinear region before the peak and substantial post-peak strain softening. High-strength concrete often consists of cement paste stronger than the aggregate; thus it exhibits brittle behavior due to the propagation of the cracks directly through the aggregates. Less brittle behavior such as in normal strength concrete is associated with more tortuous fracture surfaces dominated by the distribution of aggregates. A process zone of variable size accompanies crack propagation in concrete. Energy release and absorption during the fracture processes of concrete are accompanied with many specific mechanisms such as micro-cracking, crack bridging, and aggregate interlocking that affect the tortuous path of the main crack. Roughness of the fracture surface of concrete varies depending on the mix design. Broken concrete surfaces are commonly rough, fragmented, and composed of mountains and valleys that can be described by the concept of fractal dimension (Mandelbrot 1984).

The predictions regarding resistance of a concrete structure to a short-term overloading or its resistance to fatigue or creep crack propagation can be made only in probabilistic terms. In addition, selection of material for a full-scale structural element by collecting statistical data via identical tests is unrealistic due to time constraints and high costs. Therefore, designers are restricted to the results of small scale laboratory testing. However, there is a well-recognized scale effect in fracture that obstructs a simple extrapolation of small-scale test results. Thus, a reasonable size effect model in brittle fracture is required. In a series of studies (Issa et al. 1992, 1993, 1994, 1998) the foundation for a comprehensive systematic study (Issa et al. 1999-I, 1999-II, 2003) on the effect of aggregate size and specimen dimensions with respect to fracture properties of concrete. A review of the methodology and findings of last three studies will be conducted in the upcoming sections of this paper.

2 OVERVIEW OF SELECTED STUDIES

2.1 *Aggregate and Specimen Size Effects*

Strength and size of the aggregates affect the fracture properties of concrete significantly since the presence of aggregates tends to increase the tortuosity of the fracture path. Several researchers have investigated the effect of aggregate and specimen sizes on the fracture parameters of brittle materials. Nallthambi et al. (1984) found that the size and shape of the aggregate significantly affect the fracture toughness as a result of the increased resistance for the propagating crack. Energy requirements diminish as the angularity of the aggregate is decreased due to debonding and microcracking. Shah (1982) indicated that fracture toughness, represented by R-curves, increased with an increase in the maximum size or volume fraction of the aggregates, and that the shape of the R-curve is likely to depend on specimen geometry. Hillerborg (1985) reported that mortar shows smaller fracture energy (G_F) values than concrete and there is a trend of concrete G_F increase with an increase of the maximum aggregate size. Wolinski et al. (1987) observed an increase of G_F up to 35% between the categories of aggregate sizes of 2 to 4 mm (mortar) and 8 to 32 mm (concrete). However, within each category they reported no consistent effect of aggregate size on the fracture parameters. Saouma and Barton (1994) concluded that the fracture toughness (K_{1c}) and G_F are aggregate and specimen size independent if certain minimum dimensions are exceeded. However, both K_{1c} and G_F depend on the aggregate shape.

Nallthambi et al. (1984) found that the fracture toughness (G_{1c}) increases with an increase in specimen size. They proposed an expression for G_{1c} in terms of material properties, specimen size, notch depth, and maximum aggregate size. Perdikaris et al. (1986) indicated that the observed size effect on the fracture toughness in the static and fatigue tests suggests that G_{1c} and K_{1c} cannot be considered to be material parameters. Alexander and Blight (1988) found that K_{1c} increases as the depth of notched beam increases. They found a monotonic increase in the micro-crack zone as the depth of the specimens was increased. Wittman et al. (1990) concluded that by increasing the ligament length of compact tension specimens from 100 to 300 mm, G_F increased by 25%. Bazant and Kazemi (1991) reported that the G_F is very sensitive to specimen size and increases as specimen size increases. Size dependence comes from the size of the process zone ahead of the crack-tip. In smaller specimens, the process zone size is large compared to the size of the specimen and LEFM is not applicable, but as the size of the specimen increases, the relative size of the process zone decreases, becoming negligible for very large specimens. Issa et al. (1992, 1993) observed that K_{1c} and G_{1c} exhibited significant increase only when the size of the specimen was increased more than 3 times. They found a monotonically increasing G_F as the depth of the specimens was increased. Carpinteri (1994) proposed scaling laws and renormalization groups for strength and toughness of disordered materials. Mihashi et al. (1996) found that G_F values increased as the specimen size increased, when the crack length exceeds about a of the ligament length, local fracture energy starts to increase, and the increase rate is higher in smaller specimens than in larger ones. Linsbauer and Sajna (1996) found a slight increase in G_F with increasing sample size and reported nearly no size effect. They also found that G_{1c} shows the usual increasing trend with increasing specimen size and is characterized by significant size effect sensitivity. Jueshi and Hui (1997) found that as the specimen size increases, G_F decreases.

