Fracture Toughness Testing Of Core From The Cambro-Ordovician Section On The Oak Ridge Reservation

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ABSTRACT:The modified ring test was used to determine the mode I fracture toughness of bedrock cores from the Department of Energy Oak Ridge Reservation in east Tennessee. Low porosity sandstones, limestones, and dolostones from the lower part of the Paleozoic section in the Copper Creek and Whiteoak Mountain thrust sheets were sampled. In general, the average mode I fracture toughness decreases from sandstone, dolostone, and limestone. The fracture toughness of the limestones varies between rock units, which is related to different sedimentologic characteristics. The quality of the results was evaluated by testing cores of Berea Sandstone and Indiana Limestone, which produced results that are similar to published results.

1. INTRODUCTION

Hazardous, radioactive, and mixed wastes have been detected to depths of over a thousand feet within the fractured bedrock groundwater system on the U. S. Department of Energy's Oak Ridge Reservation. This has lead to the site being the focus of numerous studies aimed at delineating the geology and the processes that control groundwater flow and contaminant transport (e.g., Hatcher and others 1992; Solomon and others 1992). One topic that has received little attention considers the mechanical properties of the bedrock based on either laboratory or in-situ tests (Lemiszki and others 1995). The data are needed for geomechanical studies related to fracture development in the area and for hydromechanical models that couple rock mass deformation associated with fluid injection and withdrawal.

We have been testing bedrock core to determine the mode I fracture toughness of the Paleozoic stratigraphic section in or near proposed environmental restoration sites in the Oak Ridge area. Here we will present mode I fracture toughness measurements based on unconfined tests on competent lithologies within cored parts of the Cambrian and Ordovician section. To our knowledge fracture toughness tests on these rock units have either not been conducted or reported. Also we will discuss our experience with using the modified ring test to measure the mode I fracture toughness of low porosity sedimentary rocks (Thiercelin and Roegiers 1986).

