Journal of Civil Engineering (IEB), 38 (1) (2010) 81-94

Journal of
Civil Engineering
IEB

# Fracture toughness of plain concrete specimens made with industry-burnt brick aggregates

M. R. Alam, M. A. K. Azad and M. A. Kadir

*Department of Civil Engineering,*
*Chittagong University of Engineering and Technology, Chittagong 4349, Bangladesh*

Received 25 January 2010

**Abstract**

In this paper experimental and numerical determination of the fracture toughness of plain concrete specimens made with industry-burnt brick aggregates is described. Beam specimens with different initial crack depths, at the mid span of beams, were prepared according to ASTM specifications. Range of initial crack depths was taken to vary between 0.30 to 0.50 times the beam depth. Experimental failure load for each beam, with the specified initial crack depth, was determined using the 4-point bending test of the beam. Fracture toughness values were then determined for failure loads and crack depths using the equation given by ASTM specifications, for 4-point loading. Fracture toughness values were also determined numerically using finite element analysis (FEA) for different crack lengths. Mean value of fracture toughness (0.540±0.051 MPa.m$^{1/2}$) of plain concrete specimens made with brick aggregates was found to be much lower than those obtained for plain concrete specimens with stone aggregates (0.807±0.083 MPa.m$^{1/2}$). Effect of specimen widths on the fracture toughness of plain concrete was also presented in this paper.



*Keywords:* fracture toughness, plain concrete, brick aggregates, crack, finite element analysis, 4-point loading

## 1. Introduction

Concrete is one of the most commonly used building materials in the world. It is utilized in different forms such as, Normal Strength Concrete (*NSC*), High Strength Concrete (*HSC*) and Ultra High Strength Concrete (*UHSC*), depending on the requisite design strength and the importance of the structure. Unless specified earlier, NSC is used now-a-days in the constructions of most of the concrete civil engineering structures. In most of the concrete constructions of the world, stone aggregates are used as the coarse aggregates in NSC. However, in some countries of South East Asia, viz., Bangladesh, Myanmar, India, and others, where stone aggregates are not easily available, industry-burnt brick aggregates are also used as an alternative to stone aggregates. They have been used in concrete structures such as buildings, bridges, gravity dams, retaining walls, road pavements, blocks, piling, etc.

When a fracture in the form of crack develops in the structure, its load bearing capacity reduces significantly. If it develops in the major structural components such as beams/girders, columns/piers, shear wall, retaining walls, dams, etc., to a significant amount, the entire structure could collapse within a minutes. Since inherent flaws (micro level) exist in concrete material and it could be activated for any accidental combination of loads, it is important to pay attention in minimizing flaws in any concrete structural elements and inhibiting their growth under normal and accidental loads. It is also important to study the behavior of concrete with inherent flaws under static or dynamic loading. For this reason fracture toughness test of concrete is important. Fracture toughness is the resistance of a material to failure from a fracture, starting from a pre-existing crack (Broek 1989). The residual load carrying capacity of a component in the presence of defects is a function of the material's fracture toughness. The durability of structural components also depends on their sub-critical crack growth.

Since concrete is an anisotropic and heterogeneous material, cracking of concrete is a complex phenomenon. Micro-crack shielding, aggregate bridging and crack branching are developed during the cracking process. All these mechanisms can be reasonably quantified by dissipated energy during the fracture process. Therefore, energy criteria, instead of the strength criteria should be used to describe cracking of concrete meaningfully. The analysis and design of structures in the world made of concrete follow codes that rely mainly on the strength failure criteria along with additional parameters to account the mechanism of the failure that are not explicitly recognized in these methods. The risk in the current design practice for concrete is that flaws inherent in the material can grow under loading to unacceptable lengths. It is therefore imperative that necessary steps should be taken to move forward the current-understanding and design practices associated with concrete in order to reliably account for the possible failure mechanisms that may occur.

Generally cracks are always present in concrete structures prior to their deterioration or failure. The cracking strength of concrete is determined by using fracture mechanics concepts (Shah and Swartz 1989, Shah 1991). It is believed that the crack starts to propagate in concrete as the crack tip stress intensity factor reaches the fracture toughness value (that is always defined quantitatively in terms of critical stress intensity factor $K_c$ or fracture energy $G_c$). A large number, of research efforts, has been made in studying the fracture toughness of normal strength concrete, with various mixing ratios of ingredients (Kachanov 1985, Tada et al. 1985, Shah and Ouyang 1992). Kaplan (1961) was probably the first to introduce fracture mechanics to concrete beams to measure fracture toughness. Peterson (1980) and Nallathambi et al. (1984) carried out studies on the fracture of cement mortar and concrete to measure $K_c$ and $G_c$. They mentioned that LEFM (Linear Elastic Fracture Mechanics) could be applied to these systems. Saouma et al. (1994) also stated from their studies that fracture mechanics could be usefully applied for the failure investigation of concrete dams. Seleem et al. (2008) carried out studies on fracture toughness of self-compacting concrete.

