THE EFFECT OF ZERO POINT OF CHARGE ENVIRONMENT
ON ROCK FRACTURE BEHAVIOR

by

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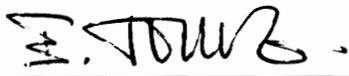
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(ABSTRACT)

This experimental investigation was conducted to assess the effect of zero point of charge (ZPC) environment on fracture behavior of rocks. The material parameters selected for this purpose were fracture toughness and specific work of fracture. These properties were determined for three rock types in five environments. Semi–circular bend specimens of dolomitic limestone, Sioux quartzite and Westerly granite were tested in aqueous solutions of aluminum chloride, calcium chloride and polyethylene oxide, all at ZPC conditions. These rocks were also tested in atmospheric air and distilled deionized water. For every rock type, the results obtained for the tests done in each of the ZPC environment were statistically compared with the results in water. This comparison was also made for air and water.

The average fracture toughness in each of the ZPC environments, for all three rock types, was found to be less than the corresponding average in water. The specific work of fracture results also indicated reduction in ZPC environments as compared to water. The statistical analysis of the results, however, showed that this reduction was significant in some but not all of the rock–environment combinations tested in this investigation.

ACKNOWLEDGEMENTS

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INTRODUCTION

Mechanical rock fragmentation is an area of considerable expenditure in the mining industry. When the total volume of rock material involved in fragmentation processes such as drilling, cutting, tunnel boring and crushing is considered, even modest improvements in the efficiencies of these processes could result in significant cost savings. This can be achieved either by improving the fragmentation tool or by modifying the mechanical behavior of rock through chemical means.

Aqueous chemical environments have been reportedly used to enhance drilling fragmentation rates. An extensive literature survey on the use of chemical additives in drilling indicates that 100 different environments have been used with varying degrees of success. The greatest success was reported at zero point of charge conditions, i.e., when drilling with environments capable of neutralizing the rock surface charge. Although enhanced drilling rates have been observed for some rocks in the limited laboratory and field tests performed, controversy still exists whether fragmentation is chemically enhanced.

Considering the potential technological value of chemically enhanced fragmentation, studies need to be carried out to develop a better understanding of the fundamental mechanisms involved in this phenomena. The first step to achieve this goal will be to assess the effects of various environments on rock properties relevant to a given fragmentation process. The relative importance and the manner in which an individual rock property may affect rock breakage will depend upon a particular rock–tool combination. However, the resistance of a rock to the initiation and propagation of fractures will always play an important

role in any fragmentation process.

The parameters used to characterize the resistance which a material offers to propagating cracks are fracture toughness and specific work of fracture. This research was conducted to assess the effects of some promising ZPC environments on these properties for certain rocks. Using fracture mechanics techniques three types of rocks were tested in five environments. The rock types selected for this study were dolomitic limestone, Sioux quartzite and Westerly granite. The ZPC environments were aqueous solutions of aluminum chloride, calcium chloride and polyethylene oxide. Distilled deionized water and atmospheric air were the control environments. A least six replicate tests were done for each rock—environment combination. The results were statistically analyzed to verify the hypothesis that ZPC environments lower the fracture toughness and specific work of fracture of rocks when compared to the control environments.

A brief summary of the reported effects of various environments on drilling and rock properties is included in chapter 1. The material properties selected for this study and methods for their determination are discussed in chapter 2. Details of experimental investigation including selection of environment, sample preparation, test setup, data acquisition and reduction are given in chapter 3. Chapter 4 contains results and their discussion. Conclusions and recommendations are outlined in chapter 5.

1. REVIEW OF LITERATURE

The use of environmental effects to enhance the efficiency of fragmentation processes was demonstrated by Russian researchers almost six decades ago (Rebinder et al., 1948). They reported increased rock drilling rates in aqueous solutions of certain salts such as aluminum chloride, calcium chloride etc. Certain other researchers later reported similar results (Shepherd, 1954; Robinson, 1967; Strebig et al., 1969). These improvements in drilling rates were attributed to the reductions in hardness due to adsorption—induced reductions in the surface energy of rocks. It was argued that crack propagation ahead of cutting tool or beneath the indentor becomes easier when surface energy of the solid is reduced by the adsorbed species. Such effects of environment on the behavior of solids were later known as Rebinder effects.

The role of Rebinder effects in fragmentation of solids was further studied by Westwood and his co—workers in the US. While drilling in "model" solids such as MgO monocrystals and soda lime glass using various surfactants, they observed that the adsorption—induced reductions in surface energy of solids are of little consequence as far as environment sensitive drilling behavior is concerned. They suggested that the influence of adsorbed species on the near surface flow dependent fracture behavior of solids is far more important because it is responsible for crack initiation in the predestruction zone ahead of bit. This suggestion was based on the premise that once cracks form, they readily propagate to form chips and it is the crack initiation, not the propagation, which determines the rate of drilling in brittle solids such as rocks (Westwood et al., 1967; Westwood and Goldheim, 1968).

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Westwood and his co-workers hypothesized that environment induced changes in the surface charge of solids affect the ease with which the near surface dislocations can move and interact to initiate cracks. They argued that the adsorption of chemicals on the surface of solids involves charge transfer between the solid and the adsorbate. This leads to alterations in the electronic structure of the near surface regions of the solid, thus causing changes in the state of ionization of dislocations, impurities, point defects, etc. As a consequence, the mutual interactions between the moving dislocations and point defects are affected causing changes in the fracture behavior (Westwood et al., 1973; Westwood and Macmillan, 1973).

During these studies, Westwood and his co-workers reported an important correlation between the surface charge and hardness of solids. According to this correlation the hardness of solids is maximum at zero point of charge (ZPC) conditions, i.e. the condition at which the surface charge of the solid is neutralized by the adsorbed species (Westwood and Macmillan, 1972; Macmillan et al., 1973).

This correlation was successfully used to vary the drilling rates in the so-called model solids. It was also reported that environments that produce hardness maxima at ZPC conditions increase cutting rates of tools designed for use in brittle solids, but decrease the efficiency of tools designed to cut via ploughing action (Westwood et al., 1973; Macmillan et al 1974a).

Westwood and his co-workers further investigated this phenomena to establish whether the ZPC effect observed on the model solids could be applied to more complex solids. They used several different types of bits to drill Westerly granite in water, various n-alcohols, and aqueous solutions of aluminum nitrate and dodecyl ammonium bromide (Westwood et al., 1974; Macmillan et al., 1975).

Their data revealed increased drilling rates at ZPC conditions as compared to water.

However further investigations indicated that scaling up laboratory studies to field conditions and achieving enhanced fragmentation in a predictable manner was not possible unless the effects of ZPC conditions on all the parameters involved in a given fragmentation process are established (Westwood et al., 1975; Mills et al., 1976).

The phenomena of chemically enhanced drilling was also studied by researchers at the US Bureau of Mines (Engelmann et al., 1987). They reported enhanced penetration rates in laboratory scale drilling of Westerly granite and Sioux quartzite using ZPC solutions of some cationic surfactants and polymers.

These results are encouraging but their application to field conditions in a predictable and optimum manner is only possible if the underlying mechanisms of this phenomena are clearly understood.

Before trying to understand the role of ZPC effects in drilling, one must consider the fragmentation process when a bit tooth impacts the rock and assess how these effects may contribute to each stage of the process. The drilling fragmentation process always involves the formation of a crushed zone, plastic deformation and generation of fragments by tensile and/or shear failure (Dutta, 1972; Lawn and Wilshaw, 1975; Swain and Lawn, 1976; Howarth and Bridge, 1988a; 1988b). The relative importance of each depends on the mechanical behavior of the rock and the action of cutting tool. For a given rock–tool combination the fragmentation may be enhanced if crushing and plastic deformation is minimized and the resistance of rock to tensile cracking and shear failure is reduced.

In addition to the effects discussed in the previous paragraphs, a number of ZPC effects that may contribute to enhanced fragmentation in rock drilling have been reported. These effects include changes in strength, frictional behavior, and crack propagation.

Uniaxial compressive strength of quartz diorite has been reported to decrease in ZPC solutions of dodecyl trimethyl ammonium bromide and aluminum nitrate as compared to strength in water (Ishido and Mizutani, 1980). In this study a maximum of 35% reduction in strength was reported at ZPC conditions. Recent studies at US Bureau of Mines indicate up to a 9% reduction in compressive strength of Westerly granite in aqueous solutions of aluminum chloride and polyethylene oxide at ZPC conditions (Tuzinski, 1989). Both of these investigations were done under saturation conditions. These researchers suggest that this reduction in compressive strength is the result of rapid growth of microcracks at ZPC conditions.

A recent investigation of ZPC effects on tensile strength of synthetic quartz shows up to a 50 % reduction its diameteral (tensile) strength in aqueous solution of aluminum chloride (Dunning et al., 1984). However in the studies of researchers at the US Bureau of Mines no reductions were found in the Brazilian strength of Sioux quartzite tested under immersed conditions in aqueous solution of aluminum chloride at ZPC concentration.

Some researchers have reported decreases in the coefficient of friction of rocks at ZPC conditions (Macmillan et al., 1974b; Mills and Westwood, 1978). Since tensile crack propagation is characterized by microcracking around the crack tip and interlocking along a portion of the crack (Labuz et al., 1985), the reduction in the coefficient of fiction is supposed to minimize the interlocking process and

accelerate the crack propagation thus enhancing the fragmentation process in drilling (Karfakis et al., 1990).

Some reports also indicate that ZPC conditions lower the stress required to initiate and propagate cracks. These reports suggest that crack growth (Ishido and Mizutani, 1980; Ishido and Nishizawa, 1984) and crack branching (Dunning and Huf, 1983; Dunning et al., 1984) are greatest at ZPC conditions. These suggestions are based on observations made during uniaxial compressive strength tests and hydraulic fracturing tests.

It has also been suggested that at ZPC conditions the rock interfacial tension is maximized (Watson and Englemann, 1985; Engelmann et al., 1988). An increase in interfacial tension may facilitate fragmentation by lowering the energy requirements for fracture initiation and propagation through prevention of fracture closure after the mechanically applied stress is removed. This process may facilitate fragmentation by the action of the drill bit, which involves the catastrophic growth of microcracks to form a rock chip by cyclically loading the rock.

Most of the researchers seem to agree that the ease of initiation and propagation of cracks under the action of the fragmentation tool play an important role in the enhancement of drilling. However, the effects of ZPC conditions on crack initiation and propagation behavior have only been observed in a few indirect studies (Ishido and Mizutani, 1980; Dunning et al., 1984).

Crack initiation and propagation behavior can be studied more meaningfully using fracture mechanics techniques. These techniques provide a quantitative description of the transformation of an intact material into a broken one. The basic material property used in fracture mechanics is fracture toughness.

It describes the resistance which a material offers to crack extension. Specific work of fracture, which is the work done to create a unit surface area, is also indicative of fracture resistance.

Although there is experimental evidence that fracture toughness of rocks is affected by chemical environments (Atkinson, 1979), the ZPC effects on this important material parameter and on specific work of fracture have never been investigated before.

The objective of this research is to assess ZPC effects on fracture toughness and specific work of fracture of rocks. The results of this study will supplement the essential information required to develop an understanding of the mechanisms involved in chemically enhanced failure in various rock fragmentation processes.