2.2 *Fractal Dimension of Concrete*

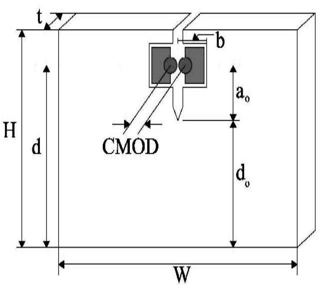
Many processes of considerable practical importance take place at or near disorderly interfaces that cannot be adequately described in terms of simple Euclidean shapes. A linkage between fractal dimension of fractured surfaces and fracture toughness was first suggest by Mandelbrot et al. (1984). There are various ways for evaluating experimentally generated concrete rough surfaces. Winslow (1985) used an x-ray scattering technique was used for measuring the fractal dimension of fractured surfaces of cement paste specimens. It was found that the surface of hydrated cement paste is fractal with high fractal dimension and the higher water-cement ratios yield less irregular surfaces. Using a replica technique, Brand and Prokopski (1993) concluded that fractured surfaces of concrete-like composites are fractal objects and higher fracture toughness is accompanied by higher values of fractal dimension. Using an image analysis technique, Lange et al. (1993) found that as fracture surface roughness increases, fracture toughness (K_{1c}) increases and that the fractal dimension increases as the roughness increases. Using the box method, Saouma and Barton (1994) observed that the fractured surfaces are fractal over the measured range of scales, the fractal dimension is independent of crack trajectory, fracture toughness values are independent of aggregate sizes, sub-angular aggregates yielded smaller fractal dimension values than rounded aggregates, and the fracture toughness (K_{1c} and G_F) increases with a decrease in fractal dimension in concrete. Issa and Hammad (1993, 1994) evaluated the fractal dimension of concrete and mortar fractured surfaces using the modified slit-island technique. They noticed that the fractal dimensions of concrete fractured surfaces increase monotonically with increasing maximum aggregate size. Carpinteri discussed important issues about the fractal nature of material microstructure and size effects on apparent mechanical properties (Carpinteri 1994).

Based on the previous review, it can be concluded that despite the controversy, the size effect is an important factor in concrete fracture. The aim of providing more clarification to this issue and eliminating the controversy were the motivation for the comprehensive systematic study conducted by Issa et al. (1999-I, 1999-II, 2003) under well controlled experimental conditions.

3 RESEARCH METHODOLOGY AND SELECTED RESULTS

3.1 *Brief Description of the Specimens Details and Testing Setup*

The comprehensive study included six sets of geometrically similar concrete specimens of various sizes with various maximum aggregates. Over 200 specimens were tested in the quasi-static cyclic mode of testing. The geometrical similarity was maintained by scaling up all the macroscopical dimensions of the specimens from one set to the next by a factor of 2 as shown in Figure 1. An additional set of intermediate size specimens (S2) was also incorporated in the study. Different concrete mixtures were used in casting of the specimens in each group. The variation between the mixtures was the sand to coarse aggregate ratio and the maximum aggregate size. The mixtures almost had comparable compressive strength and elastic modulus. The aggregate sizes that were used are 4.75, 9.5, 19, 38, and 76 mm. Two relative notch depths of 0.15 and 0.30 were used. The notch and loading fixture were designed to have a reproducible crack initiation and a controlled crack growth. After testing four types of loading fixtures, a rectangular fixture mounted with bearings and rollers to minimize friction was found to be the most appropriate for the application intended. The testing machine was equipped with displacement, load, and strain channels to control the rate of displacement, loading, and strain, respectively. Optical and acoustic imaging systems were used to monitor the fracture process. Detailed description of the test specimens, testing setup, and testing procedure can be found in Issa et al. (1999-I).



Spec. Name	II, mm	d, mm	W, mm	t, mm	a_o, mm	
					0.15d	0.30d
S1	1680	1400	1680	200	210	420
S2	1050	875	1050	125	131	263
S3	840	700	840	100	105	210
S4	420	350	420	50	53	105
S5	210	175	210	25	26	53
S6	105	88	105	12.5	13	26

Figure 1. Dimensions of test specimens.