Recent publications (Hilsdorf and Brameshuber 1991 and Kishen 2005) have shown that fracture mechanics has now been established as a fundamental approach that can explain certain nonlinear aspects of concrete behavior, help to prevent brittle failures of the structure and be an important aid in materials engineering. Shah and Ouyang (1992) discussed applications of fracture mechanics to failure of concrete structures. They demonstrated that experimental phenomena associated with the failure of concrete such as size effect on tensile strength and brittleness of concrete can be interpreted properly through fracture mechanics. Wittmann and Metzener-Gheorghita (1985) carried out studies on fracture toughness of large concrete specimens. They found that fracture toughness increases initially as crack propagates but that a length-independent value is reached asymptotically. They concluded that failure of large size concrete elements can be predicted realistically using linear elastic fracture mechanics. Karihaloo and Nallathambi (1989) and Hamoush and Abdel-Fattah (1996) evaluated the fracture toughness of plain concrete specimens. Hamoush and Abdel-Fattah carried out both theoretical and experimental investigations in this study. Three-point bending test was performed to determine the fracture toughness of cracked beam specimens. They provided crack into the specimen during casting of the specimen, using an interposed thin hard plastic plate of thickness, 1/32 in. They considered three different lengths of crack in determining fracture toughness. Swartz et al. (1982) found that naturally cracked beams (pre-cracked) yield higher failure loads and stress-intensity values than notched beams with the same crack length. They found the average stress intensity factors to be higher by 38%, 77% and 96% for pre-cracked beams than for notched beams, for the crack depth ratios of 0.3, 0.5 and 0.7, respectively.

Most of the earlier studies on fracture toughness of plain concrete specimens have used stone aggregates with other ingredients (cement, sand and water) to prepare the plain concrete specimens. However, none of the earlier studies have reported on the fracture toughness of plain concrete specimens made with industry-burnt brick aggregates. The study reported in this paper has considered the fracture toughness of normal plain concrete specimens made of brick aggregates, sand, cement and water.

## 2. Experimental procedure

### *2.1 Preparation of test specimens*

In the preparation of concrete mix for test specimens, cement, sand and brick aggregate were mixed in a ratio of 1 : 1.5 : 3 (by weight). Brick aggregates used in this study were 19 mm down and 13 mm up grades. ACV (Aggregate Crushing Value) test of aggregates was carried out according to BS 812-110 (British Standard Institution 1990a) procedure to check the quality of brick and stone aggregates. Water cement ratio was taken as approximately 0.36 by weight to maintain a slump of 63.5 mm (in a slump cone test) for better workability. Aggregate was washed with water and surface dried before mixing it with sand and cement. The initial and final setting times of cement were determined before using it with other ingredients. Sieve analysis of fine aggregates was also carried out before adding it into the mixture. In order to determine the strength of mortar, compressive strength tests of cube specimens and tensile strength tests of briquette specimens were carried out in the laboratory by mixing cement and sand in the ratio of 1:1.5. Crushing strength of concrete mix used in preparing test specimen was determined by carrying out compression test of standard concrete cylinders (dia. = 15 cm and height = 30.48 cm). These cylinders were cast from the same concrete mix that was used for preparing specimens of fracture toughness test. The compression tests of concrete cylinders were carried out after 28 days of curing in water. Before carrying out the tests, each specimen was kept in a dry place for 24 hrs. The test was performed using a calibrated 100 ton hydraulic machine under displacement control condition. A total number of 15 cylindrical specimens were tested for brick aggregates.

Geometry of test specimen for fracture toughness test was fixed as length ($L$) of 0.8128 m (32 inch), width ($B$) of 0.152 m (6 inch) and depth ($W$) of 0.2032 m (8 inch) according to ASTM C 1421 – 99 (1999) standard dimensions ($L$ = 4$W$, $B$ = 0.75$W$). Wooden moulds were made according to the specimen dimensions. Crack was introduced during the casting of specimens, by inserting a greased 1 mm thick steel plate of width equal to the specimen width, and up to the required depth of crack in the beam. The steel plate was greased first and then fixed with wooden shutters before placing concrete. Wooden mould (shutter) was also greased properly before placing the concrete mix. The concrete was prepared in a revolving drum mixer. This concrete mix was then poured into the specimen moulds carefully and tamped properly, in three layers, for each specimen. Mixing proportion of cement, sand, coarse aggregates (brick aggregates) and water was maintained the same for all specimens. Only the crack depth was changed by placing the greased steel plate, at the required depths in the specimen. Six or four test specimens were cast at a time. After keeping specimens in the room temperature for 24 hrs, the wooden shutter and the steel plate were removed from the specimens and they were placed inside a water tank for 28 days.

Table 1
Summary of laboratory fracture toughness test with specimen geometry and crack depth.

| Batch No. | Number of specimens | Crack depth | Other dimensions of the specimens |
|---|---|---|---|
| 01 | 06 | 30% of beam depth | $L$ = 0.8064 m, $B$ = 0.152 m, $W$ = 0.2032 m |
| 02 | 06 | 35% of beam depth | $L$ = 0.8064 m, $B$ = 0.152 m, $W$ = 0.2032 m |
| 03 | 04 | 40% of beam depth | $L$ = 0.8064 m, $B$ = 0.152 m, $W$ = 0.2032 m |
| 04 | 06 | 45% of beam depth | $L$ = 0.8064 m, $B$ = 0.152 m, $W$ = 0.2032 m |
| 05 | 04 | 50% of beam depth | $L$ = 0.8064 m, $B$ = 0.152 m, $W$ = 0.2032 m |
| Plain concrete specimens made with stone aggregates | | | |
| | 04 | 45% of beam depth | $L$ = 0.8064 m, $B$ = 0.15 m, $W$ = 0.2032 m |
| Plain concrete specimens with variable widths | | | |
| 01 | 04 | 45% of beam depth | $L$ = 0.8064 m, $B$ = 0.076 m, $W$ = 0.2032 m |
| 02 | 04 | 45% of beam depth | $L$ = 0.8064 m, $B$ = 0.101 m, $W$ = 0.2032 m |
| 03 | 04 | 45% of beam depth | $L$ = 0.8064 m, $B$ = 0.127 m, $W$ = 0.2032 m |