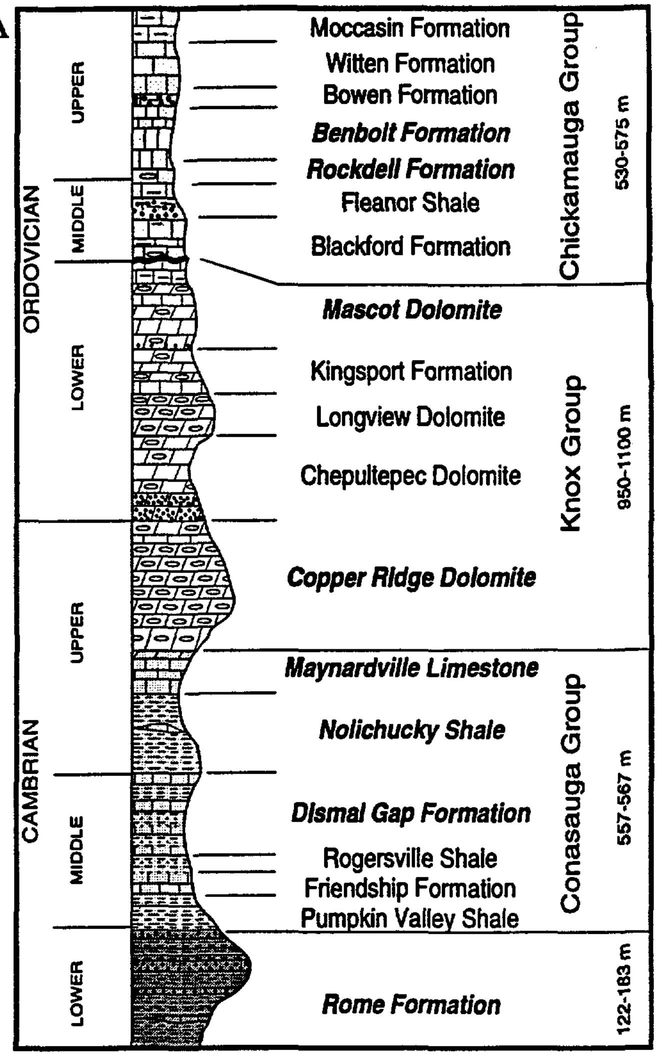
2. GEOLOGIC SETTING

Encompassing an approximately 500 km^2 area, the Oak Ridge Reservation is located in the western part of the Appalachian Valley and Ridge province in east Tennessee (Rodgers 1953). The stratigraphic units range in age from the Early Cambrian to the Early Mississippian (Hatcher and others 1992; Figure 1A). The lithologies consist of primarily shale, siltstone and sandstone (Rome Formation and Conasauga Group) and primarily limestone and dolostone (Maynardville Formation of the Conasauga Group, Knox Group and Chickamauga Group). These units record the Paleozoic depositional history of the southern part of the Appalachian basin and have undergone complex diagenesis during burial, deformation, and uplift. As a result, primary porosity in these rock units is commonly less than 5% and groundwater uses secondary porosity features such as, fractures in the noncarbonates, and fractures, bedding planes, and solution conduits in the carbonates. Because of their regularity, connectivity, and abundance, the systematic fracture sets are considered the major factor controlling groundwater flow and karst conduit development (Hatcher and others 1991).

The close relationship between the mechanical characteristics of the stratigraphic section and the geologic structures formed is evident at all scales of observation (Hatcher and Lemiszki 1991). The major structures in the area are the Copper Creek, Whiteoak Mountain, and Kingston faults, which imbricate the carbonate and noncarbonate Paleozoic sedimentary section (Figure 1B). These regional

Figure 1 (A) Stratigraphic section of the bedrock units in the Copper Creek and Whiteoak Mountain thrust sheets in the Oak Ridge area. Rock unit names in bold are where samples were taken. (B) Simplified geologic map of the Oak Ridge area located in east Tennessee (see inset map). The three main plant sites are X-10, Y-12, and K-25. Waste disposal sites outside of the plant areas occur primarily in Melton Valley and Bear Creek Valley. Note that the rock units on the map are shaded gray similar to the stratigraphic section. Coreholes CH2 and CH3 are located in the X-10 plant.

