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COMPARISON OF MEASURED FRACTURE TOUGHNESS AND SIZE-INDEPENDENT FRACTURE TOUGHNESS FOR CONCRETE

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ABSTRACT

Laboratory measured results from a broad-based experimental program have been combined with cohesive cracking simulations to determine the size-independent fracture toughness of two batches of concrete. The two batches of concrete used aggregate with a nominal maximum size of 22 mm. The batches had average compressive strengths of 36 and 52 MPa. The laboratory experimental program consisted of three sizes each of single edge (75 – 305 mm high) and round double beam specimens (305 – 1220 mm high). The two-parameter, size effect, Barker and inverse analysis data reduction methods were used to obtain measured values of fracture toughness from the test data. Each of the data reduction methods makes different assumptions about the effects of the process zone. Therefore, differences in measured fracture toughness values from the various data reduction methods are possible. The comparison shows that the single edge and round double beam specimens, up to 305 mm high, with the two-parameter, size effect and Barker data reduction methods do not produce fracture toughness values within 10% of the size-independent value. As expected, the accuracy of the various combinations of test specimen geometry, size, and data reduction method improved with larger test specimen sizes. Only the inverse analysis data reduction method produces accurate values in the range of specimen sizes that can be lifted by a single person.

KEYWORDS

concrete, fracture toughness testing, single edge specimen, round double beam specimen, two-parameter method, size effect method, inverse analysis, cohesive crack simulation

INTRODUCTION

At the scale of most civil engineering structures, macrocrack processes in concrete can not be predicted accurately using linear elastic fracture mechanics, LEFM. Fortunately, several models have been developed for use when there are non-linear fracture mechanics, NLFM, conditions. The size-independent fracture toughness, K_{Ic}, is a parameter common to all of these models for crack propagation. The size-independent fracture toughness is the value that would be obtained from a test specimen large enough that it experiences LEFM conditions. Testing specimens that large is not practical for most concrete mixes. Therefore, several data reduction methods have been developed based upon the models for crack propagation under NLFM conditions. In theory, the fracture toughness value obtained using one of these NLFM-based data reduction methods, K_{Ic}^{method}, is the same as the size-independent value, K_{Ic}. In practice, the variation of K_{Ic}^{method} values for different test specimen geometries, specimen sizes, and data reduction methods indicates that at least some of the K_{Ic}^{method} values are not K_{Ic}. A difference in values occurs when assumptions made about the fracture process zone by the data reduction method are violated.

A broad-based experimental program has been undertaken in conjunction with cohesive cracking simulations in order to determine the size-independent fracture toughness, K_{Ic}, of two mixes of concrete. With the known values for K_{Ic}, the accuracy of the K_{Ic}^{method} values has been evaluated for the various combinations of test specimen geometry, size, and data reduction method.

Concrete Mixes

Both of the concrete mixes used in this investigation had a nominal maximum aggregate size of 22 mm. One of the batches, referred to as "Normal Strength", had an average compressive strength of 36 MPa at the time when fracture toughness tests were performed. The second batch, referred to as "High Strength", had an average compressive strength of 52 MPa. Detailed descriptions of the mix design and material properties for the batches can be found in [1].

Test Specimen Geometries

In order to determine the size-independent fracture toughness of a mixture of concrete without testing extremely large specimens, more than one test specimen geometry must be used. Different geometries result in different stress states around the crack front. Different stress states might cause the process zone to develop differently. Therefore, certain combinations of test specimen geometry and data reduction method might be more likely to produce the size-independent fracture toughness for a given size of specimens.

Two test specimen geometries were selected for this study: the single edge loaded in bending, SE(B) (Fig. 1), and the round double beam loaded in bending, RDB(B) (Fig. 2). The single edge specimen has been used extensively with concrete [2]. It is the geometry chosen for three proposed standard test methods for measuring fracture properties of concrete [3-5]. The specimen is rectangular with a straight notch. As the specimen is loaded, it exhibits linear elastic response until the process zone begins to develop ahead of the notch. The peak load is reached close to when the crack begins to propagate. Data reduction is performed on data obtained around the peak load. Therefore, the determining data is acquired after the process zone has begun to develop but before crack propagation has occurred.