A total number of twenty six pre-cracked beams with constant widths were cast in the laboratory for the brick aggregates. These twenty six pre-cracked beams were divided into five batches with three batches consisting of six beams each, and two batches consisting of four beams each. Five batches were separated by crack depths of 30%, 35%, 40%, 45% and 50% of specimen depth, respectively. Four additional beam specimens, with a crack depth of 45% of specimen depth, were cast with stone aggregates using the same mixing proportion; these were tested for obtaining fracture toughness values of plain concrete specimens made with stone aggregates. During the preparation of all the above specimens, width, depth and length of the specimens were kept constant. Summary of laboratory tests with specimen geometry and crack depths are shown in Table 1.

Effect of specimen widths on the fracture toughness of plain concrete was also examined in this study. For this, only the width of the beam was changed and all the other dimensions such as length and depth of the beam and crack length were kept constant. A total number of twelve varying-width beams were cast with a crack depth of 45% of beam depth. These were divided into three batches with four beams in each batch. The variation of beam widths taken into consideration was 76 mm (3 inch), 101 mm (4 inch) and 127 mm (5 inch), respectively. All beam specimens were tested by following ASTM C 1421 – 99 specifications. Four-point bending load was applied up to failure during test of the specimens. The outline of these tests is shown in Table 1.

### *2.2 Testing procedure*

After curing the test specimens for 28 days, they were removed from the water tank and kept in a dry place for 24 hours to evaporate the moisture from their external surfaces. Loading positions and supporting positions of the specimen were clearly marked and were made smooth and even, using a metal hand grinder and sand paper. Swiveling supports (in one vertical plane, perpendicular to the length) were provided at a distance 12.5 mm (0.5 inch) from both ends of the beam. Four-point loading positions were fixed at ¼ th of span length from both supports. This loading was chosen for obtaining pure bending at the middle-half portion of the beam where crack was present. Load was applied on the beam monotonically without any jerk and it was increased continuously at a rate of 10 kN/min until the test specimen failed. Failure load was recorded from a digital load meter. A dial gauge with a sensitivity of 0.01 mm was used for measuring the load point deflection. Displacement controlled load was applied on the specimen. Load was recorded at each 5 division increments of the dial gauge up to failure load. All specimens were tested under simply supported conditions. The complete setup of test specimen for fracture toughness test is shown in Figure 1.


Figure 1. Experimental setup for fracture toughness test of beam specimen.

### 2.3 Results and discussions

The results obtained from different tests are given in Tables 2 and 3. Table 2 shows the values of different properties of materials used in this study. Table 3 shows the crack depth and peak load for each test beam and the corresponding computed fracture toughness. From this table it is seen that the magnitude of the maximum load varies with the depth of crack. Typical load-deflection plots up to peak load for various *a/W* ratios are shown in Fig. 2 for specimens made with brick aggregates. Fig. 2 also shows the load-deflection plot for beam made with stone aggregates, with *a/W* ratio of 0.45. From all the load-deflection curves it is seen that material behaves almost linearly at the beginning of the applied load and becomes nonlinear near the peak load. A part of this nonlinearity could be attributed to the coalescence of tensile micro-cracks (development of fracture process zone) before the subsequent crack extension. The remaining part is due to the nonlinear compression behavior near maximum loads. It was found that when the load reached its maximum value, the test specimen began to lose its resistance very fast, which could not be plotted properly. For this reason, only the load deflection plots up to peak load have been showed in this study. From this graph it is also seen that peak load for the beam with smaller crack depth is found to be higher than those for large crack depths. Shapes of the load-deflection curves obtained for most of the test specimens were almost similar. The peak load was then used to determine the fracture toughness.

Table 2
Different test results of cement, sand, aggregate and plain concrete

| Name of test | Test results |
|---|---|
| *F.M.* (Fineness Modulus) of sand | 2.53 |
| Initial and final setting time of Portland cement | 1 hr. 45min. and 2 hr 08 min. |
| Slump value (average of 05 tests) | 63.5 mm |
| 7 days compressive strength of cement mortar (average of 10 tests) | 26.9 MPa (3900 psi) |
| 28 days compressive strength of cement mortar (average of 10 tests) | 35.9 MPa (5200 psi) |
| 7 days tensile strength of cement mortar (average of 10 tests) | 2.3 MPa (340 psi) |
| 28 days tensile strength of cement mortar (average of 10 tests) | 3.35 MPa (490 psi) |
| 28 days cylinder compressive strength of cement concrete with brick aggregates (average of 15 tests) | 19.3 MPa (2800 psi) |
| Aggregate crushing value of brick aggregate (average of 03 tests) | 35.70% |
| Aggregate crushing value of stone aggregate (average of 03 tests) | 28.15% |

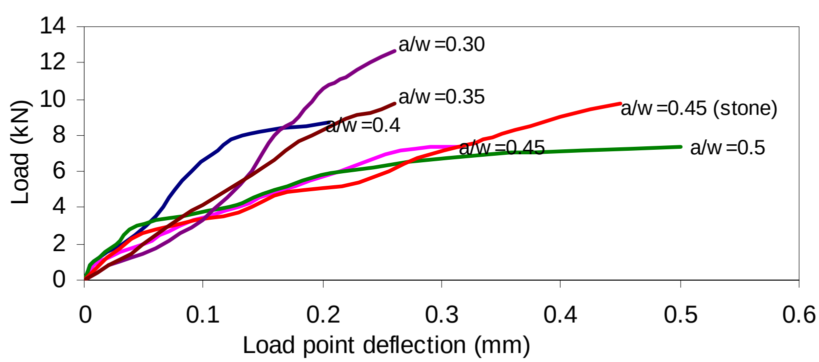


Fig. 2: Typical load-deflection plots up to peak load for various *a/W* ratios.