3.2 *Size Effect on the Fracture Toughness*

Critical load-CMOD curve was obtained for each specimen, and the envelopes were used in the analysis and comparison of the data. The data was presented in dimensionless form for the sack of comparison. The fracture energy indicated the existence of a strong scale effect; the fracture energy increased with the specimen dimensions as well as with the maximum aggregate size. Additional investigation for the effects of the specimen size and the aggregate size on the fracture properties was conducted in Issa et al. (1999-I) based on fracture mechanics analysis. The analysis indicated that G_{1c} increases with the crack length (R-curve behavior), with the specimen size, and with the maximum aggregate size d_{max}. After considering the G_{1c} values of various specimen sizes for fixed relative crack length, a power relationship was observed between G_{1c} and d_{max} for maximum aggregate size larger or equal 9.5 mm. This relationship was not observed for the specimens made with d_{max} of 4.75 mm, which was attributed to the fact that the maximum coarse aggregate size used in these specimens is similar to the maximum grain size of sand. In addition, for a constant crack length, a power relationship between G_{1c} and W was observed for specimens with W larger or equal to 420 mm. It is noteworthy to mention that, the lower two sizes of specimens did not follow this trend. The increase in fracture toughness with an increase in specimen size is most probably associated with the ratio of process zone and specimen size. Since the process zone is relatively large in a small specimen, its fracture characteristic is lower. As the specimen becomes bigger, the relative size of the process zone becomes smaller, and the fracture characteristics rise. The rate of increase in G_{1c}, with respect to an increase of the dimensionless crack length (normalized by the specimen width), increases with both specimen size and maximum aggregate size increase.

The crack trajectories deviate from the rectilinear path more in the specimens with larger aggregate sizes. Fracture surfaces in concrete with larger aggregate sizes exhibit higher roughness than that for smaller aggregate sizes. For completely similar specimens, the crack tortuosity was greater for the larger size specimens. In no case, a two identical specimens exhibited the same fracture path, however, there were a distinct and well reproducible statistical features of crack trajectories in similar specimens. Bridging and other forms of crack face interactions that are the most probable causes of high toughness, were more pronounced in the specimens with larger maximum size aggregates.

3.3 *Size Effect on the Fractal Dimension*

The potential application of the fractal dimension for characterizing the fracture surface of concrete was studied for three sets of specimens: S1, S3, and S4 (Figure 1). The correlations between the fracture properties and the fractal dimension of the fractured surface were also explored (Issa et al. 2003). Fractured surfaces were analyzed using the modified slit-island technique. The fractal dimension results correlates very well with surface roughness, the rougher the surface, the higher the fractal dimension. The results showed that the fractal dimension, increases with the increase in the specimen assize and with the maximum aggregate size as well. In addition, it was observed that the tougher the material, the higher the fractal dimension, which indicate that the fractal dimension and fracture toughness can be correlated. For the specimens with larger size aggregates, bridging and other forms of crack face interaction take place resulting in a more tortuous path of the crack. The increase in the fractal dimension with specimen size can be attributed to the fact that the specimen becomes tougher with increase in size.

3.4 *Fractal Dimension versus Fracture Toughness*

For each specimen, graphs of fractal dimension (D) and fracture energy were very similar except for the magnitude. Fractal dimension and fracture energy results of the specimens of corresponding maximum aggregate size were best fitted with linear regression. A correlation between fractal dimension and fracture toughness, represented by fracture energy, was evident. The following relationship can be suggested in Issa et al. (2003):

$$G_F = G_F^{o}\left[1 + k(D-2)\right] \tag{1}$$

Where G_F^{o} is the fracture energy for smooth (2D) surface and k is the slope of the best-fit line. The k values of best-fit lines were different for different size specimens.

On other hand, image analysis of the fractured surfaces, divided into four equal regions, of S1 specimens showed that the fractal dimension does not vary with the crack length. However, the fractal dimension for the furthest region from the notch-tip showed a lower value for all specimens. No correlation was found between fractal dimension and energy release rate, which was found to increase with crack length (Issa et al. 1999-II).

3.5 *Sensitivity of Fracture Behavior of Concrete to Notch/Depth Ratio*

Previous studies have reported that fracture properties of concrete depend on the notch/depth ratio. Kaplan (1961) found that G_{1c} for specimens with notch/depth ratio of 0.33 was the highest and those for the notch/depth ratios of 0.17 and 0.50 were close, i.e., a bell-shaped trend was noticed. Tognon and Cangiano (1989) also noticed a bell-shaped trend of K_{1c}. Gjorv et al. (1977) found that, compared with identical specimens of notch/depth ratio of 0.1, K_{1c} values decreased 10% and 36% on average for specimens with notch/depth ratios of 0.3 and 0.5, respectively. Nallathambi et al. (1984) found that an increase in the notch/depth ratio of the specimen decreases the G_{1c} because of the reduction in net fracture zone area. Alexander and Blight (1988) noticed a relatively small variation in effective fracture surface energy for the beams with notch/depth ratios of 0.2 to 0.4. However, for specimens with a notch/depth ratio of 0.5, the effective fracture surface energy values were about 40% lower on average. Both Shah (1990) and Ji et al. (1997) studies showed that as the depth of the notch increases, G_F decreases.