A



MAP KEY

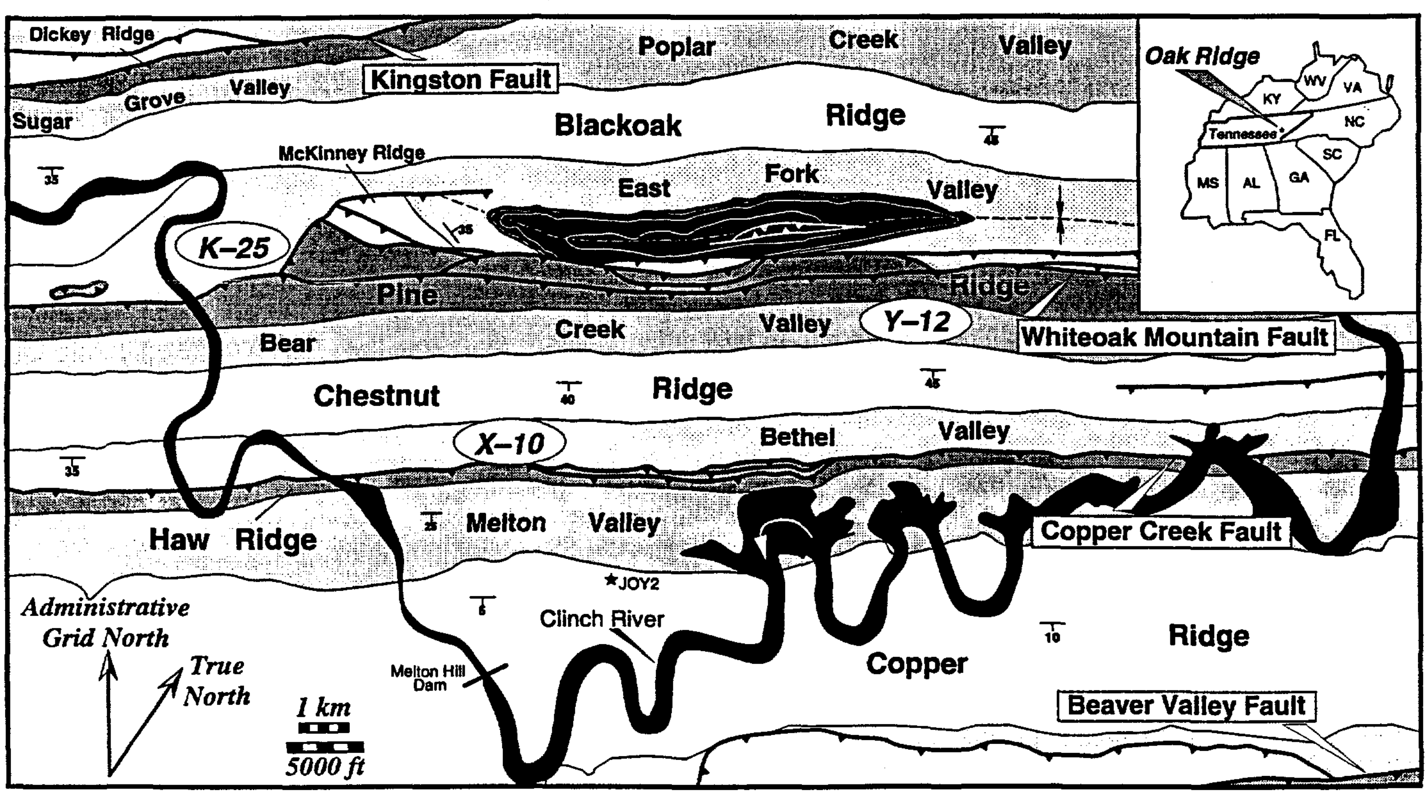
40 Strike & Dip of Bedding

Stratigraphic Contact

Thrust Fault (barbs on hanging wall)

Syncline Axial Trace

B



thrust faults commonly occur in the weaker shale bearing units (Rome Fm. and Conasauga Group) and not in the stronger carbonates (Knox Group). At a smaller scale, the two most pervasive pre-thrusting fracture sets occur in all stratigraphic units and define an orthogonal extension fracture system on bed-tops that is perpendicular to bedding (Hatcher and others 1992). The spacing, bed-normal length, and even orientation of the fractures within each set have been shown to be in part controlled by the mechanical differences between interbedded lithologies (Lemiszki 1992).

Because the site encompasses a large area and is located in moderately dipping sedimentary rocks, nearly 2000 m of the Paleozoic section is involved in the groundwater system. The core available sampled approximately 85% of the rock units (Figure 1A). Core samples of the Rome Formation, Conasauga Group, and Knox Group were picked from the JOY2 corehole, and samples of the Chickamauga Group were picked from coreholes CH2 and CH3 (Figure 1B).

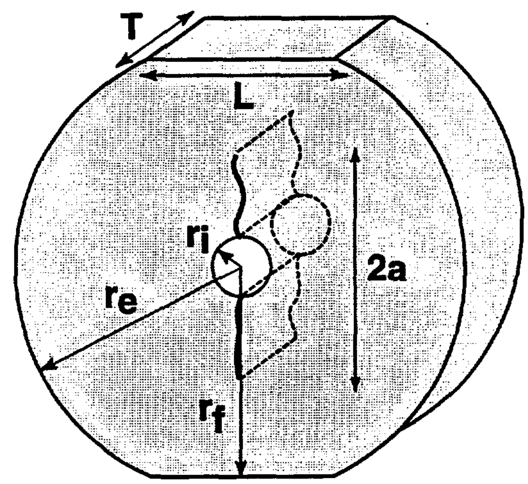
3. THE MODIFIED RING TEST

The modified ring test was developed to measure fracture toughness in smaller, but more homogeneous samples of rock core (Thiercelin and Roegiers 1986). As discussed in Thiercelin (1987), Thiercelin (1989), and Whittaker and others (1992), one important aspect of the test is that the sample geometry and applied compressive load inhibits the development of a large microcracking process zone ahead of the crack tip. Because the process zone is small and does not reach the specimen boundaries then plane strain is achieved and the test is a valid linear elastic fracture mechanics test even though it uses small specimens. This test is well suited for our needs because of the size of the core, the characteristics of the core, and because the amount of core available for testing was limited.

3.1 *Specimen Characteristics*

The modified ring test specimen geometry requires using only competent lithologies that do not chip during sample preparation, such as sandstones, limestones, and dolostones. Although stylolites and calcite filled veins are pervasive in the core samples, specimens were prepared that minimize hetereogeneities that could affect crack propagation and the test results.