These fracture toughness values were considered as fracture toughness at the onset of crack extension and shown in Table 3 and Fig. 3. From the experimental results given in Table 3 it is seen that the fracture toughness values of plain concrete specimens made with brick aggregates for mode I loading vary from 0.451 MPa.m$^{1/2}$ to 0.68 MPa.m$^{1/2}$. These values were calculated based on the empirical equation (Eq. 1) given by Srawley and Gross (1976) for single edge straight through cracked rectangular beam under four-point loading.

Table 3
Fracture toughness of plain concrete specimens made with industry-burnt brick aggregates

| Specimen No. | Crack depth in % of beam depth (beam depth = 20.32 cm) | Load (Expt.) (kN) | Experimental fracture toughness, $K_{Ic}$ (MPa.m$^{1/2}$) | Numerical fracture toughness, $K_{Ic}$ (FEA) (MPa.m$^{1/2}$) | Difference between Expt. and FEA (%) |
|---|---|---|---|---|---|
| 1 | 30% | 12.2 | 0.591 | 0.598 | 1.10 |
| 2 | | 11.0 | 0.532 | 0.539 | 1.24 |
| 3 | | 13.6 | 0.658 | 0.666 | 1.22 |
| 4 | | 11.5 | 0.557 | 0.564 | 1.26 |
| 5 | | 12.5 | 0.605 | 0.613 | 1.26 |
| 6 | | 12.7 | 0.615 | 0.623 | 1.27 |
| 7 | 35% | 8.2 | 0.451 | 0.467 | 3.55 |
| 8 | | 9.8 | 0.538 | 0.550 | 2.23 |
| 9 | | 8.9 | 0.489 | 0.495 | 1.23 |
| 10 | | 9.25 | 0.508 | 0.514 | 1.18 |
| 11 | | 9.8 | 0.538 | 0.550 | 2.23 |
| 12 | | 9.0 | 0.494 | 0.502 | 1.62 |
| 13 | 40% | 8.8 | 0.551 | 0.557 | 1.09 |
| 14 | | 8.7 | 0.544 | 0.550 | 1.10 |
| 15 | | 8.75 | 0.548 | 0.554 | 1.09 |
| 16 | | 8.75 | 0.548 | 0.554 | 1.09 |
| 17 | 45% | 6.9 | 0.495 | 0.496 | 0.20 |
| 18 | | 6.75 | 0.484 | 0.489 | 1.03 |
| 19 | | 6.7 | 0.481 | 0.485 | 0.83 |
| 20 | | 7.0 | 0.502 | 0.507 | 1.00 |
| 21 | | 7.4 | 0.531 | 0.536 | 0.94 |
| 22 | | 6.75 | 0.484 | 0.489 | 1.03 |
| 23 | 50% | 7.1 | 0.590 | 0.595 | 0.85 |
| 24 | | 7.35 | 0.611 | 0.615 | 0.65 |
| 25 | | 5.94 | 0.494 | 0.498 | 0.81 |
| 26 | | 7.25 | 0.602 | 0.608 | 1.00 |
| | | | Mean, μ = 0.540<br>S.D., σ = 0.051 | Mean, μ = 0.547<br>S.D., σ = 0.051 | |

From Fig. 3 it is seen that fracture toughness values did not vary much from their mean values. The formula used to determine fracture toughness ($K_{Ic}$) of plain concrete specimens made with both brick aggregates and stone aggregates is given in Eq. 1.

$$K_{Ic} = \frac{P(l_1 - l_2)\sqrt{a}}{BW^2} * \frac{3}{2\left(1 - \frac{a}{W}\right)^{\frac{3}{2}}} * Y \tag{1}$$

where,

$$Y = \left\{ 1.989 - 1.33\frac{a}{W} - \frac{\left[3.49 - 0.68\frac{a}{W} + 1.35\left(\frac{a}{W}\right)^2\right]\frac{a}{W}\left(1 - \frac{a}{W}\right)}{\left(1 + \frac{a}{W}\right)^2} \right\}$$

for $0 \le \frac{a}{W} \le 0.6, \quad \frac{l}{W} = 4$

where, $P$ = Load, $l_1$ = The center to center support length, $l_2$ = Loading span, $B$ = Width of the beam, $W$ = Depth of the beam, $a$ = Crack depth

Fracture toughness values of plain concrete specimens made with stone aggregates for mode I loading (see Table 4) were also determined using the same empirical equation (Eq. 1) and found to be in the range of 0.70 MPa.m$^{1/2}$ to 0.933 MPa.m$^{1/2}$.