2. FRACTURE TOUGHNESS

2.1 THE CONCEPT OF STRESS INTENSITY

According to the theory of fracture mechanics, brittle fracture of materials is governed by a variable called the stress intensity, K, which depends on the stress, crack length, and geometry. For the case of a central crack in a wide plate (Dowling, 1989; Figure 1);

$$K = \sigma \sqrt{\pi a} \qquad\qquad 2.1$$

where σ is the stress averaged over the gross area. If either the stress or the crack length is increased sufficiently, K reaches a critical value, K_c, which causes sudden brittle fracture. The variable K is a measure of the severity of the crack, while the constant value K_c is the limiting value of K that can be resisted by a given material. This limiting value K_c is known as fracture toughness. Equation 2.1 can be generalized as

$$K = F \sigma \sqrt{\pi a} \qquad\qquad 2.2$$

The factor F is a dimensionless function that depends on the geometric configuration. In general it can be expressed as

$$F = f(a / w) \qquad\qquad 2.3$$

where the dimension w is defined as the maximum possible crack length. Critical stress intensity or fracture toughness can be determined if the function F for a given geometry is known. A consistent value of K_c can only be obtained if conditions of plane strain are ensured. Such a value of K_c is known as plane strain fracture toughness and is considered to be an intrinsic material property.
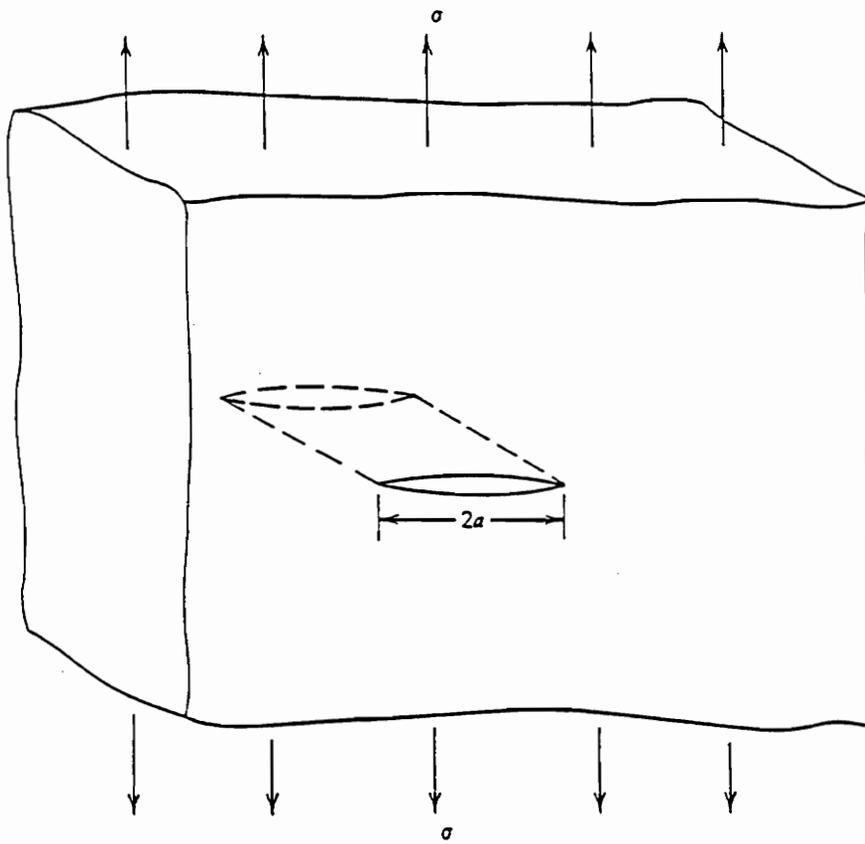
Figure 1. Through–Thickness Crack in an Infinite Plate (After Collins, 1981)

2.1.1 Stresses at a Crack Tip

Crack extension can be described by any one or a combination of three displacement modes (Figure 2). Each mode describes the relative movement of the two crack faces. In Mode I, which is called the opening mode, crack faces move apart perpendicular to the plane of crack. For mode II, the sliding mode, the crack faces slide relative to one another in a direction normal to the leading edge of the crack. Mode III, the tearing mode, also involves relative sliding of the crack faces, but in a direction parallel to the leading edge of the crack. In mode I, crack propagation is caused by tension loading, whereas in the other two cases propagation is caused by shear loading. The superposition of two or three of these modes is referred to as mixed mode loading. Most of the crack problems involve Mode I and are due to tension loads. Even where a crack is initially in shear, it will often change direction as it propagates primarily due to tension. This is because cracks propagate more easily in tension than in either of the shear modes. This discussion is limited to mode I displacements.

A coordinate system for describing the stresses in the vicinity of a crack is shown in Figure 3. The polar coordinates r and θ lie in the x–y plane, which is normal to the plane of the crack. The stresses near the crack tip are found by the following equations (Irwin 1957) ;

$$\sigma_x = \frac{K_I}{\sqrt{2\pi r}} \; [\cos\tfrac{\theta}{2} \, (1 - \sin\tfrac{\theta}{2} \, \sin3\tfrac{\theta}{2})] \qquad\qquad 2.4$$

$$\sigma_y = \frac{K_I}{\sqrt{2\pi r}} \; [\cos\tfrac{\theta}{2} \, (1 + \sin\tfrac{\theta}{2} \, \sin3\tfrac{\theta}{2})] \qquad\qquad 2.5$$
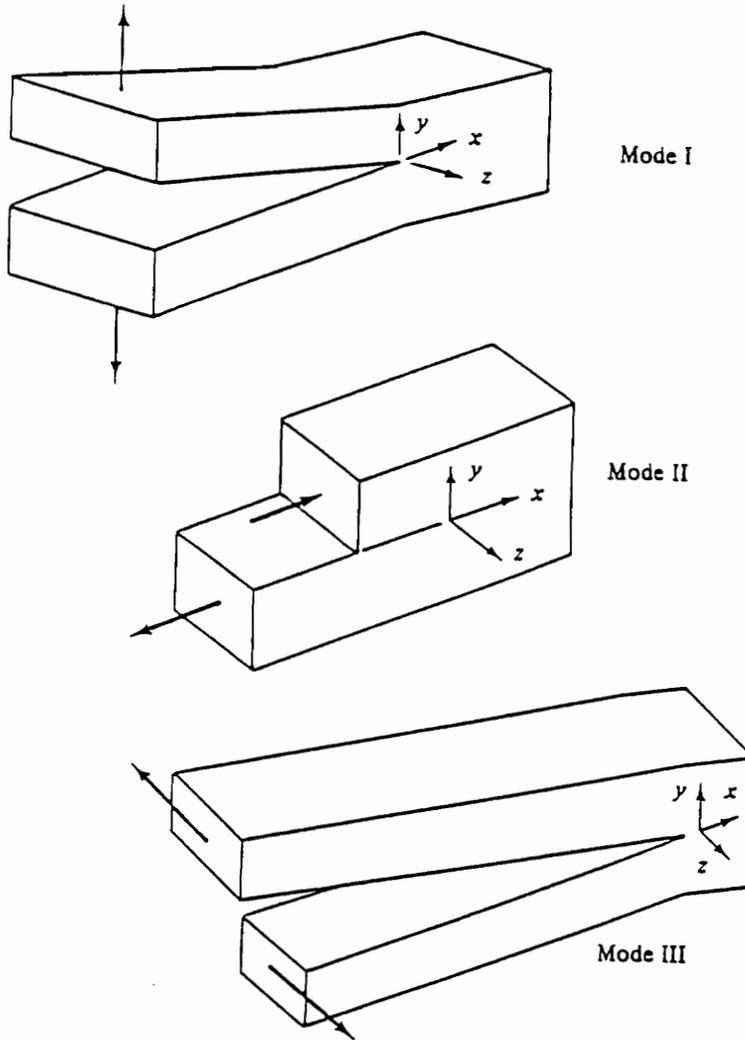
Figure 2. Basics Modes of Crack Displacement (After Caddell, 1980)
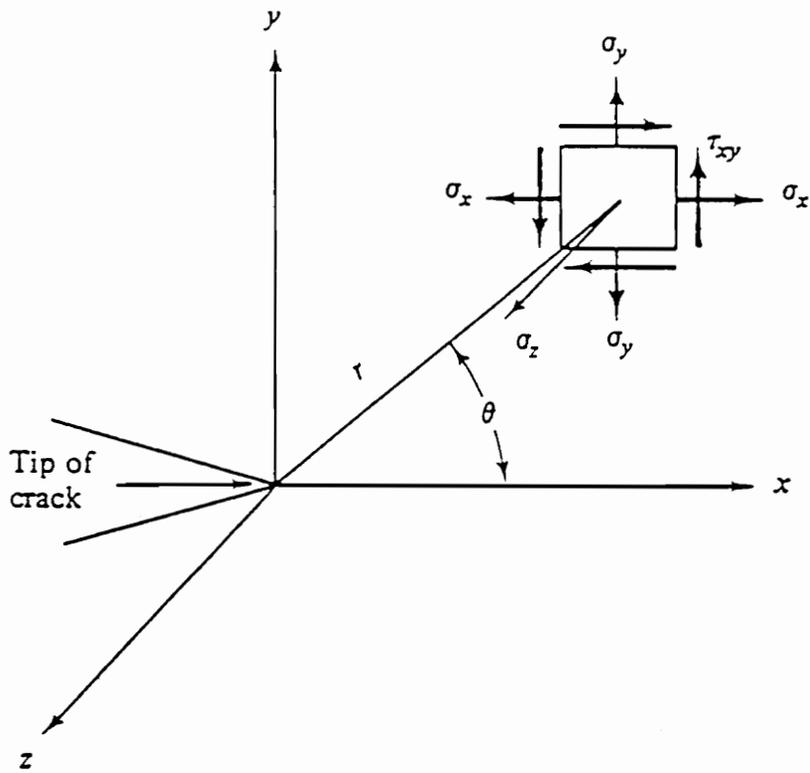
Figure 3. Stress State in the Vicinity of a Crack Tip (After Caddell, 1980)

$$\tau_{xy} = \frac{K_I}{\sqrt{2\,\pi r}}\,(\cos\tfrac{\theta}{2}\,\sin\tfrac{\theta}{2}\,\cos3\tfrac{\theta}{2}) \qquad\qquad 2.6$$

$$\sigma_z = 0 \text{ (plane stress case)} \qquad\qquad 2.7$$

$$\sigma_z = \nu(\sigma_x + \sigma_y) \text{ (plane strain case)} \qquad\qquad 2.8$$

$$\tau_{yz} = \tau_{zx} = 0 \qquad\qquad 2.9$$

These equations are based on an isotropic, homogeneous, linear–elastic material. In the first three equations, the stresses all approach infinity as r approaches zero at the crack tip. In reality the infinite stresses cannot exist in materials. The material deforms in the vicinity of the crack thus reducing the stresses to a finite value.

2.1.2 Plastic Zone

The region in the vicinity of the crack tip where the material yields is called the "plastic zone." Intense deformations in this zone make the crack tip blunt with a finite amount of opening which causes redistribution of stress in the proximity of crack tip (Figure 4). Likewise in brittle materials a region containing a high density of microcracks may develop at the crack tip, within which the material is partially coherent. This region is called the process zone.