The geometry of the test specimen is shown in Figure 2. Sample preparation involves (1) using a diamond saw to cut cores into disks, (2) using a diamond coring bit to drill a smooth hole in the center of the disk, and (3) grinding two diametrically opposed flat surfaces on the outer surface of the



r_e = Core Radius = 30.4 mm
r_i = Inner Hole Radius = 4.4 mm
r_f = Loading Flat Radius = 30.0 mm
L = Loading Flat Width = 10 & 20 mm
T = Sample Thickness = 30 mm
2a = Crack Length

Figure 2 Modified ring test specimen geometry and dimensions used in this study.

disk. The parameters describing the geometry of the specimen are the internal hole radius (r_i), the external radius (r_e), the radius to the loading flat (r_f), the width of the loading flat (L), and the thickness (T). The nominal dimensions of the specimens tested are listed in Figure 2.

All of the bedrock core from the area has the same diameter so r_e is fixed. Therefore, amount of rock that is available for crack propagation (cracking span) is controlled by r_i and L. As either L or r_i increases the cracking span decreases. The r_i must be greater than any sample flaws in order to focus the point of crack initiation, but small enough to develop a uniform tensile stress field in the majority of the cracking span for mode I crack growth. The cracking span is maximized if the width of the loading flat is small, but if too small, then local failure of the specimen at the platen contact points is likely to occur (e.g., Mellor and Hawkes, 1971). The specimen parameters were chosen to maximize the size of the cracking span given the fixed external radius.

3.2 *Stress Intensity Calibration*

An advantage of the modified ring test is that the crack length at which stable crack propagation begins is fixed based on the geometry of the test specimen. As a result, the crack length during the test does not need to be recorded. The crack length at which unstable crack propagation becomes stable can be determined from a stress intensity factor versus crack length curve (Thiercelin and Roegiers 1986). The mode I crack tip stress intensity during crack growth for a particular modified ring geometry was computed using a fracture mechanics finite element modeling program written for the Macintosh computer (Bryson 1990). The curve produced based on our sample dimensions has the following boundary conditions (Figure 3):

- No-slip at the loading platen-specimen contact.
- Constant distributed compressive force applied to the loading flat.
- $\nu = 0.25$, E = 50,000 MPa, L = 10 mm.

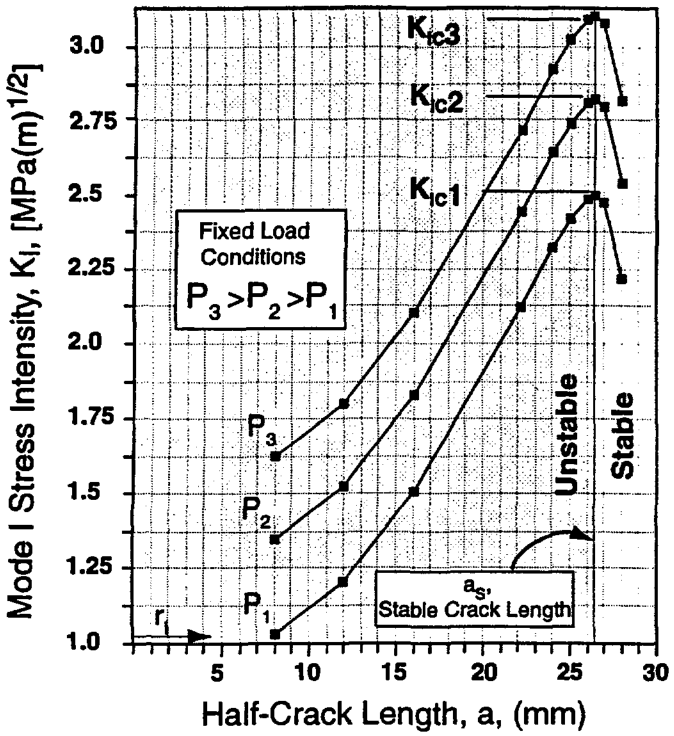


Figure 3 Mode I stress intensity as a function of crack length under constant load boundary conditions for the specimen dimensions in Figure 2 and L = 10 mm. See text for discussion.