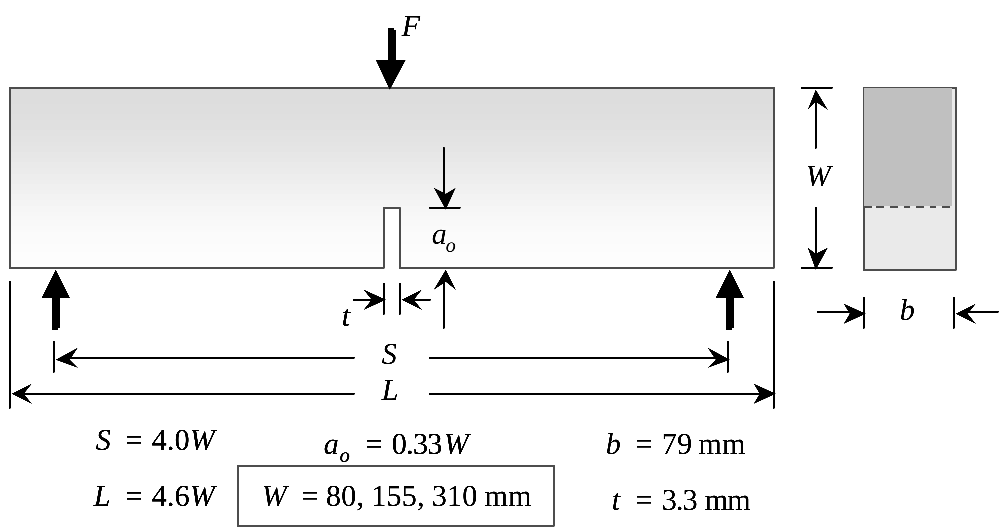

Figure 1. Single edge specimen loaded in bending, SE(B)

The round double beam is a specimen geometry used in a standard for measuring the fracture toughness of rock [6] and ceramics [7]. The specimen is cylindrical with a chevron shaped notch. Because of the chevron notch, the crack initially propagates in a stable manner during testing. When the crack reaches the critical length, around mid-height, the peak load is reached and propagation becomes unstable in load control. Data reduction is performed on data obtained around this transition point. Therefore, the determining data is acquired after the process zone has begun to develop and stable crack propagation has occurred.

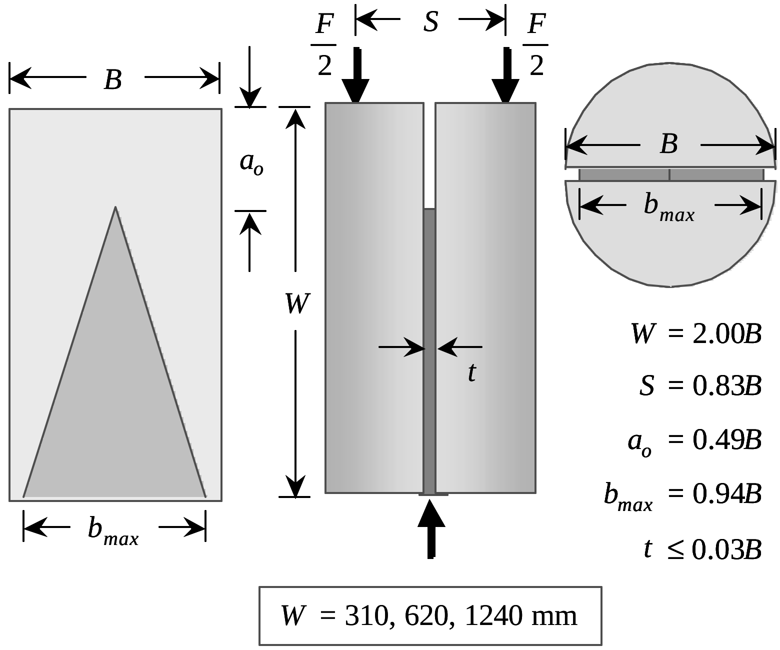

Figure 2. Round double beam specimen loaded in bending, RDB(B)