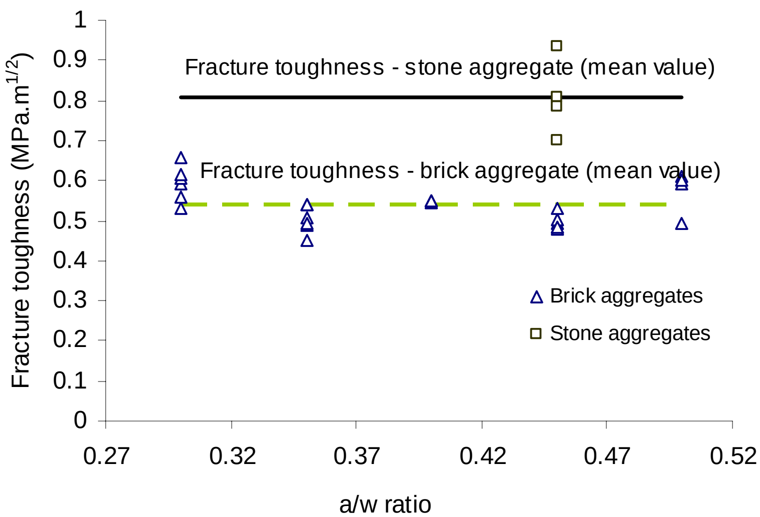


Figure 3. Fracture toughness for various *a/W* ratios
(*a* = crack depth, *W*= depth of the specimen = 0.2032 m)

Table 4
Fracture toughness of plain concrete specimens made with stone aggregates

| Specimen No. | Crack depth in % of beam depth (beam depth=8 inch) | Load (kN) | Fracture toughness $K_{IC}$ (MPa√m) |
|---|---|---|---|
| 1 | 45% | 11.25 | 0.807 |
| 2 | | 13 | 0.933 |
| 3 | | 9.75 | 0.700 |
| 4 | | 10.95 | 0.786 |
| | | | Mean, μ = 0.807 |
| | | | S.D., σ = 0.083 |

A summary of fracture toughness values given by other investigators are compared with present test results and shown in Table 5. From this table it is seen that fracture toughness values given by Hamoush and Abdel-Fattah (1996) are almost constant [0.92 to 0.98 ksi $(in)^{1/2}$ (1.02 to 1.08 $MPa.m^{1/2}$)]. Present test results for plain concrete specimens made with locally available brick aggregates seem quite different from those given by other investigators except those given by Morita and Kato (1979). Morita and Kato used light weight aggregates in their experiment. Industry-burnt brick aggregates could be considered as similar to light weight aggregates as its aggregate crushing value and cylinder crushing strength were found to be less than those of stone aggregates (see Table 2). Test results for plain concrete specimens made with stone aggregates were obtained very close to the values given by other investigators.

Fig. 4: Direction of crack propagation in the specimen made with industry-burnt brick aggregates from the pre-existing crack

(a) (b)

Fig. 5: Failure surfaces of tested beam made with; (a) Locally available brick aggregates and (b) Stone aggregates

After performing the test on each specimen, crack surface of each part was examined carefully. The crack extension profile of test specimen made with brick aggregates is shown in Fig. 4. It is seen that the extending crack plane does not deviate from the pre-existing crack plane in the specimen. Some of post failure surfaces (brick aggregate and stone aggregate) are shown in Fig. 5. It is observed that both aggregate and mortar failures occur in all of the tested beams made with brick aggregates and failure surfaces are found to be smooth and even. By examining the failure surface of the tested beam made with stone aggregates, it is observed that mostly bond failure (rather than through-the-thickness stone aggregate failure) between cement mortar and stone aggregates had occurred. Therefore, uneven surfaces are seen along the direction of crack extension in the stone aggregate specimens. This uneven bond failure increases the fracture toughness of plain concrete specimens made with stone aggregates.

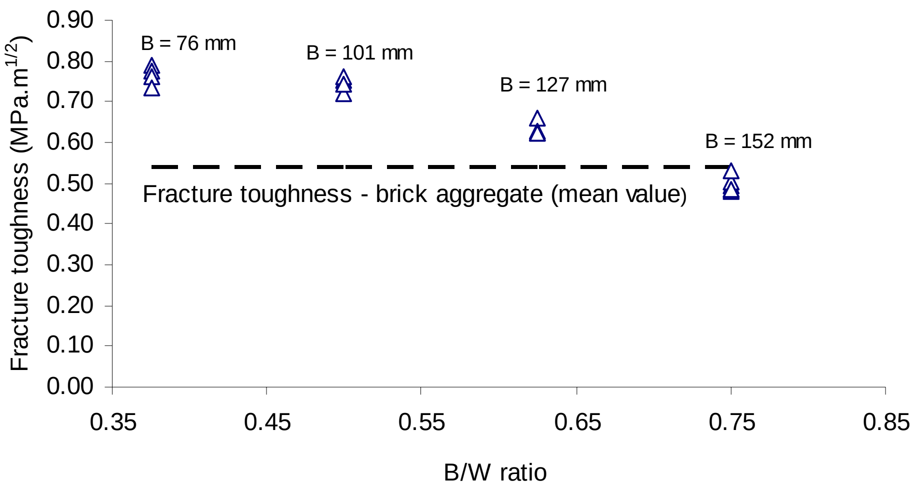


Fig. 6. Fracture toughness for various width – depth (*B/W*) ratios of test specimen (depth of the specimen, W = 0.2032 m)

The experimental results obtained for different widths of cracked beam are shown in Fig. 6. It is seen that when specimen width is reduced from the standard ASTM width (B = 0.75 W), i.e., 152 mm to 127 mm, 127 mm to 101 mm and 101 mm to 76 mm, fracture toughness increases gradually. However, the rate of change of increment of fracture toughness value is found greater for change in specimen's width from 127 to 101 mm and from 101 to 76 mm than the change in specimen width from 152 to 127 mm.