Prior to crack growth, the constant load condition produces the stress field in the specimen shown in Figure 4. Mode I cracks initiate at the high tensile stress gradient associated with the apices of the center hole. Stress intensity increases as the crack propagates in the fairly constant tensile stress field region (Figure 3). As the crack grows towards the loading flat, however, the magnitude of the tensile stress in the specimen decreases. As a result, the stress intensity at the crack tip begins to decrease after reaching a maximum. The fracture toughness (K_{IC}) is measured at the stress intensity maximum in the K_I vs a curve (Figure 3). This is the crack length (a_s) where it is assumed that unstable crack growth becomes stable under controlled tensile stress conditions. Note that the model is growing the crack under constant load boundary conditions and so once

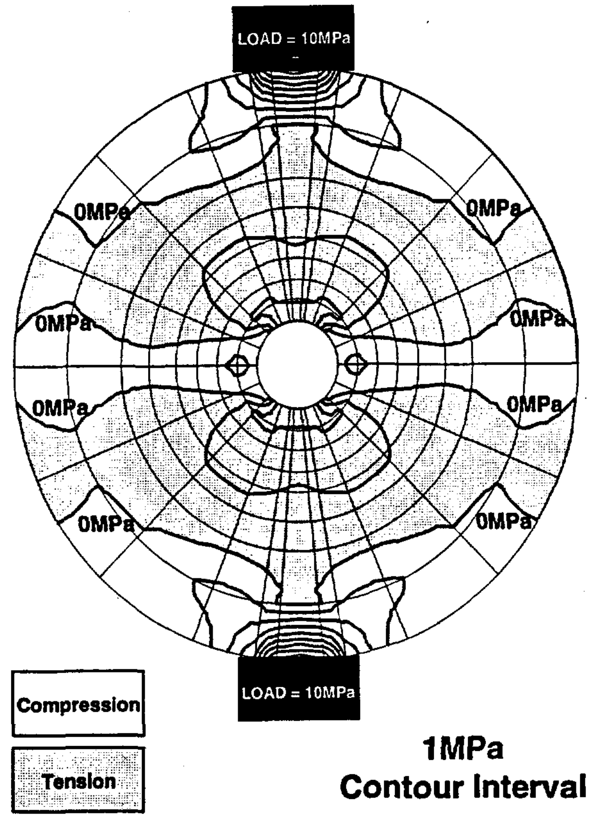


Figure 4 Maximum principal stress distribution in specimen before mode I crack propagation.

past the stable crack length, the crack cannot continue to grow unless the load on the specimen is increased. Therefore, the additional crack lengths modeled under the constant load are done just to accurately determine the stress intensity curve maximum point. Thiercelin and Roegiers (1986) discussed how the stable crack length corresponding to the maximum in the K_I vs a curve will vary as a function of the width of the loading flat, which allows for the fracture toughness to be measured for different crack lengths.

3.3 *Fracture Toughness Measurement*

Specimens were tested on an Interlaken hydraulic testing machine which was monitored by an Interlaken Technology model 3200 controller (Interlaken Technologies 1992). During testing the load, load-line displacement, and time was recorded by an Interlaken Technology Universal Testing Program installed on a microcomputer.

The only independent variable that needs to be determined during testing is the load at which the unstable crack becomes stable, because based on the modeling we already know the effective crack length when this is achieved. As shown on the load vs displacement plot, initially there is a linear rise of the load prior to crack propagation (Figure 5). During unstable cracking the load drops, because under fixed grip conditions, the drop in load is