In the experimental investigation (Issa et al. 1999-I and 1999-II), two notch/depth ratios of 0.15 and 0.30 were investigated for each set of specimens that vary in terms of size and maximum aggregate size. It was found that for geometrically similar specimen's size and maximum aggregate size, K_{1c} and the energy release rate values for long-notch specimens are lower than those for short-notch specimens and This may be attributed to that the deep notching prevents true instability from occurring, i.e., strain energies are low. It was also found that the fracture processes differ in damage intensity depending on the depth of notching. Examination of the results reveals that the variation in fracture energy with specimen size and notch-depth are mutually dependent indicating that the size of the specimen should be taken into consideration in analyzing the effect of the notch depth on the fracture properties of concrete.

3.6 *Suggested Areas of Future Research*

It is very important to recognize that during the past ten years, new concrete types such as lightweight concrete (LWC), self-consolidating concrete (SCC), fiber reinforced concrete, and ultra high strength concrete, are being developed to meet innovative architectural and structural designs. The methodology and findings of the reviewed studies provide a solid foundation for novel systematic evaluation of the fracture properties of such concrete types. The authors believe that compilation of all of the data of the dependable studies, grouping the data of similar parameters, and exploring relationships between the fracture properties and the fractal dimension based on a statistical fracture mechanics approach (Chudnovsky and Kunin 1987, 1992, Chudnovsky et al. 1997) would be a unique accomplishment.

4 CONCLUSIONS

The principal conclusion that can be drawn from the previous discussion are that changing the specimen size only or the maximum aggregate size only, or both of them will result in significant change in the fracture properties and fractal dimension of concrete. The fractal dimension correlates well with the fracture toughness of concrete and surface roughness of fractured concrete surfaces.

ACKNOWLEDGMENTS

This study was funded by a contract awarded to the University of Illinois at Chicago (UIC) by the National Science Foundation (NSF), Grant Number: CMS 9522306. The NSF financial support is gratefully acknowledged.

REFERENCES

Alexander, M.G. & Blight, G.E. 1988. A comparative study of fracture parameters in notched concrete beams. *Magazine of Concrete Research*: 40(142): 50-58.

Bazant, Z. & Kazemi, M. 1991. Size dependence on concrete fracture determined by Rilem work-of-fracture method. *International Journal of Fracture*: 51: 121-128.

Brandt, A.M. & Prokopski G. 1993. On the fractal dimension of fracture surfaces of concrete elements. *Journal of Materials Science*: 28: 4762-4766.

Carpinteri, A. 1994. Scaling laws and renormalization groups for strength and toughness of disordered materials. *International Journal of Solids and Structures*: 31:291-302.

Carpinteri, A. 1994. Fractal nature of material microstructure and size effects of apparent mechanical *properties. Mechanics of Materials*: 18:89-101.

Chudnovsky, A. & Kunin, B. 1987. A probabilistic model for brittle crack formation. *Journal of Applied Physics*: 62(10): 4124-4129.

Chudnovsky, A. & Kunin, B. 1992. A statistical fracture mechanics, microscopic simulation of complex hydrodynamic phenomena. In M. Mareschal & B.L. Holian (eds), *Plenum Press*, New York.

Chudnovsky, A., Kunin, B., and Gorelik, M. 1997. Modeling of brittle fracture based on the concept of crack trajectory ensemble. *Engineering Fracture Mechanics*: 58(5-6): 437-457.

Gjorv, O.E., Sorensen, S.I., and Arnesen, A. 1977. Notch sensitivity and fracture toughness of concrete. *Cement and Concrete Research*: 7, 333-344.

Hillerborg, A. 1985. Results of three comparative test series for determining the fracture energy G_F of concrete. *Materiaux et Constructions*: 18(107): 407-413.

Issa M.A. & Hammad, A. 1993. Fractal characterization of fracture surfaces in mortar. *Cement and Concrete Research*: 23(1): 7-12.

Issa M.A. & Hammad, A. 1994. Assessment and evaluation of fractal dimension of concrete fracture surface digitized images. *Cement and Concrete Research Journal*: 24(2): 325-334.