Data Reduction Methods

Each NLFM-based data reduction method makes different assumptions about the effect of the process zone when the determining data is acquired. Therefore, four data reduction methods were used in this study. The two-parameter data reduction method was used on each SE(B) result to obtain K_{Ic}^{TP} values. The method is based upon the two-parameter model for crack propagation [8]. The two-parameter method asserts that the global response of a structure with a crack experiencing NLFM conditions can be reproduced by considering the structure to have an effective crack experiencing LEFM conditions. Compliance is used to determine the effective crack length.

The size effect data reduction method was used on groups of SE(B) results to obtain K_{Ic}^{SZ} values. The method is based upon the size effect model for crack propagation [9]. The method assumes that the nominal strength of geometrically similar specimens is only a function of one specimen dimension. Linear regression is used to obtain the fracture energy or fracture toughness.

The Barker data reduction method was used on each RDB(B) result to obtain K_{Ic}^{BR} values. The method is based upon the Griffith energy criterion for crack propagation [10]. The method uses compliance to convert an LEFM-based K_{Ic}^{method} value into an NLFM-based value.

An inverse analysis data reduction method was used on groups of SE(B) and RDB(B) results to obtain K_{Ic}^{INV} values. The inverse analysis data reduction method used in this study is based on a cohesive crack model for crack propagation. The method selects the optimum cohesive zone properties to reproduce the behavior of all sizes of both specimen geometries for a single mix of concrete.

SIZE-INDEPENDENT FRACTURE TOUGHNESS VALUES

Determination of the size-independent value of fracture toughness, K_{Ic}, for concrete mixtures has been a significant challenge for the research community. Consistent results for a single size or single geometry or single data reduction method do not ensure that the result is the size-independent value. To determine K_{Ic} with reasonable certainty requires consistent results from a variety of combinations of test specimen geometry, size and data reduction method.

In order to determine the K_{Ic} values for the two concrete mixes in this study, all of the measured K_{Ic}^{method} values were compared. The results are summarized in Figures 3 and 4. The K_{Ic}^{TP} values increased with SE(B) specimen depth for the range of specimens tested. The K_{Ic}^{BR} values increased with RDB(B) specimen depth until the 610 mm deep specimen results and possibly after. The K_{Ic}^{SZ} values are included; however, the scatter in the measured peak loads severely limits the precision of the data reduction method. The K_{Ic}^{INV} values are similar across all specimen sizes and geometries investigated for both mixes. For the Normal Strength mix, the K_{Ic}^{BR} values appear reach and remain near the K_{Ic}^{INV} value. In addition, the K_{Ic}^{BR} values are approaching the K_{Ic}^{INV} values for the High Strength mix.

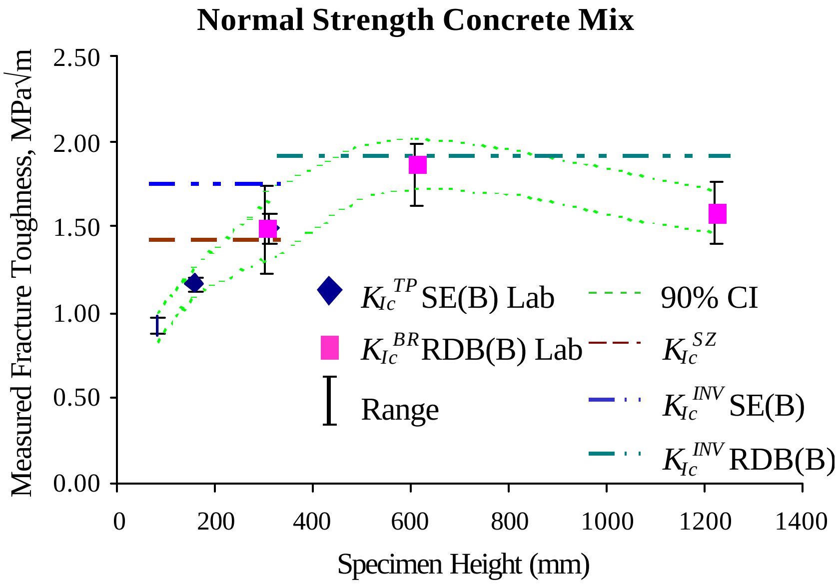

Figure 3. Measured fracture toughness value for specimens from the Normal Strength batch