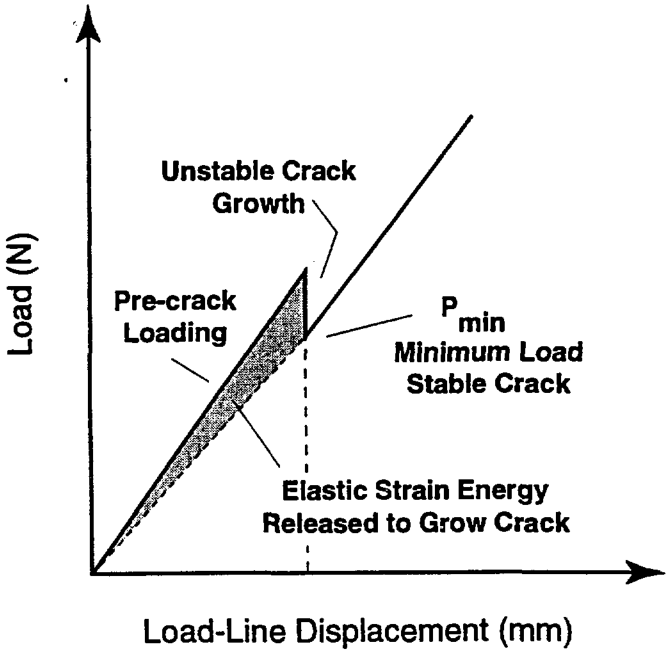


Figure 5 Schematic typical Load-Displacement curve developed during modified ring testing.

representative of the stored elastic strain energy in the specimen that is released during crack growth (Figure 5). Unstable crack propagation is commonly associated with an audible "pop-in" and occurs at a fixed load-line displacement. The load reaches a local minimum point, which is when the magnitude of the crack normal tensile stresses in the specimen produced by that minimum load decreases to the point where unstable crack propagation stops and becomes stable. If the test is allowed to continue at a constant rate of displacement, the load increases linearly and ultimately complete failure of the specimen occurs either along cracks formed along the outer edge of the sample perpendicular to the loading flat or by shear fracturing around the loading flat.

The local minimum load (P_{min}) recorded during the test is input in the foregoing finite element model. Any change in the magnitude of P_{min} causes the curve to shift parallel to the K_I axis, but does not affect the curve shape (Figure 3). Note that during the actual test, however, the shorter crack lengths are propagating when the load is more than P_{min}. In a fixed grips arrangement the displacement during crack growth remains nearly constant, but the load is dropping as the crack grows. Furthermore, after P_{min} is reached the load increases again, and therefore the second part of the K_I vs a curve also does not represent the true stress intensity factor for this part of the test. Instead the stress intensity is increasing and the crack may continue to grow until failure. Therefore, the K_I vs a curve produced for a P_{min} is only valid for the K_I point at which the crack growth becomes stable. As a result it is only necessary to run the model for each test using only the known a_s and P_{min}.

4. TEST RESULTS & DISCUSSION

Table 1 lists the experimental results to date. There is a total of 67 tests conducted on samples from the Oak Ridge area. Some tests were considered invalid because a stable crack and a local load minimum was not achieved, while others were not used because specimen flaws (stylolites and veins) may have influenced crack growth. The average mode I fracture toughness values for each lithology within a particular stratigraphic unit are based on 2 to 8 tests.

Table 2 contains the results of 33 successful tests for the Berea sandstone and Indiana limestone. These tests were conducted to evaluate the quality of our test results. Tests were conducted on cores cut from quarry blocks. The fracture toughness results are within the range of previous estimates based on the modified ring test method and other mode I fracture toughness tests methods (Whittaker and others 1992).

Some tests were unsuccessful because of the displacement rate. The displacement rate of the loading platens has an important influence on achieving crack stability in the specimen. We tested various rates and found that if the rate of displacement is too great, then crack growth is quickly followed by complete failure of the sample (e.g., 0.00211 mm/s). Although when this occurs the machine may record a short pause at a local minimum load, the load keeps dropping and therefore is undefined. The majority of successful tests were conducted at a rate of 0.0003 mm/s.

Fischer and others (1996) recently presented a finite element modeling study of the modified ring test specimen that examined how the effective crack length determined from the modeling is dependent on the boundary conditions used in the model. If the model does not reasonably reproduce the test conditions, then the effective crack length (i.e., K_{IC}) determined by the K_I vs a curve may be in error by as much as 25%. Because of the stiffness of the testing platens we used a no-slip boundary condition on the loading flats (Jaeger and Cook 1984). If no-slip conditions prevail then the value of Poisson's ratio will affect the computed stable crack length under the applied load boundary condition (Fischer and others 1996). An increase in Poisson's ratio from 0.25 to 0.45 causes the stable crack length to decrease, which reduces the value calculated for K_{IC} (Figure 6). Therefore, a second measure of the fracture toughness was calculated when ν=0.45, at a stable crack length of 25 mm (Table 1). The difference in the calculated fracture toughness, however, is minor and well within the standard deviation of the results.