## 3. Finite element analysis

Present test results obtained using the empirical equation of Srawley and Gross (1976) give values quite different than those given by other investigators (see Table 5). In order to examine the consistency of these fracture toughness values, detailed plane stress finite element analyses were carried out using ABAQUS 6.7 (2007) FEA software. This program determines the stress intensity factor through the evaluation of contour integral and it also assumes uniform distribution of concrete material all along the beam length.

In FEA, it was assumed that material was homogenous and isotropic. Modulus of elasticity used in FEA was calculated based on supplied empirical formula $57500\times(f'_c)^{1/2}$ (Winter et al. 1964) and it was found to be 20.98 GPa for $f'_c$ = 2800 psi (cylinder compressive strength of concrete made with brick aggregates according to Table 1). Poisson's ratio was considered as 0.18 (Poisson's ratio for plain concrete generally varies from 0.15-0.20). Eight-noded isoparametric plane stress elements (second order elements) were used to model the half the beam specimen. Since geometry, loading, material properties and boundary conditions were found to be the same about the crack plane, half the specimen length was taken into consideration in FEA (half symmetry). To obtain $1/\sqrt{r}$ ($r$ = radial distance from crack tip) strain singularity at the crack tip, second order elements with the shifting of mid-side node to quarter point near the crack tip and collapsing of the element side to a single crack tip node were considered. Very fine mesh was introduced around the crack tip. Element size was increased gradually from crack tip to outward beam edges.

Table 5
Comparison of Mode I fracture toughness between present study and other investigators

| Investigator | $K_{Ic}$ (MPa.m$^{1/2}$) | Material, size of specimen and test method |
|---|---|---|
| Present study | 0.45 – 0.658<br>(0.540±0.051)<br>0.70 – 0.933<br>(0.807±0.083) | -13-20 mm size industry burnt brick aggregates<br>- Specimen size, 800 × 155 × 200 mm<br>- a/w ratio 0.3 to 0.5 and<br>- 4-pt. bend test<br>-13-20 mm size stone aggregates (gravel) |
| Kaplan (1961) | 0.67 - 1.13 | - 3-pt. and 4-pt. bend tests, stone aggregates<br>- Specimen size, 508 × 152 × 152 mm |
| Walsh (1972) | 0.5 - 1.0 | - 3-pt. bend test, stone aggregates<br>- Specimen size, Length = 254 -1270 mm, Depth = 76 – 381 mm and Width = 75 mm |
| Mindess et.al. (1977) | 0.88 | - 4-pt. bend test, stone aggregates<br>- Specimen size, 356 × 76 × 76 mm |
| Morita and Kato (1979) | 0.5 -0.6 | - Light weight aggregate<br>- 4-pt. bend test<br>- Independent of a/w ratio<br>- Specimen size, 420 × 100 × 100 mm |
| Strang and Byant (1979) | 0.6 – 1.1 | - Concrete with different aggregate size<br>- 3-pt. bend test, stone aggregates<br>- Specimen size, 48 × 12 × 12 mm to 800 × 100 × 200 mm |
| Refai and Swartz (1987) | 0.56 – 1.378 | - 3-pt. bend test<br>- Concrete strength 53.1 to 55.8 MPa<br>- a/w ratio 0.29 to 0.67<br>-Crushed marble aggregate size, 19 mm<br>- Specimen size 381 × 76 × 102 mm and 1143 × 76 × 305 |
| Jenq and Shah (1985) and John and Shah (1989) | 0.787 – 1.127 | - 3-pt. bend test<br>--stone aggregates of size 19 mm<br>- Concrete strength, 25.2 MPa<br>- a/w ratio, 0.293 to 0.333<br>- Specimen size 305 × 29 × 76 mm, 609 × 57 × 152 and 914 × 86 × 229 |
| Karihaloo and Nallathambi (1989) | 0.867±0.063 | - 3-pt. bend test<br>- Stone aggregates of size 20 mm<br>- a/w ratio, 0.2, 0.3 and 0.4<br>- Specimen size, 600 × 80 × 76 mm to 1800 × 80 × 300 mm |
| Alexander (1987) | 0.867±0.063 | - 3-pt. bend test<br>- Stone aggregates of size 19 mm<br>- a/w ratio, 0.4<br>- Specimen size, 400 × 100 × 100 mm, 800 × 100 × 200 mm and 2000 × 100 × 500 |
| Hamoush and Abdel-Fattah (1996) | 1.014 – 1.076 | - 3-pt. bend test, stone aggregates<br>- a/w ratio, 0.167, 0.393 and 0.750<br>- Specimen size, 760 × 150 × 150 mm |
| Bear and Barr (1977) | 0.804±0.43 | - Round bar with circumferentially notched<br>- 4-pt. bend test, stone aggregates |

Simply supported boundary conditions and 4-point load were applied to the generated finite element model. Peak value of the load of load-deflection curve, obtained from experimental studies, was considered as the cracking load in finite element analysis. Symmetry boundary condition (by constraining of all nodal displacements perpendicular to the symmetry plane) was applied along the plane of symmetry of the beam. FE modeling of the half beam is shown in Fig. 7.