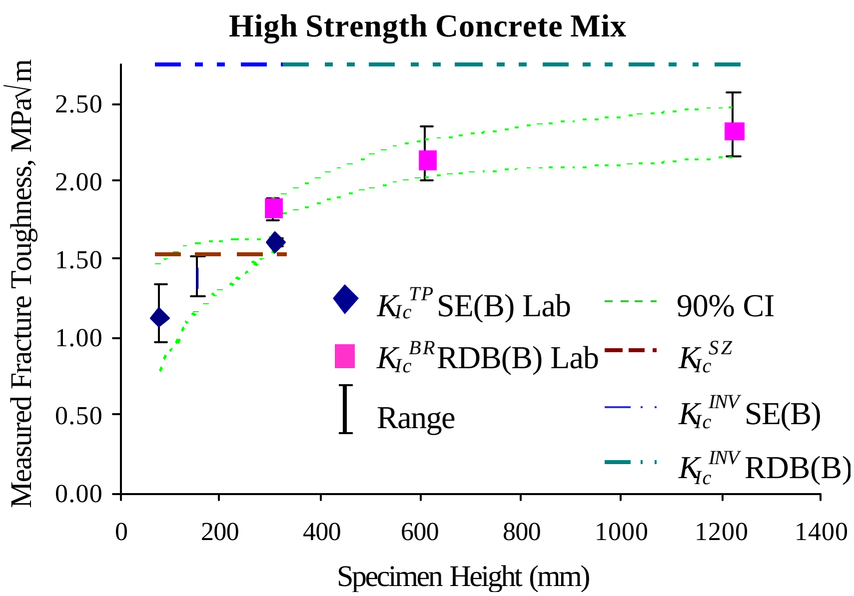

Figure 4. Measured fracture toughness value for specimens from the High Strength batch

Although such comparisons can not conclusively show what the K_{Ic} values are for these two mixes, one can reasonably argue that the K_{Ic} value for each mix is within 10-20% of the K_{Ic}^{INV} value. Therefore, for the purpose of comparing measured and size-independent fracture toughness values, the K_{Ic} value for the Normal Strength mix is taken to be 1.9 MPa√m. The K_{Ic} value for the High Strength mix is taken to be 2.7 MPa√m.

COMPARISON WITH MEASURED FRACTURE TOUGHNESS VALUES

The individual K_{Ic}^{method} values can now be compared to the size-independent K_{Ic} values. The accuracy of the measured values is calculated as the ratio K_{Ic}^{method}/K_{Ic}. The accuracies for the Normal Strength specimens are plotted versus specimen height in Fig. 5. The accuracies for the High Strength specimens are plotted in Fig. 6. The accuracy of the K_{Ic}^{INV} values is approximately 100% and was therefore omitted from the figures.