Table 1 Experimental results for rock units in the Oak Ridge area.

Stratigraphic Unit	Lithology	Porosity %	Successful Tests\ Total Tests	Average K_{IC} $MPa\sqrt{m}$	Average K_{IC} $MPa\sqrt{m}$
Rome Formation					
Maroon	Sandstone	5.0	2\5	1.9	1.7
Gray	Sandstone	0.8	7\8	2.3	2.2
Conasauga Group					
Dismal Gap Formation	Limestone	0.7	2\2	0.6	0.6
Nolichucky Shale	Limestone	1.3	5\5	0.8	0.7
Maynardville Limestone					
Chances Branch Member	Dolostone	1.0	5\6	1.2	1.1
Low Hollow Member	Limestone	0.5	8\9	1.4	1.4
Knox Group					
Copper Ridge Dolomite	Dolostone	3.4	7\9	1.6	1.5
Mascot Dolomite	Dolostone	0.6	2\5	1.3	1.2
Chickamauga Group					
Rockdell Formation	Limestone	2.5	7\7	0.7	0.7
Benbolt Formation	Limestone	0.5	6\6	1.3	1.2
				$\nu = 0.25$	$\nu = 0.45$
				a= 26.5 mm	a= 25 mm

Table 2 Experimental results for the Berea sandstone and Indiana limestone.

Stratigraphic Unit	Porosity %	# of Tests	Average K_{IC} $MPa\sqrt{m}$
Berea Sandstone	16.0	24	1.4
Indiana Limestone	10.0	9	1.2
			$\nu = 0.25$
			a= 22 mm

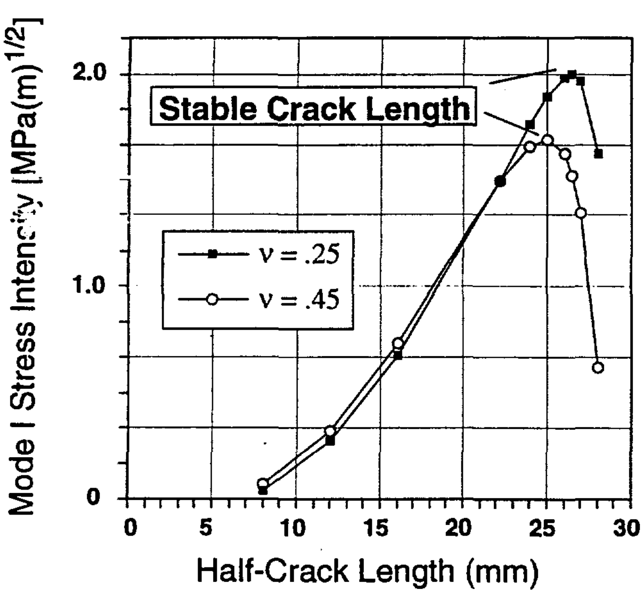


Figure 6 Mode I stress intensity versus crack length curves depicting the change in stable crack length for different values of Poisson's ratio under applied load and no-slip boundary conditions.

The fracture toughness results are typical for the sedimentary rock types tested. The gray, silica cemented sandstone from the Rome Formation has the highest fracture toughness of all the rock types tested. The very high fracture toughness is attributed to the well cemented, low porosity matrix and fine grained quartz composition. Dolostones from the Knox Group have a slightly higher fracture toughness compared to the limestones, which generally have the lowest fracture toughness of all the competent rock types tested. Furthermore, the fracture toughness is not constant between the different limestone bearing units. For example, limestones from the Rockdell Formation have a consistently lower fracture toughness than limestones from the Benbolt Formation. Limestones from the Dismal Gap Formation have the lowest fracture toughness. The limestones from the different stratigraphic units generally have different textures (crystalline vs grains, grain size, and diagenetic history), all of which contribute to the fracture toughness properties of the material.

Within particular stratigraphic intervals tested we expected more variability in the fracture toughness results because of the heterogeneities present in the samples. Another reason is related to potential differences in fracture toughness as a function of crack propagation direction with respect to bedding (Scott and others 1991). Because the core samples are unoriented we cannot relate the crack propagation direction in the sample and resulting fracture toughness to a particular bedding direction. The consistent response in the load deformation curve for particular stratigraphic intervals, however, suggests that sample heterogeneities and crack propagation direction had little effect on the fracture toughness (Figure 7).