Linear Elastic Fracture Mechanics (LEFM) is applicable to the stress intensity concept only if the plastic zone is relatively small compared to the specimen size. If the zone of yielding is too large then more general elasto–plastic
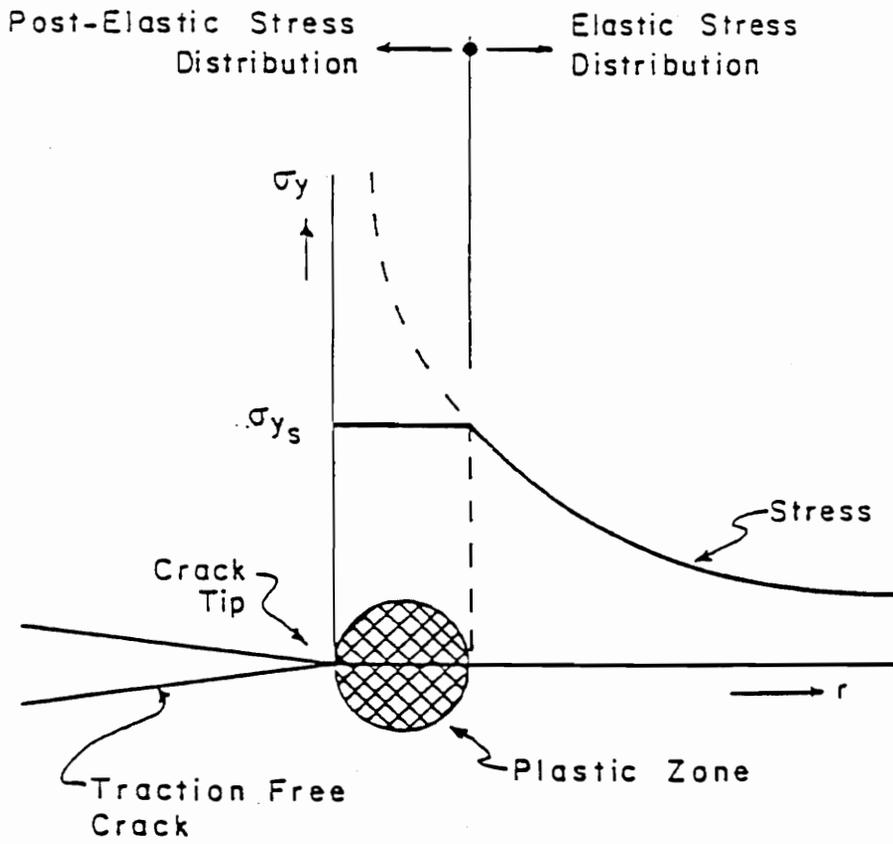
Figure 4. Assumed Stress Distribution and Plastic Zone at Crack Tip (After Basham, 1989)

fracture mechanics theory is needed.

The size of this zone can be estimated using equations 2.4 to 2.9. For plain strain case, the estimated plastic zone size for metallic materials is

$$r_p = 1 \, / \, 3 \, \pi \, [K_{IC} \, / \, \sigma_t]^2 \qquad\qquad 2.10$$

For brittle materials like rocks the equivalent of plastic zone is process zone. The size of this zone is not known.

2.2 Fracture Toughness Testing

The plane strain fracture toughness of metallic materials is determined experimentally by the standard test method E399–83 (ASTM, 1983). This method utilizes a variety of precracked notched specimens: three point bend specimen, compact tension specimen, arc shaped specimen and disc shaped compact specimen (Figure 5). These specimens are loaded either in tension or three point bending. The load versus displacement across the notch at the specimen edge is recorded. The load corresponding to a 2% apparent increment in crack extension is established by a 5% deviation from the linear portion of load versus displacement record (Figure 6). The K_{IC} value is calculated from this load by equations that have been established by elastic stress analysis of the specimens. The validity of the determination of K_{IC} depends on the establishment of a sharp crack condition at the crack tip in a specimen of adequate size.

2.2.1 Test Methods for Rocks

The strict specifications on specimen size and configuration as laid down in E399–83 (ASTM, 1983) are impracticable for rocks. The test methods for rocks are generally based on specimens derived from rock cores. However, the
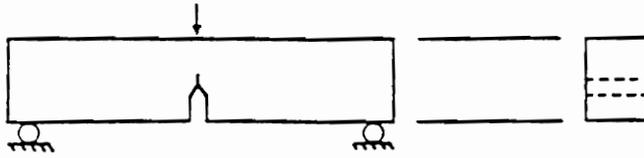
Three-Point Bend Specimen
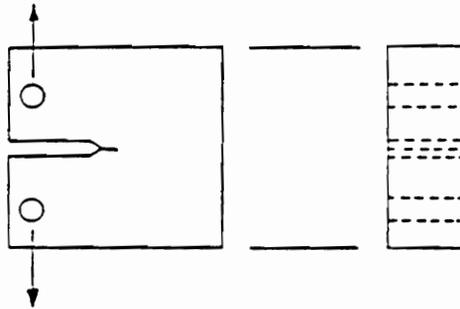
Compact Tension Specimen
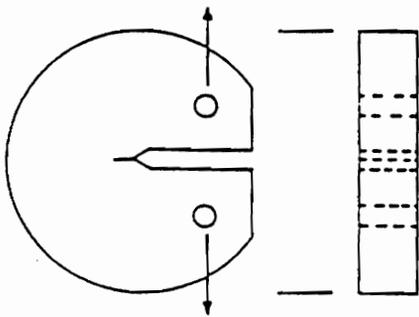
Disk-Shaped Compact Specimen
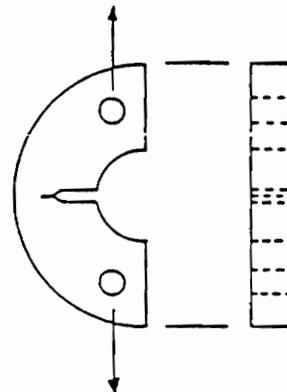
Arc-Shaped Specimen

Figure 5. Test Specimens For Metallic Materials (After ASTM, 1983)
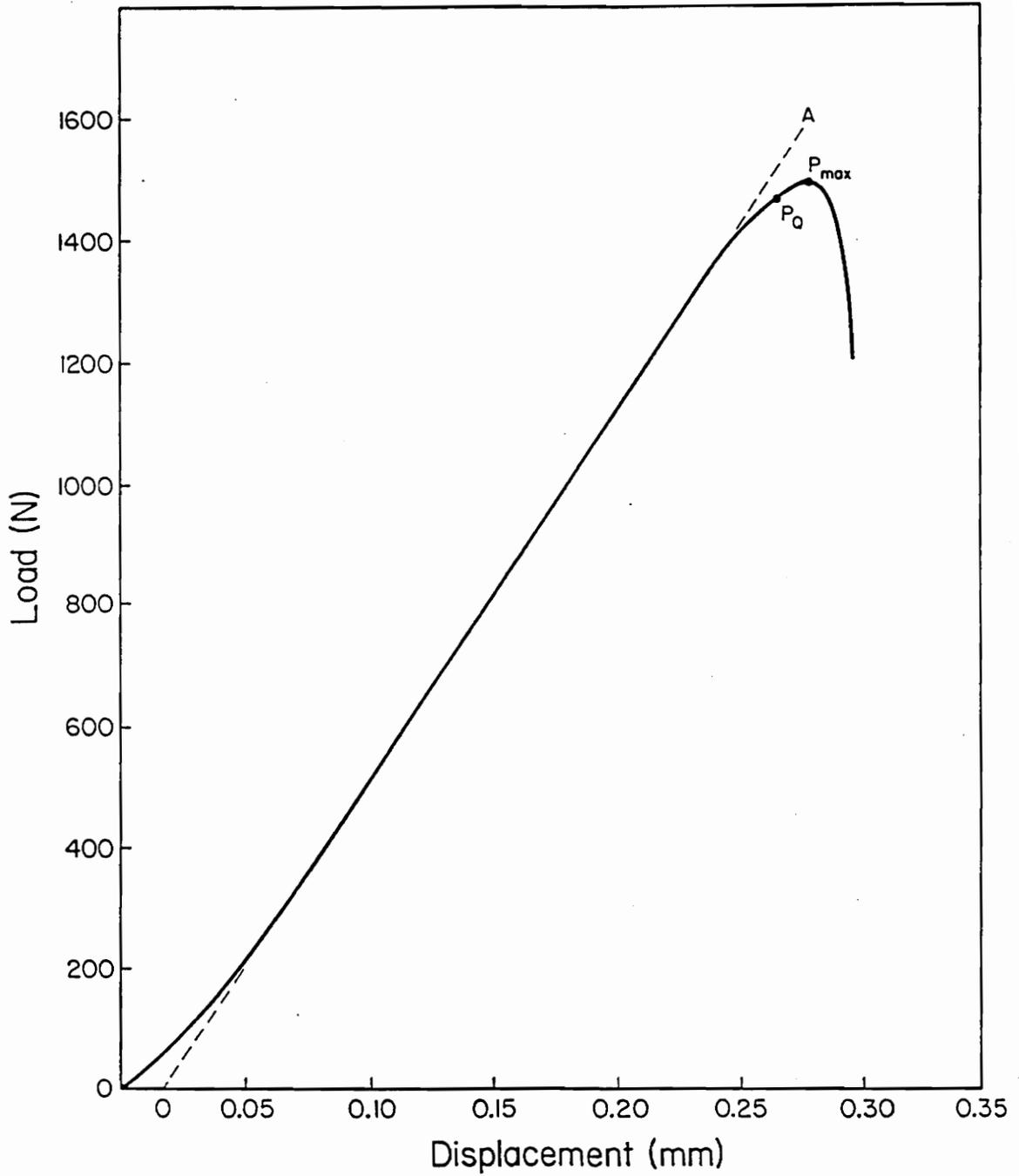
Figure 6. A Typical Load Displacement Record

underlying principles are the same regardless of the material type or specimen shape. Although a variety of core based specimen configurations have been used by different researchers, no test method has been standardized for fracture toughness testing of rocks. The three commonly used specimen configurations are

    i   Chevron Bend (CB) specimen (Ouchterlony, 1988)

    ii   Short Rod (SR) specimen (Ouchterlony, 1988)

    ii   Semi–Circular Bend (SCB) specimen (Chong and Kuruppu, 1984)

The first method uses a core specimen having a chevron or V–notch cut perpendicular to its axis (Figure 7). The specimen is loaded into a three–point bending fixture. The load compresses the specimen, forcing apart the notch sides and causing transverse splitting of the specimen in the ligament. The fracture toughness is calculated from load versus displacement data using appropriate equations.

In the second method a chevron notch is cut along the axis of the core specimen (Figure 8). A tensile force is applied perpendicular to the plane of the notch to pull apart the notch sides. The tensile force induces crack propagation into the ligament causing lengthwise splitting of the specimen. Load versus displacement data is used to calculate the fracture toughness.

The third specimen is a bending specimen and it requires a three–point bending fixture (Figure 9). This specimen was selected for this investigation.