Issa, M.A., Hammad, M.A., and Chudnovsky, A. 1992. Fracture surface characterization of concrete. *Proceedings of the Ninth Conference, Engineering Mechanics, ASCE*, NY, N.Y.: 127-130.

Issa, M.A., Hammad, M.A., and Chudnovsky, A. 1993. Correlation between crack tortuosity and fracture toughness in cementitious materials. *International Journal of Fracture* 60: 97-105.

Issa, M.A., Hammad, M.A., and Chudnovsky, A. 1994. RESPONSE: Discussion of "correlation between crack tortuosity and fracture toughness in cementitious materials. By Weisheng Lei and Bingsen Chen. *International Journal of Fracture*: 65: R37-R39.

Issa, M.A & Chudnovsky, A. 1998. Size effects in the fracture of concrete materials. *National Science Foundation Grantees Conference*, Monterrey, Mexico.

Issa, M.A., Issa, M.A., Islam, MS, and Chudnovsky, A. 2000. Size effects in concrete fracture: Part I, experimental setup and observations. *International Journal of Fracture* 102(1):1-24.

Issa, M.A., Issa, M.A., Islam, MS, and Chudnovsky, A. 2000. Size effects in concrete fracture: Part II, analysis of test results. *International Journal of Fracture*: 102(1):25-42.

Issa, M.A., Issa, M.A., Islam, MS, and Chudnovsky, A. 2003. Fractal dimension-a measure of fracture roughness and toughness of concrete. *Engineering Fracture Mechanics*: 70:125-137.

Ji, X.H., Chan, S.Y.N., and Feng, N.Q. 1997. A fractal model for simulating the formation of microcracks in the fracture process zone and a theoretical explanation of the size effect of the fracture energy of concrete. *Magazine of Concrete Research*: 49(180): 253-258.

Jueshi, Q. & Hui, L. 1997. Size effect on fracture energy of concrete determined by three-point bending. *Cement and Concrete Research*: 27(7): 1031-1036.

Kaplan, M.F. 1961. Crack propagation and the fracture of concrete. *Journal of the American Concrete Institute*: 58(5): 591-609.

Lange, D.A., Jennings, H.M., Shah, S. 1993. Relationship between fracture roughness and fracture behavior of cement paste and mortar. *Journal of American Ceramic Society*: 76(3): 589-597.

Linsbauer, H.N. & Sajna, A. 1996. Size effect sensitivity - three point bending test versus wedge splitting test. *Size-Scale Effects in the Failure Mechanisms of Materials and Structures*. E & FN Spon, London: 427-439.

Mihashi, H., Nomura, N., and Kim, J.K. 1996. Fracture mechanics properties and size effect in concrete. *Size-Scale Effects in the Failure Mechanisms of Materials and Structures*, E & FN Spon, London: 399-410.

Mandelbrot, B.B., Passoja, D.E., Paullay, A.J. 1984. Fractal character of fracture surfaces of metals. *Nature*:308:721-722.

Nallthambi, P., Karihaloo, B., and Heaton, B. 1984. Effect of specimen and crack sizes, water/cement ratio and coarse aggregate texture upon fracture toughness of concrete. *Magazine of Concrete Research*: 36(129): 227-236.

Perdikaris, P., Calomino, A., and Chudnovsky, A. 1986. Effect of fatigue on fracture toughness of concrete. *Journal of Engineering Mechanics*: 112(8): 776-791.

Saouma, V.E. & Barton, C.C. 1994. Fractals, fractures, and size effects in concrete. *Journal of Engineering Mechanics*: 120(4): 835-854.

Shah, S. 1982. Dependence of fracture toughness on specimen geometry and on composition. *Fracture Mechanics of Concrete*, A. Carpinteri & A., Ingraffea, (eds), Martinus Nijhoff Publishers: 111-135.

Shah, S. 1990. Experimental methods for determining fracture process zone and fracture parameters. *Engineering Fracture Mechanics*:35(1/2/3): 3-14.

Tognon, G. & Cangiano, S. 1989. Fracture behavior of high strength and very high strength concretes. *Fracture Toughness and Fracture Energy*, eds. Mihashi et al., Balkema, Rotterdam.

Winslow, D.N. 1985. The fractal nature of the surface of cement paste. *Cement and Concrete Research*: 15: 817-824.

Wittmann, F.H., Mihashi, H., and Nomura, N. 1990. Size effect on fracture energy of concrete. *Engineering Fracture Mechanics*: 35(1-3): 107-115.

Wolinski, S., Hordijk, D., Reinhardt, H., and Cornelissent, H. 1987. Influence of aggregate size on fracture mechanics parameters of concrete. *International Journal of Cement Composites and Light Concrete*: 95-103.