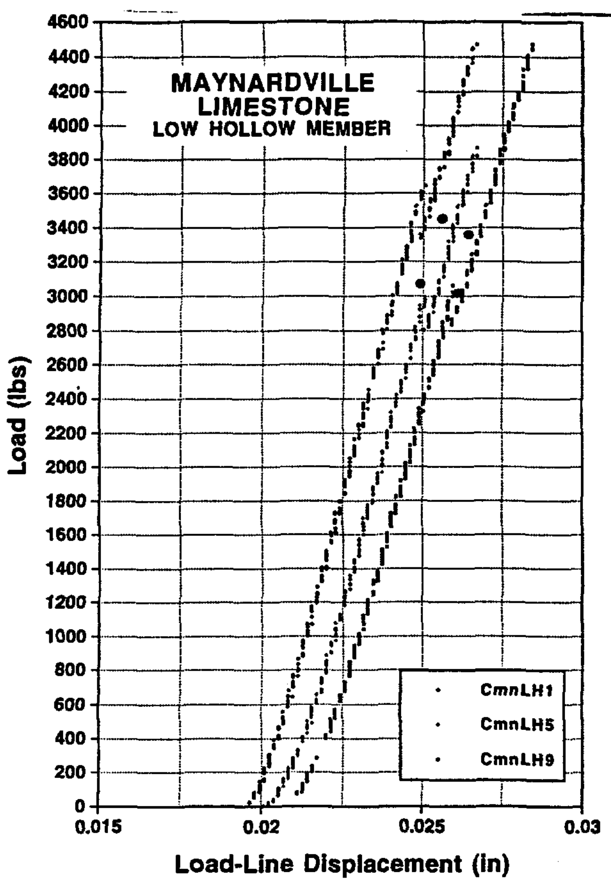


Figure 7 Load-Displacement plots for three tests on the Maynardville Limestone-Low Hollow Member. Additional minimum load points from other tests are indicated by the black circles.

We plan to better evaluate if the stable crack length determined by the finite element model is representative of the crack length in the specimen at the local minimum load point. A few of the tests reported here were stopped after the minimum load was reached and the crack lengths were measured. Crack length measurements were made under magnification on the surface from dyed and undyed cracks. In addition, the crack length in some sandstones was measured based on a change in surface roughness of the crack when the specimen was later cracked apart (Figure 8). Although preliminary, the measured crack lengths are close to that predicted by the finite element model. Future tests will include crack detection gauges placed along the expected trajectory of the cracks to better record the crack position at local the minimum load point.

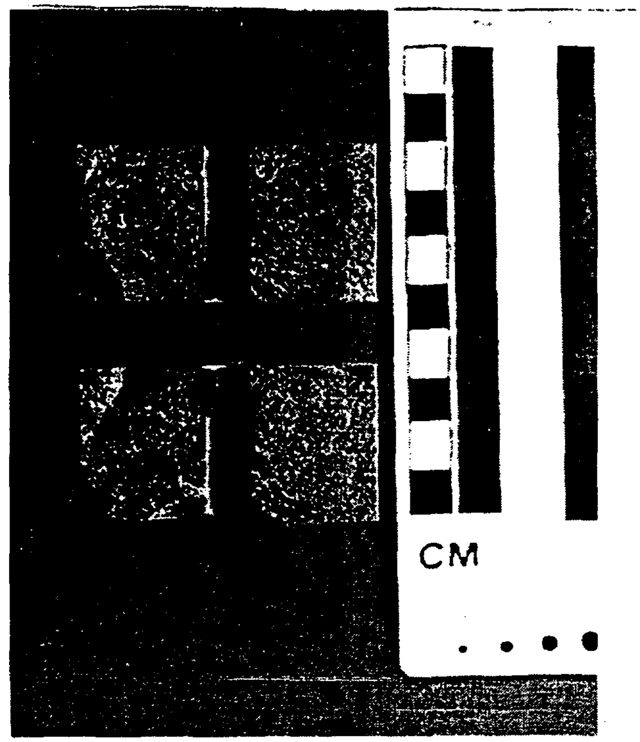


Figure 8 Crack surfaces in Rome Formation sandstone specimen.

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