2.2.2 Semi–Circular Bend Specimens

The SCB specimen is obtained by first cutting a disc from a rock core and then cutting the disc into two halves. A straight notch is cut at right angles to the straight edge of the semi–circular specimen. Three–point loading causes crack
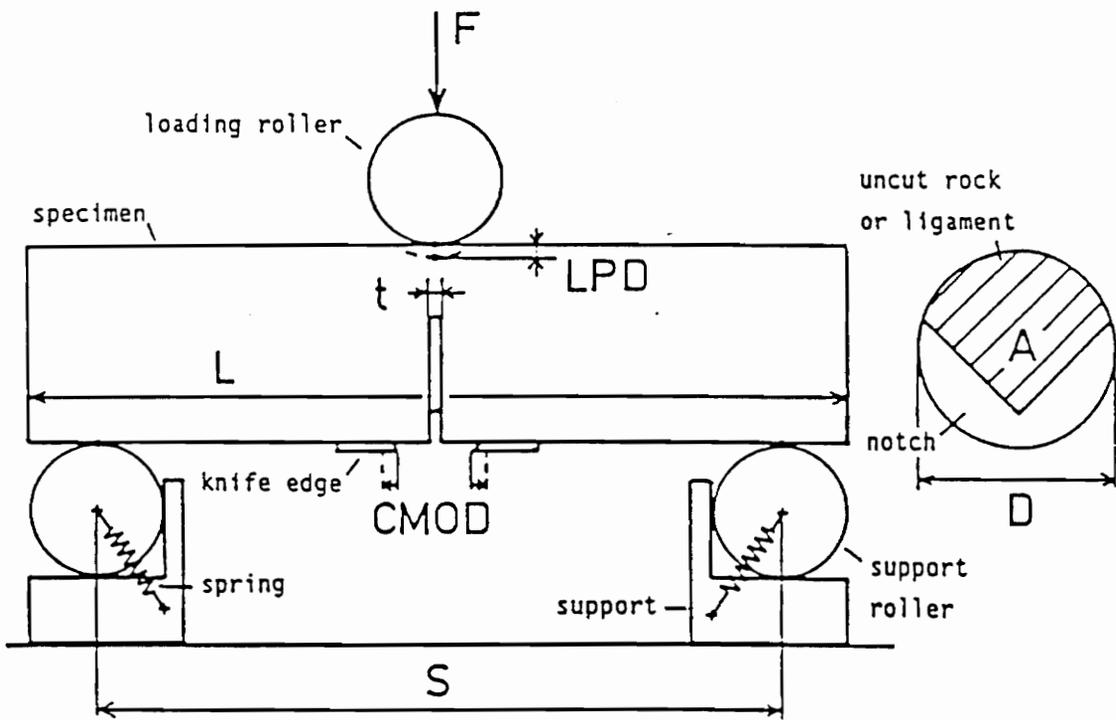
Figure 7. Chevron Bend Specimen (After Ouchterlony, 1988)

End view
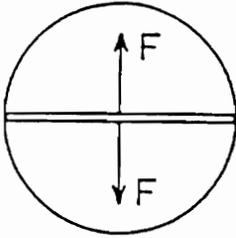
Mid section view
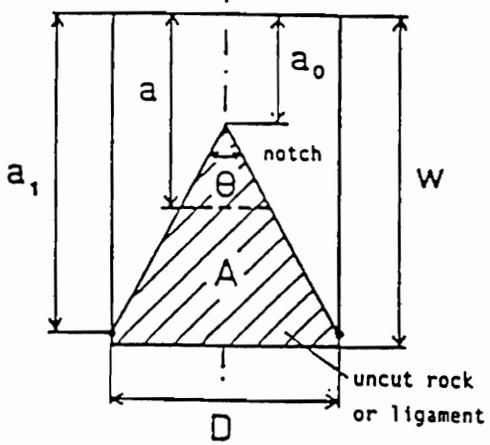
Side view
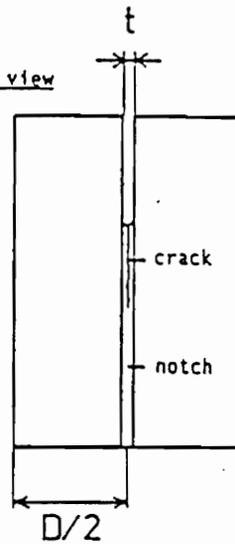
Figure 8. Short Rod Specimen (After Ouchterlony, 1988)
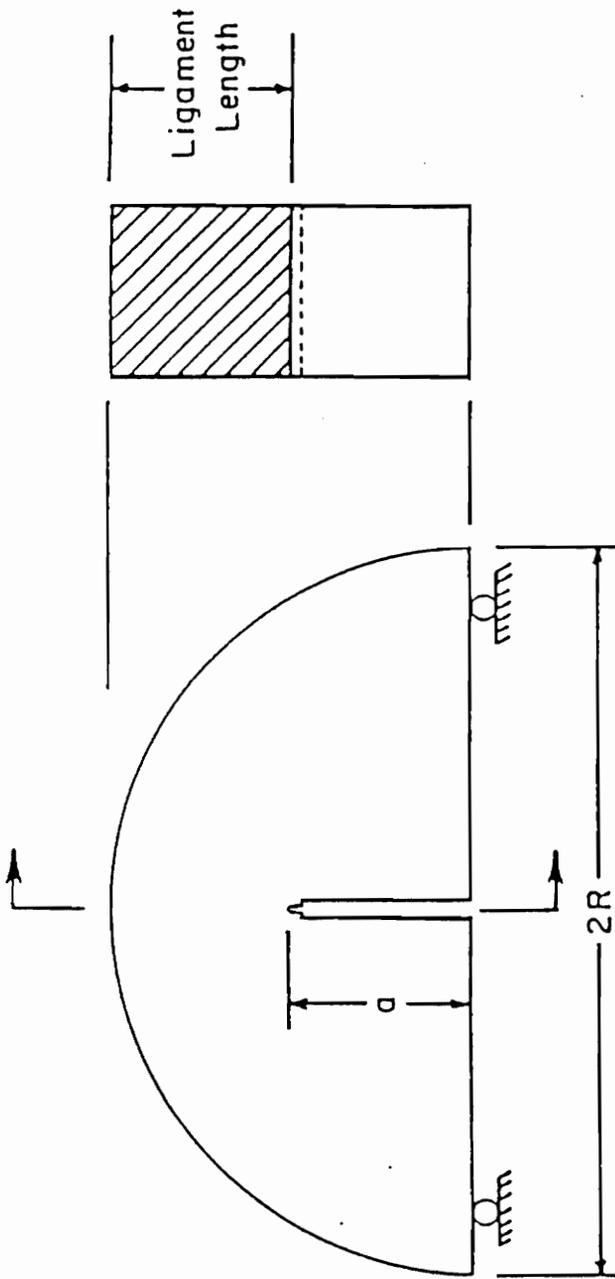
Figure 9. Semi–Circular Bend Specimen

growth in the ligament and transverse splitting of the specimen.

The SCB specimen is compressed to failure using the three—point bending fixture. From the load displacement curve the critical load is determined as explained in section 2.2. The fracture toughness is obtained using the following equation

$$K_{IC} = \overline{K}_I \, \sigma_u \, \sqrt{\pi a}$$ 2.11

where

$$\sigma_u = \frac{P}{2Rt}$$ 2.12

and

a = notch length

t = thickness of specimen

R = radius of specimen

$\overline{K}_I$ = Mode I normalized stress intensity factor. The values of this non—dimensional factor against various a/R ratios can be found from a numerically calibrated curve (Figure 10 after Chong and Kuruppu, 1984).

P_Q = Critical load as described in section 2.2.

The testing model is simple to fabricate and load. It requires very little machining. This method has been reported to yield reliable results even for relatively small thickness and ligament lengths (Karfakis et al., 1986). The calculated fracture toughness is valid only if $P_{max} < 1.1 \, P_Q$.

2.3 Specific Work of Fracture

During crack extension, energy is consumed in creating new surface area. The less energy a material absorbs, the lower its fracture resistance. Although the
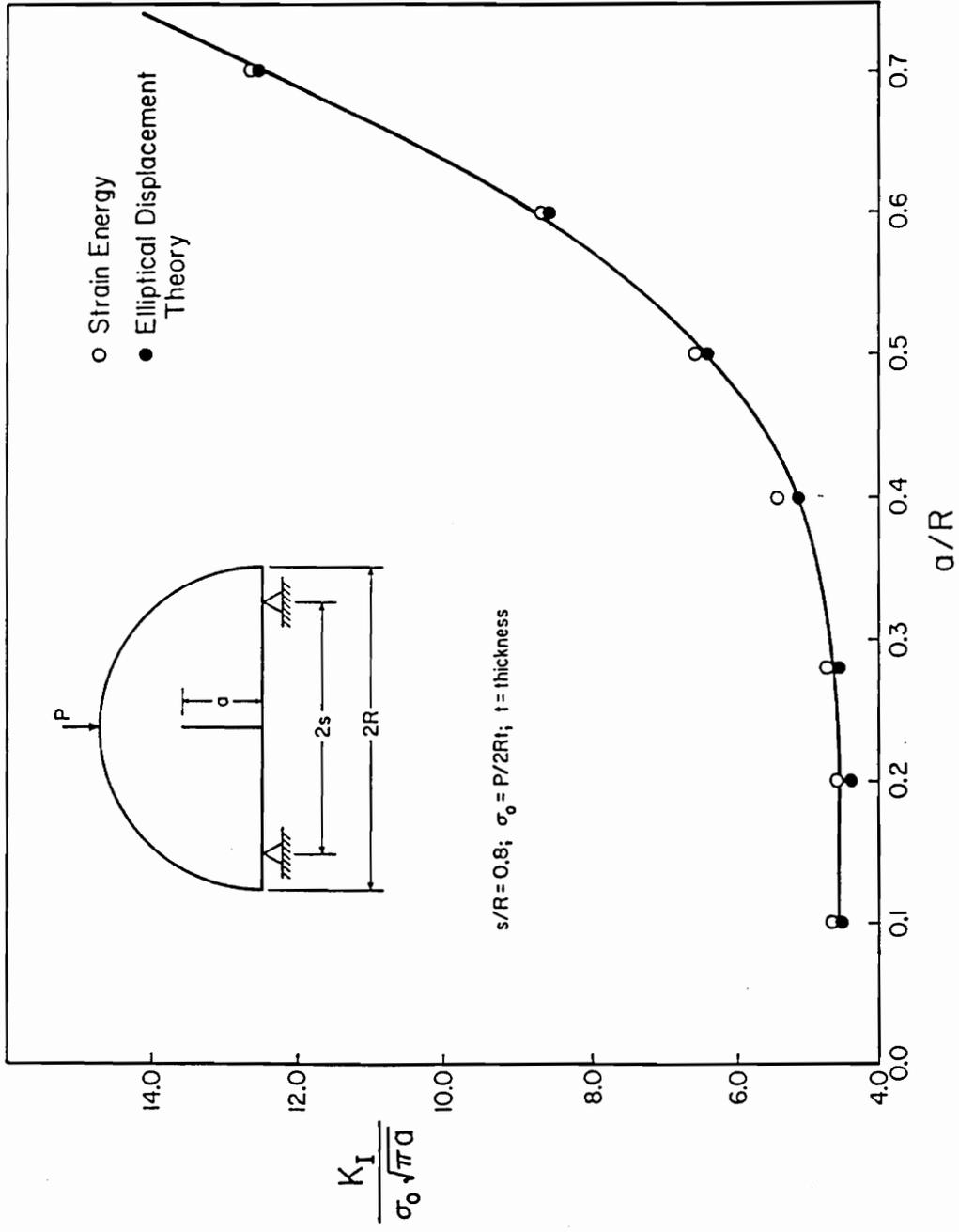
Figure 10. Mode—I Normalized Stress Intensity Factor (After Chong and Kuruppu, 1984)

material property used to measure fracture resistance is fracture toughness, the experiment setup used to measure fracture toughness generates information which can be used to calculate an additional parameter indicative of fracture resistance. This parameter is specific work of fracture, i.e., the work done to create a unit surface area.