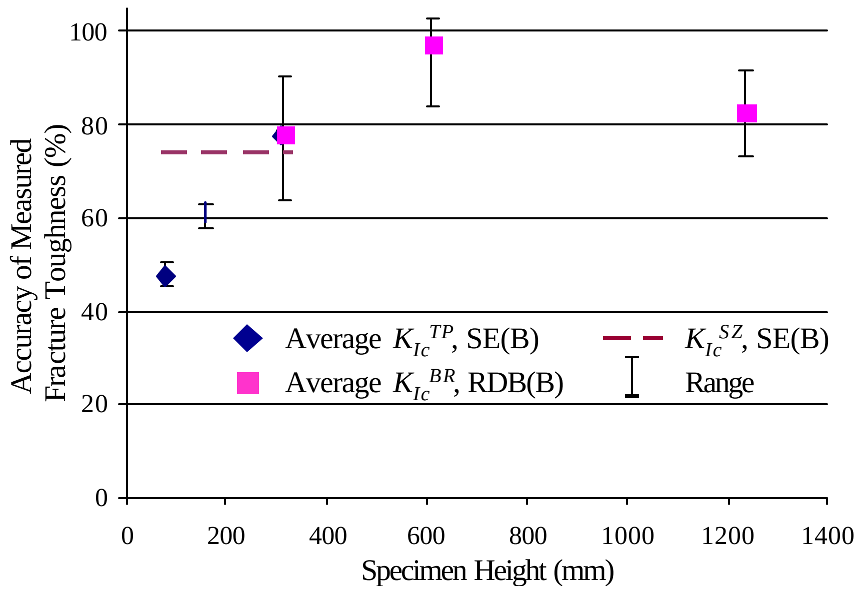

Figure 5. Accuracy of measured fracture toughness value for specimens from the Normal Strength batch

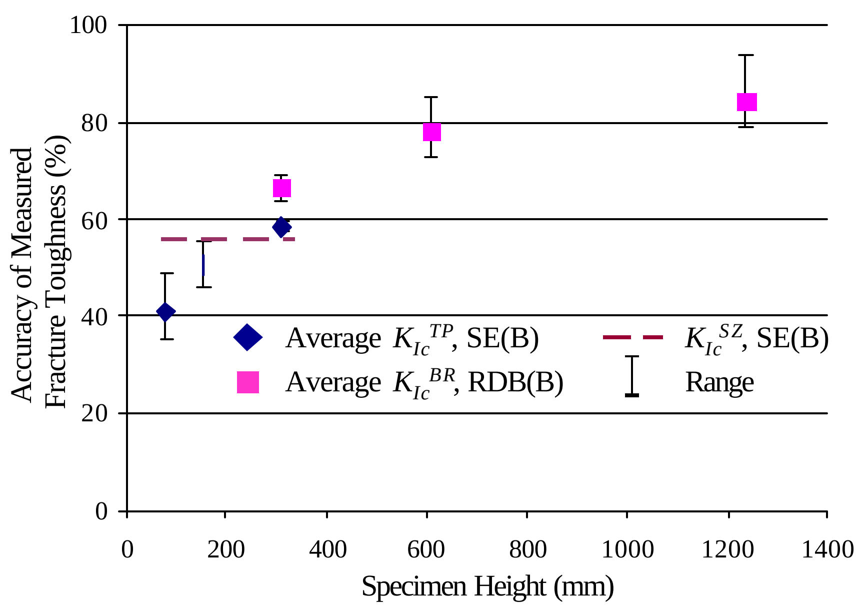

Figure 6. Accuracy of measured fracture toughness value for specimens from the High Strength batch

CONCLUSIONS

The poor accuracy of the K_{Ic}^{TP} and K_{Ic}^{SZ} values from the three sizes of SE(B) specimens clarifies the observations of Elices and Planas [11]. The results of their study implied that the critical energy release rate obtained from the two-parameter or size effect data reduction methods would be different from the energy release rate obtained from inverse analysis using a quasi-exponential tension softening diagram for typical laboratory sized SE(B) specimens. They predicted the difference would be approximately a factor of two. They were unable, however, to determine which of the data reduction methods would be more accurate. The results presented in Figs. 3 and 4 show that the inverse analysis data reduction method has produced the more accurate result.

The laboratory measured fracture toughness results from the Normal Strength batch of specimens appear to have converged to K_{Ic} with specimens that are 610 mm high. For the High Strength specimens, the results for the 1240 mm high RDB(B) are approaching K_{Ic}, but even larger specimens would be required to obtain K_{Ic} directly.

A practical test for measuring the fracture toughness of concrete will use specimens small enough to be carried by one person. Of the six sizes of specimens tested in this study, the largest that can be moved by a single person are the specimens 305 mm high. The average measured fracture toughness values for these and the smaller specimens are 20 – 60% below K_{Ic}. The systematic inaccuracies of the measured fracture toughness values have important implications for predicting crack propagation in concrete structures.

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