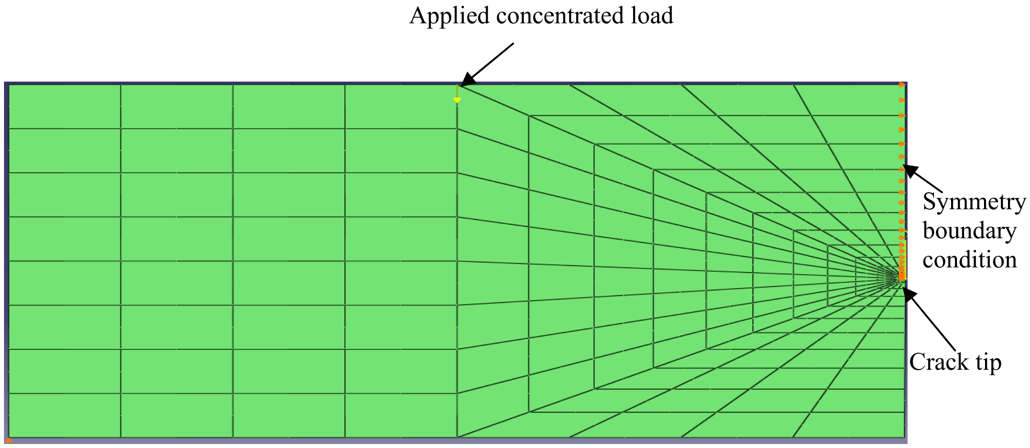


Figure 7. Finite element model of half specimen

When any crack develops in the beam, stress concentration generally occurs at the tip of the crack. Since present FEA of beam deals with a flexural crack at the center of the beam, therefore, it was necessary to check whether stress concentration occurs at the crack tip or not for the system considered in the present FEA. For this, contour plot of stresses was considered. Contour plot of stress in local-1 direction (tensile stress) around the crack region is shown in Fig. 8. It is seen that maximum tensile stress develops at the crack tip (due to strain singularity at the crack tip). Since concrete behaves like a quasi-brittle material, there will be a crack processing zone ahead of the crack, before the crack extends further. Therefore, the tensile stress that extends the crack will be the stress at some distance away from the crack tip and its value will be much lower than the tensile stress developed at the crack tip.

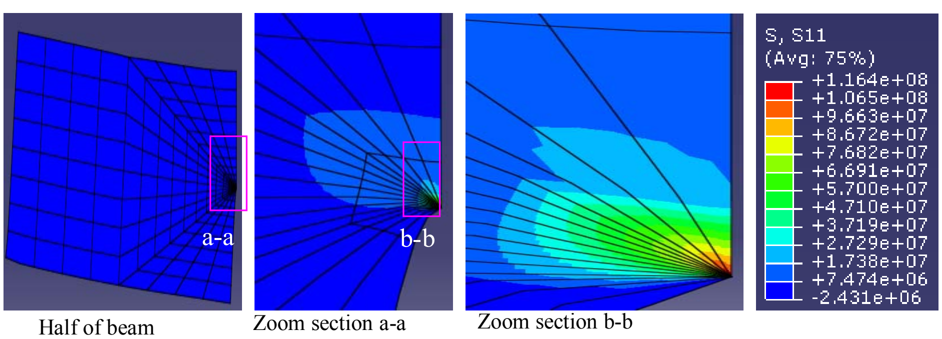


Figure 8. Stress contour plot for stress in local 1-direction around the crack tip

Mode I stress intensity factors were found directly from the ABAQUS post processor through the measurement of contour integral. In this case, each contour determines one stress intensity factor. Elements included in the first contour were all crack tip elements and successive rows of elements were considered for elements of 2$^{nd}$ contour, 3$^{rd}$ contour, and so on. Due to high crack tip stresses and development of crack processing zone ahead of the crack tip, average stress intensity factor of first three contours was considered as the stress intensity factor for the applied load. These stress intensity factors were then compared with the fracture toughness values obtained from experimental studies. The mode I stress intensity factors obtained from FEA for specimens with different crack depths and made with brick aggregates are given in Table 3. A close examination of Table 3 shows small variation of results between experiment and finite element analyses. Stress intensity factors obtained from FEA were found to be 0.2% to 3.55% higher than those obtained from experimental study. Consideration of concrete as a homogeneous and isotropic material in FEA could be the reasons for obtaining the higher values of mode I stress intensity factor. In FE modeling any inherent flaws or small cracks are not considered except the predefined crack. However, flaws (or even cracks) do occur in concrete material. It is almost impossible to make the beam specimen perfectly homogeneous and isotropic in the laboratory. Therefore, the fracture toughness values obtained from the experimental studies are considered to be the correct fracture toughness of plain concrete specimens made with brick aggregates.

## 4. Conclusion

Experimental testing and numerical finite element analysis were carried out to evaluate the fracture toughness of plain concrete specimens made with locally available industry-burnt brick aggregates. The variation of fracture toughness with respect to pre-crack depths, starting at 30% of beam depth and extending to 50 % of beam depth, was not found to be significant in both experimental and numerical studies. Fracture toughness values were found to lie between 0.451 to 0.658 MPa.m$^{1/2}$ (mean value 0.540 ± 0.051 MPa.m$^{1/2}$) for plain concrete specimens made with brick aggregates and 0.70 MPa.m$^{1/2}$ to 0.93 MPa.m$^{1/2}$ (mean value 0.807 ± 0.083 MPa.m$^{1/2}$) for plain concrete specimens made with stone aggregates. Fracture toughness values obtained from FE analysis of the same specimens were found to be very close to the experimental results. Maximum variation in fracture toughness values between experimental and numerical studies was found to be less than 4.0%.

When post-failure surfaces were examined, combined failure of mortar and brick aggregates was found in test specimens made with brick aggregates. Only mortar failure was found in the test specimens made with stone aggregates. Present test results were also compared with those given by other investigators. Comparison with earlier published results indicated that fracture toughness values of plain concrete made with brick aggregates were lower than those of plain concrete made with stone aggregates. Therefore, it could be concluded from this study that fracture toughness of plain concrete made with industry-burnt brick aggregates is lower than those of stone aggregates, i.e., brick aggregates has lesser resistance to crack propagation than stone aggregates. Fracture toughness values were found to be higher when widths of the specimen were reduced from their ASTM specified standard width.