In the test setup used for determination of fracture toughness, the load versus load line displacement (LLD) data is recorded until the specimen has virtually no residual strength. From this data the total work of fracture W_f, which is required to separate the notched specimen into two halves can be calculated as

$$W^f_{SCB} = \int_0^\infty P \, d \, (LLD) \qquad 2.13$$

A computer program is used to evaluate the above equation. The program generates an equation, through polynomial regression, for the load versus LLD data and yields the total work of fracture by integrating it (Figure 11). Relating W^f_{SCB} to the ligament area, A, the specific work of fracture is obtained as

$$R_{SCB} = W^f_{SCB} / A \qquad 2.14$$
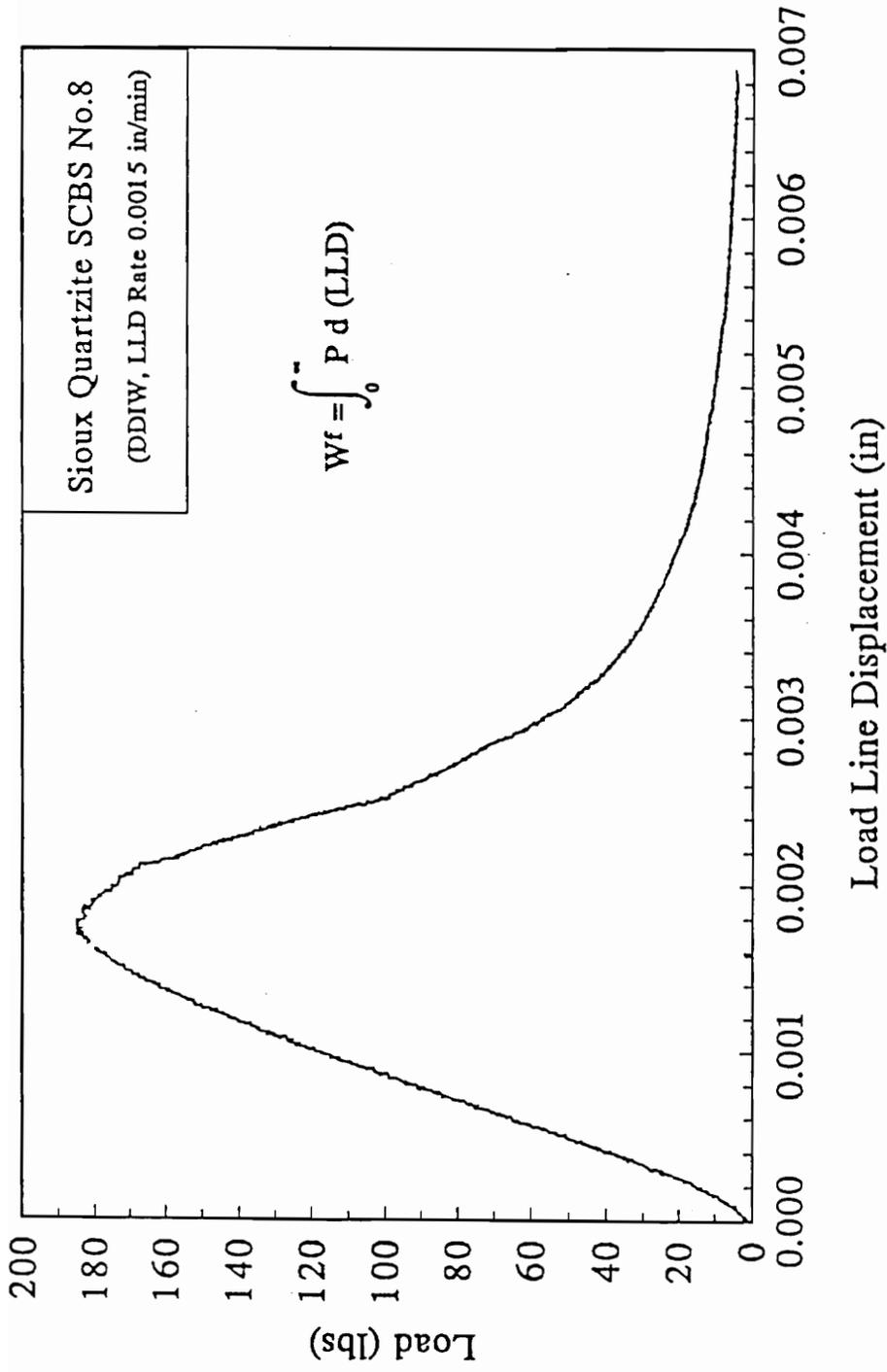
Figure 11. Specific Work of Fracture Determination

3. EXPERIMENTAL INVESTIGATIONS

Using fracture mechanics techniques (Chong and Kuruppu, 1984; Ouchterlony, 1988), three rock types were tested in five environments. These tests were done to assess the effects of ZPC environment on fracture behavior of rocks. Parameters investigated were fracture toughness and specific work of fracture.

3.1 Rock Specimens

The three rock types selected for this study were dolomitic limestone, Sioux quartzite and Westerly granite. All of these three are high strength rocks occurring massively in nature and are being mined as dimension stone. These have fine grained, equigranular textures and are relatively free from fractures. Mineralogically these represent three distinct varieties. Sioux quartzite is a high silica (almost 100%) monominerallic rock, Westerly granite is a polyminerallic rock, and dolomitic limestone is a sedimentary rock. Some of the mechanical properties of these rocks are summarized in Table I and their chemical analysis is given in Table II. For dolomitic limestone this data was obtained from tests performed at VPI & SU and US Bureau of Mines − Twin Cities Research Center (USBM − TCRC). The data for the other two rock types is from Krech et al. (1974).

The test specimens of dolomitic limestone were prepared from rock blocks obtained from a dimension stone quarry near Blacksburg. The specimens for the other two rock types were supplied by the USBM−TCRC.

Semi−Circular Bend specimens (Plate 1) were used in this experimental investigation. Figure 9 shows the specimen geometry and the three point loading

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Table I. Mechanical Properties of the Tested Rocks

Properties	Rock Type			
		Dolo. Limestone	Sioux Quartzite	Westerly Granite
Porosity.................(%)		2.32	0.14	0.35
Density dry...............(lbs/ cu. ft)		169.95	164.74	164.74
Specific Gravity...................		2.79	2.64	2.64
Compressive Strength...(10E+3 psi)		41.0	73.2	33.8
Tensile Strength..........(10E+3 psi)		2.79	1.57	1.39
Young's Modulus.........(10E+6 psi)		10.01	8.18	7.20
Poisson's Ratio.................		0.281	0.138	0.213

Table II. Whole-Rock Analysis (%)

Mineral	Dolomitic Limestone	Sioux Quartzite	Westerly Granite
SiO_2	15.93	98.41	69.96
Al_2O_3	2.02	0.76	14.57
Fe_2O_3	0.96	0.19	1.77
MgO	15.90	Trace	0.75
CaO	25.17	0.69	3.31
Na_2O	0.17	0.09	4.15
K_2O	1.27	Trace	4.59
H_2O+	Trace	Trace	Trace
H_2O-	38.33	Not Detected	Not Detected
TiO_2	0.17	Trace	0.59
P_2O_5	0.02	Trace	0.31
MnO	0.06	Trace	Trace
Total	100.00	100.14	100.00

Plate 1. Semi-Circular Bend Specimens

arrangement. The following steps were involved in preparation of these specimens.

i   Four–inch diameter cores were drilled from rock slabs using a diamond impregnated core bit.

ii   These cores were then cut into 1–inch thick discs using a 24–inch diameter diamond–impregnated circular rock saw.

iii The disc sides were ground flat and parallel to each other by a grinding wheel.

iv   Each disc was then cut into two semi–circular halves and numbered for future reference.

v   A notch was then cut through the center of each half disc by a radial arm saw using a 6 inch diameter, .o6 inch thick diamond blade. The notch was oriented at right angles to the straight edge of the specimens so that the three–point bending would cause transverse splitting of the specimen.

vi   Ahead of the main notch, a pilot notch was cut with a .006–inch thick diamond wafering blade.

vii The specimens were then washed in water and dried for two weeks at room temperature prior to testing.

For each of the three rock types about 100 samples were prepared. Each sample was numbered in such a way that it would show the identity of the rock slab, the core and the individual half–disc. For each rock, type about 50 samples were then randomly selected for this study. The remaining samples were saved for use in an other study. The individual sample dimensions were recorded only for reference and as a counter check, because the dimensions used in the calculation of fracture toughness and specific work of fracture were measured after the

completion of each test.

The thickness, t, of all specimens was approximately 1–inch. This thickness is considered to be sufficient to give consistent and reliable rock fracture toughness (Chong and Kuruppu, 1984). Unlike metallic materials, this dimension is not critical for rock samples as far as the requirement of plane strain conditions is concerned (Basham, 1989). The 1–inch thickness is recommended primarily to minimize the effect of material variation across the crack tip, simultaneously reducing instability during the loading process.

The crack length, a, of the specimens tested varies from 1.25 to 1.35 inches. The maximum possible crack length, R, varies from 1.94 to 2.01 inches. Therefore the a/R ratio which is required to compute the normalized stress intensity factor (Figure 10) is well within the recommended range for this specimen configuration.

3.2 Testing Environments

To evaluate the effects of ZPC environment on fracture toughness and specific work of fracture, testing was done in five different environments. Aqueous solutions of aluminum chloride, calcium chloride and polyethylene oxide were the three ZPC environments. The two control environments were atmospheric air and distilled deionized water. For each of the 15 rock–environment combinations, the ZPC concentration was determined by the USBM–TCRC. Table III summarizes the results of these ZPC tests.

The ZPC environments used in this study were selected mainly on the basis of encouraging results reported by previous researchers. However the criteria for selection of such environments essentially require (Mills and Westwood, 1978) that:

Table III. ZPC Solution Concentrations

Solution	Dolomitic Limestone	Sioux Quartzite	Westerly Granite
PEO in DDIW (ppm)	7.50	15.00	15.00
AlCl3 in DDIW (mol/l)	1.06E-05	7.00E-07	7.26E-07
CaCl2 in DDIW (mol/l)	5.00E-04	1.12E-02	1.22E-02

i   The environment should be able to reduce the rock surface charge to zero at relatively low concentration.

ii   It should be nonflammable in concentrated form.

iii   It should be commercially available.

iv   It should be water soluble.

v   It should be non—toxic and non—corrosive.

vi   It should be biodegradable.

vi   It should be cheap.

Since almost all rocks are negatively charged in water, cationic surfactants are the only major choice from which to select the environments which fulfill the other conditions. Certain long chain non—ionic polymers, such as polyethylene oxide selected for this study, are the exceptions because they have the ability to neutralize the rock surface charge. Aluminum chloride and calcium chloride are the examples of cationic surfactants.

3.3 Experimental Setup

All testing is done with the MTS 810 closed loop servohydraulic 110 kips material testing system, interfaced with microcomputers for test control, data acquisition and reduction (Plate 2).

For post—peak load behavior investigation, Level II testing (Ouchterlony, 1988) prescribes a continuous measurement of load and LLD beyond the maximum load. This requires the displacement rate to be controlled. Displacement controlled tests are performed under load line displacement rate control. The tests permit the load versus LLD recordings to be made until the specimen has virtually no residual strength (Figure 12). The load is measured using a 2000 lb load cell

Plate 2. Experimental Set Up

Sioux Quarzite Sample No. 34
($AlCl_3$, LLD 0.001 5 in/min)

Load Line Displacement (in)

Load (lbs)
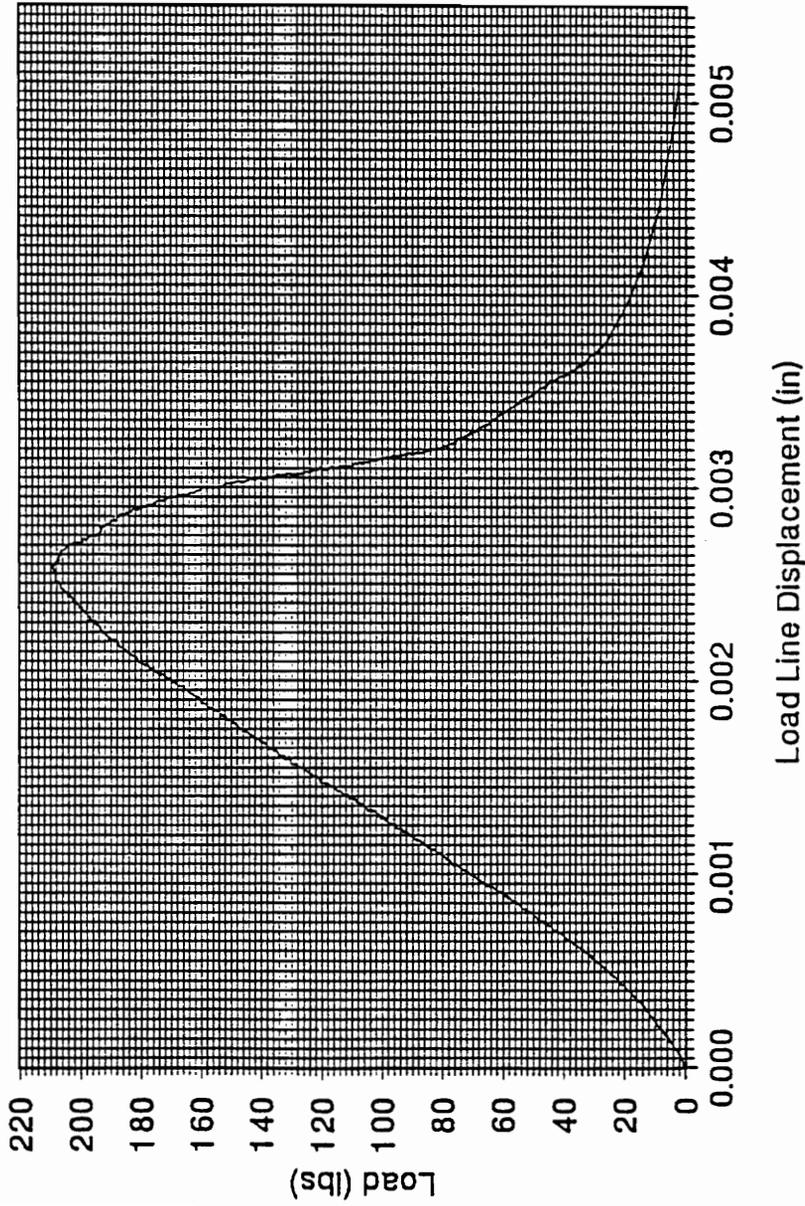
Figure 12. Complete Load vs Load Line Displacement Curve

and the LLD is measured using an extensometer. As a counter check for LLD, crack mouth opening displacement (CMOD) is also measured. The test set up and instrumentation is diagrammatically illustrated in Figure 13 and Plate 3.

3.3.1 Testing Equipment

The MTS servo–control system used in this investigation consists of four major components: a stiff loading frame, a 110 kips actuator, a micro console, and a hydraulic power supply. The servo–control loop contains a command and function module, and a servo–amplifier. The command and function signals are electronically monitored by the servo–amplifier and a servo valve then adjusts the actuator pressure. The actuator pressure is responsible for the amount of force applied to the specimen.

This machine can be operated under load, displacement, or strain control. The success of post–peak load investigation depends upon the right choice of control. In tests done under load control the machine is programmed to increase the load monotonically with time. Under such a control when the peak strength of the specimen is reached, a catastrophic failure occurs because the load carrying capacity of the specimen is reduced.

A stable post–peak behavior can be achieved if the machine is programmed to increase the axial displacement monotonically with time. In this investigation all tests were done under load line displacement control. A strain gauge extensometer was used to measure the load line displacement both for system feedback control and to established the load versus LLD relationship for determination of fracture toughness and specific work of fracture. This gauge measures the displacement of the bottom of the specimen relative to support
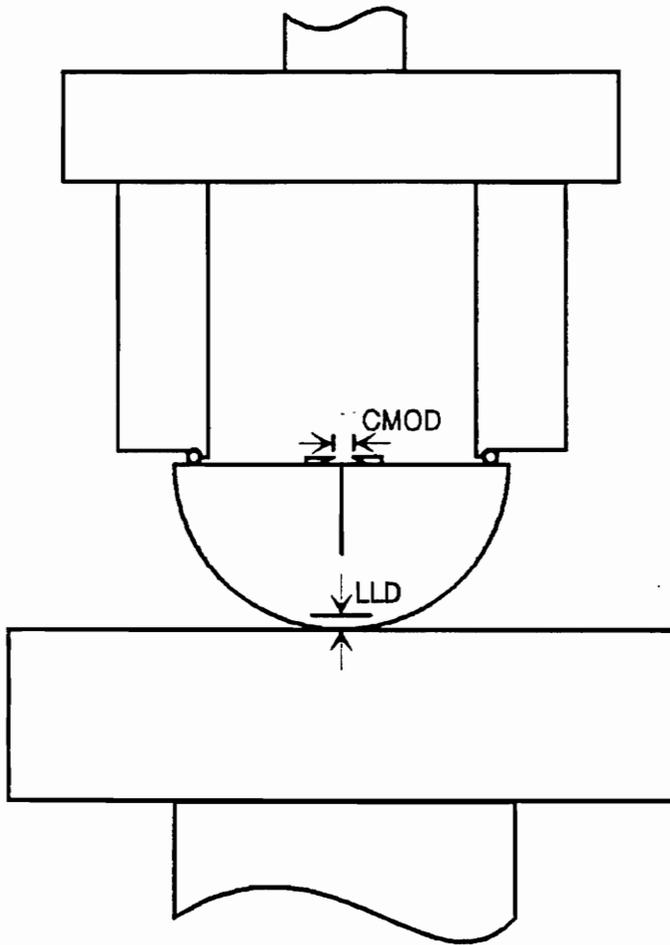
Figure 13. Diagrammatic Illustration of Instrumentation

Plate 3. Instrumentation Set Up

rollers (Figure 13). This arrangement yielded extremely stable post—peak load behavior. During each test, the load vs LLD data was also plotted on an X—Y plotter in addition to the computerized data acquisition. This sophisticated test system is fully computerized. It is hooked—up with an IBM personal computer which uses Test Link software to control the machine functions.

3.3.2 Data Acquisition and Reduction

A fully automated data acquisition system employing the software Notebook from Labtech and Zenith data systems was used to continuously record load, load line displacement, stroke and crack mouth opening displacement. This data was stored on diskettes for later processing to determine the parameters of interest. Up to 2000 data points were recorded for each specimen, the number of recorded points being dependent upon the duration of each test.

Axum, graphics and data analysis software from Trimetrix, was used to process and plot the load versus LLD data. Critical load was obtained from this plot using the procedure outlined in section 2.2 (Figure 6). Fracture toughness was calculated on the basis of this load using equation 2.11 (section 2.2.2).

Another computer program Zacsoft, developed in the Mining Engineering Department at VPI&SU, was used to process the load versus LLD data for determination of specific work of fracture. This program uses an IMSL subroutine to generate the regression equations of load versus LLD plots, and then integrates these equations to calculate the area under the curve for each specimen (Figure 11). Specific work of fracture was then calculated by dividing this area under the curve, which represents the total work of fracture, by the ligament area (equation 2.14).

3.4 Experimental Procedure

SCB specimen testing involved the following steps:

1 Clean the rock specimen and affix to it the knife edges with a quick setting epoxy.

2 Allow about 10 minutes for the knife edges to be firmly cemented with the specimen.

3 Turn the power on for micro console of MTS system and make sure that the hydraulic pressure is set at "low."

4 Select load as the control mode.

5 Reset interlocks and zero the load.

6 Turn the power on for the computer which is to control the test.

7 Load the program Testlink and specify the displacement rate.

8 Switch on the XY—plotter, put the paper in and install the recording pen.

9 Switch on the data acquisition computer, load the program Labtech and specify the file in which the data is to be stored.

10 Place the specimen in the loading frame in such a way that its position and orientation with reference to the loading rollers is correct. A specially designed aligning device is used for this purpose.

11 Install the extensometer for the measurement of load line displacement and attach the CMOD gauge.

12 Using the manual control on the micro console panel, load the specimen very slowly just up to 2 to 4 lbs so that a contact of rollers with the specimen is achieved.

13   Change the control mode from load to displacement.

14   Press "enter" to start the test. The test now runs under displacement rate control. The test data is collected by the data acquisition computer while the Load versus LLD curve is plotted on the XY—plotter.

15   Stop the test when the post peak load is almost zero.

16   Take off the gauges from the specimens and measure its dimensions, i.e. t, a, and R. Take at least three measurements for each dimension and record the average values.

The data for each test is then processed as described earlier to calculate the desired rock properties.

4. RESULTS AND DISCUSSION

This experimental investigation was conducted to assess the effects of ZPC environment on fracture toughness and specific work of fracture of rocks. Using fracture mechanics techniques, semi–circular bend specimens of three types of rocks were tested in atmospheric air, distilled deionized water and three separate ZPC environments. The rock types tested in this study were dolomitic limestone, Sioux quartzite and Westerly granite. The ZPC environments were aqueous solutions of polyethylene oxide, aluminum chloride and calcium chloride.

For each of the 15 rock–environment cases at least five specimens were tested. As outlined in sections 2.2 and 2.3, the data obtained from the individual tests was processed to compute fracture toughness and the specific work of fracture. For each of these 15 cases, the average values and standard deviations were then calculated for statistical analysis of the results.

For a particular rock type, the statistical analysis involved the comparison of means for each of the ZPC environments with the mean for water. The means for air and water were also compared. These comparisons were done using pooled–t test at an error rate of 5%. In the pooled–t test two population means can be tested for similarity by comparing the calculated value of a test statistic (t_{obs}) with a known value (t_{cri}).

4.1 Fracture Toughness Results

For each of the individual tests, the fracture toughness was computed using equation 2.11. The data required for this computation included: the specimen dimensions (a, R, and t); the critical load (P_Q) obtained from load versus LLD

plots; and the normalized stress intensity factor ($\overline{K}_I$) obtained from a calibrated curve (Figure 10). This information and the calculated fracture toughness for all of the tested specimens is given in appendices A, B and C for dolomite, quartzite and granite respectively.

For dolomitic limestone, the fracture toughness results are summarized in Table IV and Figure 14. The average value of fracture toughness in each of the three ZPC environments (939 psi$\sqrt{\text{in}}$ for PEO, 914 psi$\sqrt{\text{in}}$ for $AlCl_3$, and 1055 psi$\sqrt{\text{in}}$ for $CaCl_2$) was less than the average value in water (1085 psi$\sqrt{\text{in}}$). Similarly, the average toughness in water was less than the average in air (1211 psi$\sqrt{\text{in}}$). The statistical analysis showed that the reduction of fracture toughness from air to water (10%), water to PEO (13%) and water to $AlCl_3$ (16%) is significant at an error rate of 5%. The reduction from water to $CaCl_2$ (3%) was, however, non—significant at the desired 95% confidence level (Table V).