**References**

ABAQUS 6.7. (2007). Dassault Systems, Lowell, Massachusetts, USA

Alexander, M. (1987). "Data from tests on notched concrete beams", University of Witwatersrand, Johannesburg.

ASTM. (1999). "Standard test methods for determination of fracture toughness of advanced ceramics at ambient temperature", ASTM designation C 1421 – 99, American Society for Testing Materials, Philadelphia

Bear, T. J. and Barr, B. (1977). "Fracture toughness tests for concrete", International Journal of Fracture; 13, 92-96.

British standard institution (1990a). "Methods for determination of aggregate crushing value (ACV)", BS. 812-110, BSI, London

Broek D. (1989). "The practical use of fracture mechanics", Kluwer Academic Publishers, Dordrecht and Boston.

Hamoush, S.A. and Abdel-Fattah, H. (1996). "The fracture toughness of concrete", Engineering Fracture Mechanics; 53(3), 425-432.

Hilsdorf, H.K. and Brameshuber, W. (1991). "Code-type formulation of fracture mechanics concepts for concrete", International Journal of Fracture; 51, 61-72.

Jenq, Y.S. and Shah, S.P. (1985). "A two parameter fracture model for concrete", Journal of Engineering Mechanics; 111(4), 1227-1241.

John, R. and Shah, S.P. (1989). "Fracture mechanics analysis and high strength concrete", Journal of Materials in Civil Engineering, ASCE; 1(4), 185-198.

Kachanov, M. (1985). In fracture toughness and fracture energy of concrete, ed. FH Wittmann, Amsterdam Elsevier.

Kaplan, M.F. (1961). "Crack propagation and the fracture of concrete", Journal of the American Concrete Institute; 58(5), 591-610.

Karihaloo, B., L. and Nallathambi, P. (1989). "Fracture toughness of plain concrete from three-point bend specimens", Materials and Structures; 22, 185-193.

Kishen, J.M.C. (2005). "Recent developments in safety assessment of concrete gravity dams", Current Science; 89(4), 650-656.

Mindess, S., Lawrence, F.V. and Kesler, C.E. (1977). "The J-integral as a fracture criterion for fiber reinforced concrete", Cement and Concrete Research; **7**(6), 731-742.

Morita, K. and Kata, K. (1979). "Fundamental study on evaluation of fracture toughness of artificial lightweight aggregate concrete", Review of the Thirty-Third General Meeting, The Cement Association of Japan, Tokyo, 175-177.

Nallathambi, P., Karihaloo, B.L and Heaton, B.S. (1984). "Coarse aggregate texture upon fracture toughness of concrete", Magazine of Concrete Research; 361(129), 227-236.

Peterson, P.E. (1980). "Fracture energy of concrete, practical performance and experimental results", Cement and Concrete Research; 10(1), 99-101.

Refai, M. E. and Swartz, S. E. (1987). "Fracture behavior of concrete beam in three-point Bending considering the influence of size effect", Report No. 190, Engineering Experimental Station, Kansas State University, Manhattan, KS.

Saouma, V.E., Boggs, J. and Morris, D. (1994). "Safety assessment of concrete dams using fracture mechanics", Proceedings of the 18th ICOLD (International Commission on Large Dams) Conference, Durban, South Africa, 1415-1435.

Seleem, M.H., Sallam, H.E.M., Attwa, A.J., Heiza, K.M. and Shaheen, Y.B. (2008). "Fracture mechanics of self compacting concrete", Mesomechanics-2008, Jan 28- Fab. 01, 2008, HBRC, Giza, Egypt, 1-10

Shah, S.P. (1991), Toughening mechanisms in quasi-brittle materials. Kluwer Academic Publisher, Dordrecht.

Shah, S.P. and Ouyang, C. (1992). "Measurement and modeling of fracture processes in concrete in Materials Science of Concrete", Vol.III, edited by Scalny, J., American Ceramic Society, Westerville, OH, 243-270.

Shah, S.P. and Swartz, S.E. (1989), Fracture of concrete and rock, Springer-Verlag, New York.

Srawley, J. E. and Gross, B. (1976). "Side-cracked plates subjected to combined direct and dending Forces", Cracks and Fractures, ASTM STP; 601, 559-579.

Strange, P.C. and Bryant, A.H. (1979). "The role of aggregate in the fracture of concrete", Journal of Materials Science; 14, 1863-1868.

Swartz, S.E., Hu, K. K. and Huang, C.M.J. (1982). "Stress intensity factor for plain concrete in bending-prenotched versus precracked beams", Experimental Mechanics, 412-417.

Tada, H., Paris, P.C. and Irwin, G.R. (1985), The stress analysis of crack handbook. 2nd Paris Productions Inc., St. Louis, MO.

Walsh, P.F. (1972). "Fracture of plain concrete", Indian Concrete Journal; 44(11), 469-470, 476.

Winter, G., Urquhart, L.C., O'Rourke, C.E. and Nilson, A.H. (1964). "Design of Concrete Structures", 7th Edition, McGraw-Hill, Inc.

Wittmann, F.H. and Metzener-Gheorghita, I. (1985). "Fracture toughness of concrete determined on large specimens", Materials and Structures; 18, 93-95.