For Sioux quartzite, the summary of fracture toughness results is given in Table VI and Figure 15. The average fracture toughness in each of the three ZPC environments (1025 psi$\sqrt{\text{in}}$ for PEO, 1038 psi$\sqrt{\text{in}}$ for $AlCl_3$ and 1046 for $CaCl_2$), in this case too, was observed to be less than the average value in water (1132 psi$\sqrt{\text{in}}$). The average fracture toughness in water showed a slight increase, rather than decrease, as compared to the average value in air (1115 psi$\sqrt{\text{in}}$). This increase was, however, not statistically significant. The reduction in toughness observed in each of the ZPC environments compared to water (9% for PEO, 8% for $AlCl_3$ and 8% for $CaCl_2$) was significant at the desired confidence level (Table VII).

TABLE IV. SUMMARY OF FRACTURE TOUGHNESS(Kic) RESULTS FOR DOLOMITE

Environment	No. Of Samples	Kic(psi*sqrt in)		% Red. Compared to Water
		Average	St.Dev	
AIR	6	1211	73	-10%
DDIW	6	1085	61	-
PEO	5	939	34	13%
ALCL3	6	914	91	16%
CACL2	6	1055	98	3%
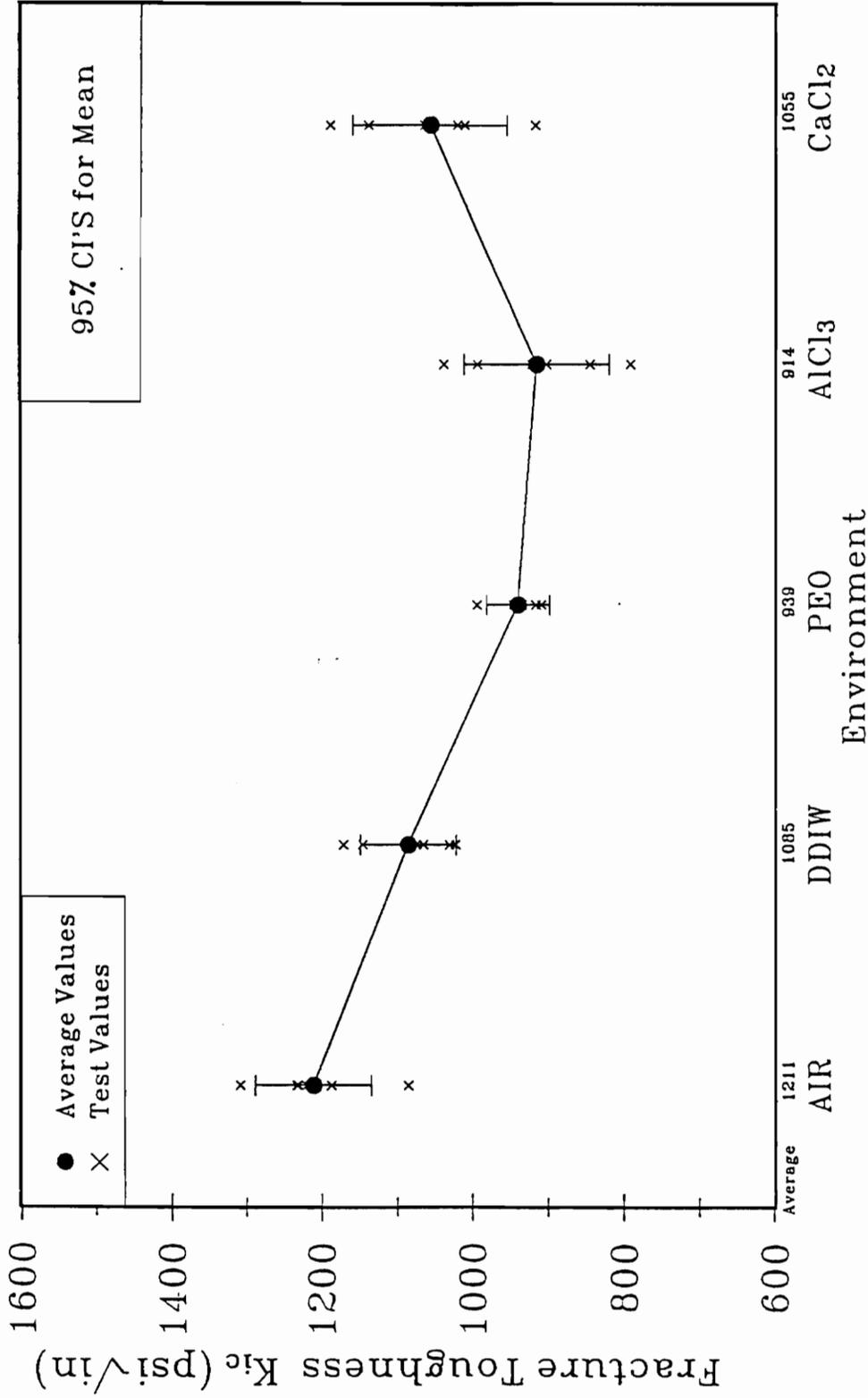
Figure 14. Fracture Toughness Results For Dolomite

Table V . T- Test Results of Fracture Toughness Test Data
(Dolomitic Limestone)

AIR vs WATER

	N	MEAN	STDEV
AIR	6	1211	73
WATER	6	1085	61

Tcrit = 1.81   Tobs = 3.25

WATER vs PEO

	N	MEAN	STDEV
WATER	6	1085	61
PEO	5	939	34

Tcrit = 1.83   T obs = 4.77

WATER vs AlCl3

	N	MEAN	STDEV
WATER	6	1085	61
ALCL3	6	914	91

Tcrit = 1.81   Tobs = 3.83

WATER vs CaCl2

	N	MEAN	STDEV
WATER	6	1085	61
CACL2	6	1055	98

Tcrit = 1.81   Tobs = 0.63

TABLE VI. SUMMARY OF FRACTURE TOUGHNESS(Kic)
RESULTS FOR QUARTZITE

Environment	No. Of Samples	Kic(psi*sqrt in)		% Red. Compared to Water
		Average	St.Dev	
AIR	6	1115	42	-
DDIW	6	1132	65	-
PEO	6	1025	100	9%
ALCL3	6	1038	98	8%
CACL2	6	1046	72	8%
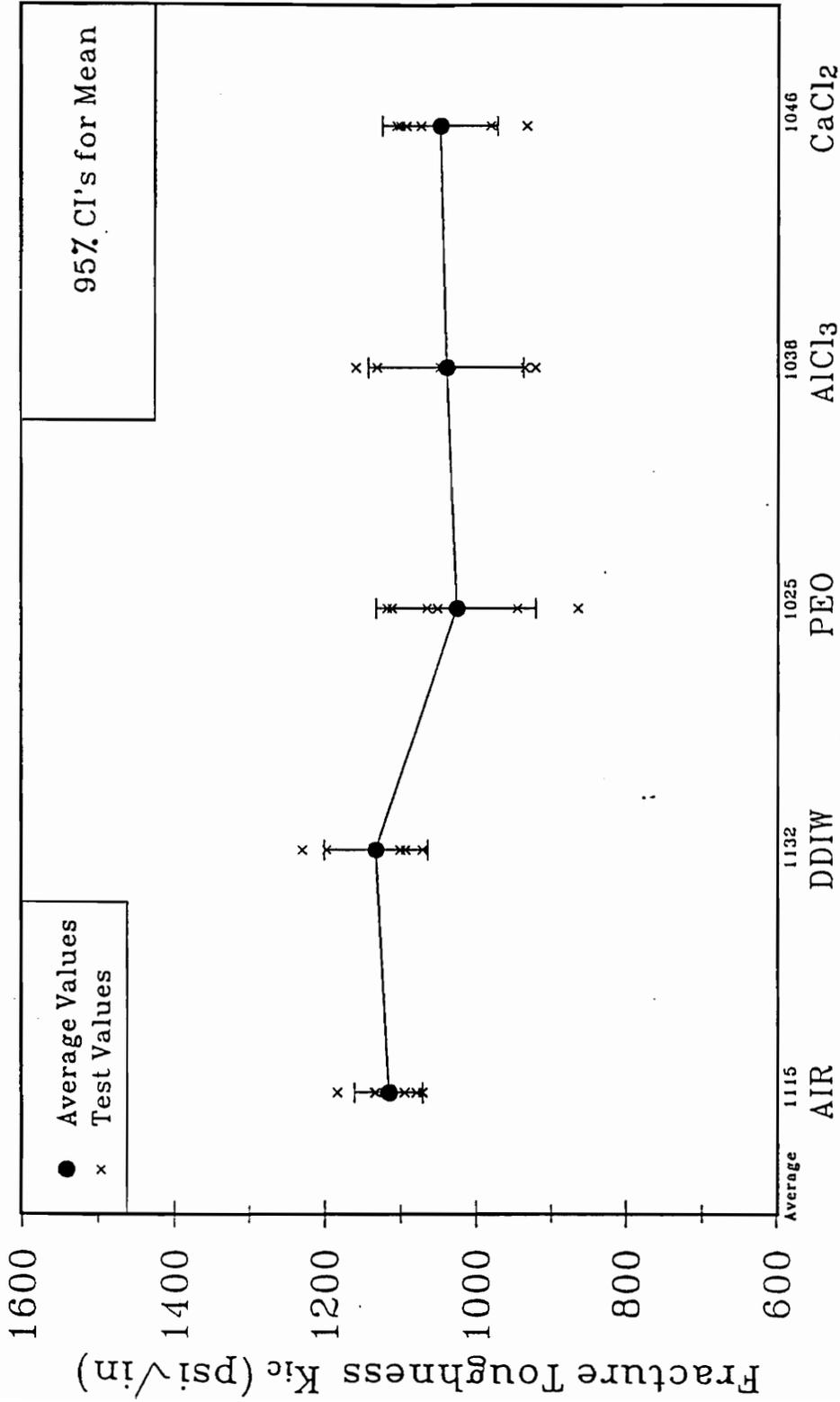
Figure 15. Fracture Toughness Results For Quartzite

Table VII . T- Test Results of Fracture Toughness Test Data
(Sioux Quartzite)

AIR vs WATER

	N	MEAN	STDEV
AIR	6	1115	42
WATER	6	1132	65

Tobs = -.64

Tcrit = 1.81

WATER vs PEO

	N	MEAN	STDEV
WATER	6	1132	65
PEO	6	1025	100

T obs = 2.19

Tcrit = 1.81

WATER vs AlCl3

	N	MEAN	STDEV
WATER	6	1132	65
ALCL3	6	1038	98

Tobs = 1.96

Tcrit = 1.81

WATER vs CaCl2

	N	MEAN	STDEV
WATER	6	1132	65
CACL2	6	1046	72

Tobs = 2.16

Tcrit = 1.81

For Westerly granite, the results are summarized in Table VIII and Figure 16. Although the average toughness in each of the ZPC environments (655 psi$\sqrt{in}$ for PEO, 668 psi$\sqrt{in}$ for AlCl$_3$ and 615 psi$\sqrt{in}$ for CaCl$_2$) were less than the average in water (669 psi$\sqrt{in}$), the reduction was significant only for CaCl$_2$ solution (8%). Also, the average toughness in water was less than the average in air (804 psi$\sqrt{in}$) and this reduction (17%) was significant too (Table IX).

4.2 Specific Work of Fracture Results

In this investigation, all the specimens were tested under displacement control at an LLD rate of .00015 in/min. This arrangement yielded a satisfactory post—peak curves. For every specimen tested, the load versus LLD data were plotted and the area under the curve was computed by integrating the polynomial equation generated by regression analysis. This area represents the work done to break the specimen apart (eq. 2.13). Dividing the area under the curve by the ligament area of the specimen then gave the specific work of fracture (eq. 2.14). The specimen dimensions, the ligament area, and the calculated specific work of fracture for all the specimens tested are given in appendices D, E, and F for dolomite, quartzite and granite respectively.

For dolomitic limestone, the specific work of fracture results are summarized in Table X and Figure 17. The average specific work of fracture in each of the three ZPC environments (4.395 ft.lbs/ft^2 for PEO, 4.268 ft.lbs/ft^2 for AlCl$_3$ and 4.333 ft.lbs/ft^2 for CaCl$_2$) was less than the average in water (4.523 ft.lbs/ft^2). The average in water was, however, more than the average in air (3.291 ft.lbs/ft^2). The increase in average specific work in water compared to air (27%) was significant; however, the reduction observed in each of the ZPC

TABLE VIII. SUMMARY OF FRACTURE TOUGHNESS(Kic)
RESULTS FOR GRANITE

Environment	No. Of Samples	Kic(psi*sqrt in)		% Red. Compared to Water
		Average	St.Dev	
AIR	6	804	20	-17%
DDIW	6	669	61	-
PEO	6	655	39	-
ALCL3	6	668	29	-
CACL2	6	615	32	8%
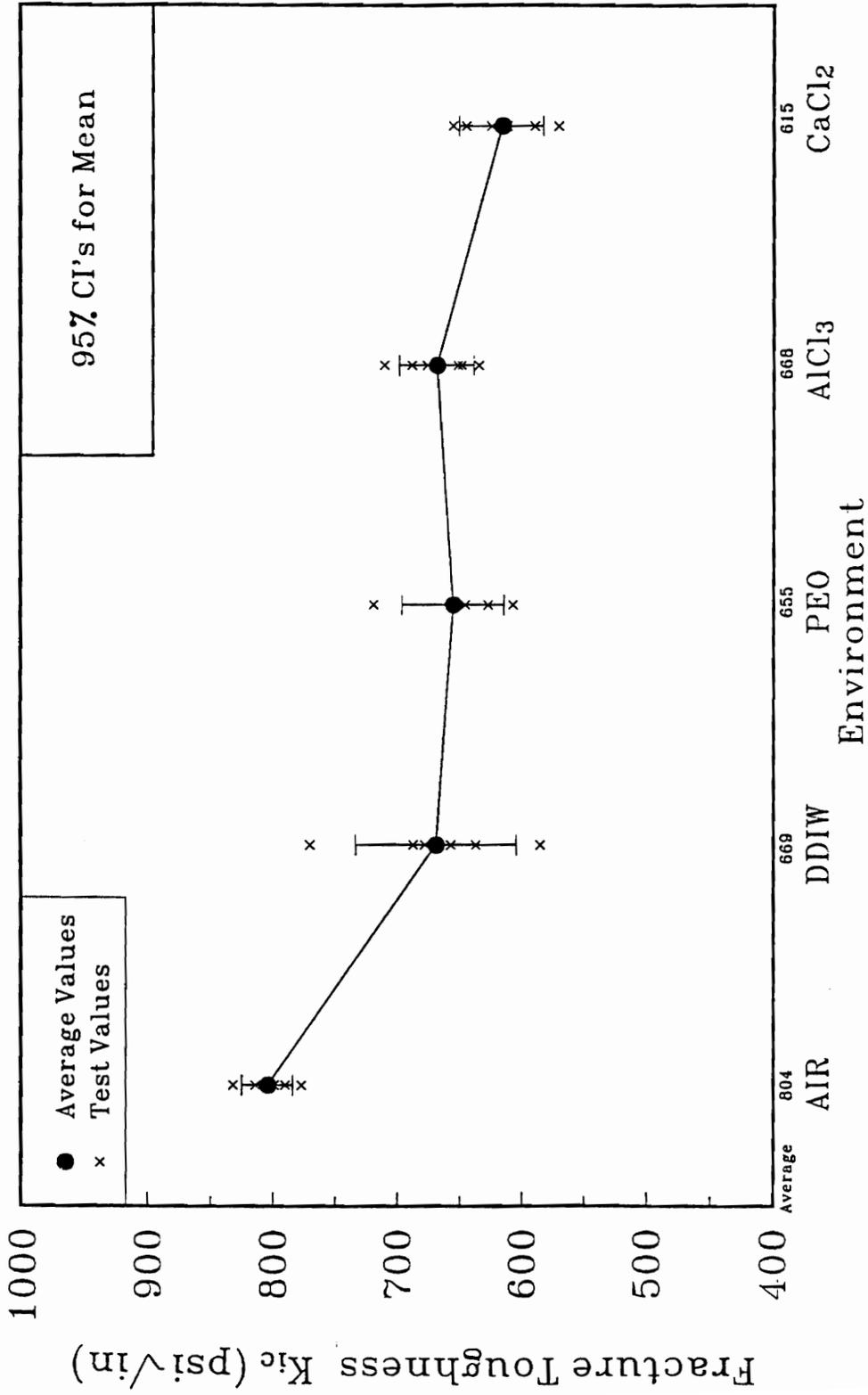
Figure 16. Fracture Toughness Results For Granite

Table IX . T- Test Results of Fracture Toughness Test Data
(Westerly Granite)

AIR vs WATER

	N	MEAN	STDEV
AIR	6	804	20
WATER	6	669	61

Tcrit = 1.81   Tobs = 2.63

WATER vs PEO

	N	MEAN	STDEV
WATER	6	669	61
PEO	6	655	39

Tcrit = 1.81   T obs = 0.70

WATER vs AlCl3

	N	MEAN	STDEV
WATER	6	669	61
ALCL3	6	668	29

Tcrit = 1.81   Tobs = 0.98

WATER vs CaCl2

	N	MEAN	STDEV
WATER	6	669	61
CACL2	6	615	32

Tcrit = 1.81   Tobs = 1.90

TABLE X. SUMMARY OF SPECIFIC WORK OF FRACTURE(R)
RESULTS FOR DOLOMITE

Environment	No. Of Samples	R(lbs.ft/ft^2)		% Red. Compared to Water
		Average	St.Dev	
AIR	6	3.291	0.547	27%
DDIW	6	4.523	0.377	-
PEO	5	4.395	0.545	3%
ALCL3	6	4.268	0.187	6%
CACL2	6	4.333	0.671	4%
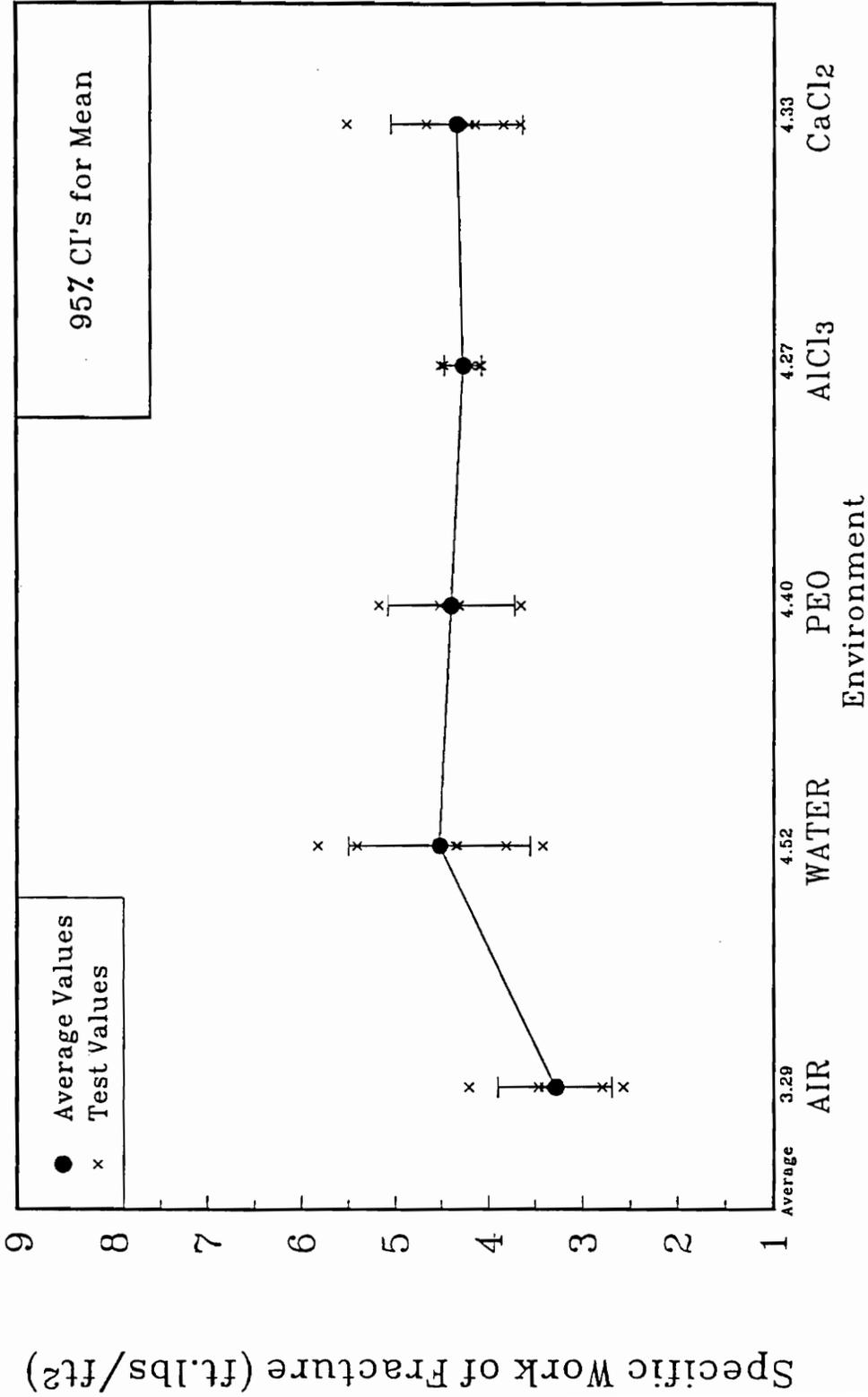
Figur 17. Spec. Work of Frac. Results for Dolomite

Table XI. T-Test Results of Specific Work of Fracture Test Data
(Dolomitic Limestone)

AIR vs WATER

	N	MEAN	STDEV
AIR	6	3.291	0.574
WATER	6	4.523	0.377

Tcrit = 1.81   Tobs = -2.78

WATER vs PEO

	N	MEAN	STDEV
WATER	6	4.523	0.377
PEO	5	4.395	0.545

Tcrit = 1.83   Tobs = .28

WATER vs AlCl3

	N	MEAN	STDEV
WATER	6	4.523	0.377
ALCL3	6	4.268	0.187

Tcrit = 1.81   Tobs = .66

WATER vs CaCl2

	N	MEAN	STDEV
WATER	6	4.523	0.377
CACL2	6	4.332	0.671

Tcrit = 1.81   Tobs = .41

environments compared to water (3% for PEO, 6% for $AlCl_3$ and 4% for $CaCl_2$) was statistically non–significant (Table XI).

For Sioux quartzite, the summary of specific work of fracture results is given in Table XII and Figure 18. The average specific work of fracture obtained in each of the three ZPC environments (7.007 ft.lbs/ft^2 for PEO, 6.912 ft.lbs/ft^2 for $AlCl_3$ and 6.845 ft.lbs/ft^2 for $CaCl_2$) were less than the average in water (7.770 ft.lbs/ft^2). The reduction (10% for PEO, 11% for $AlCl_3$ and 12% for $CaCl_2$) was significant for all the three cases. There was a slight increase in the average specific work in water as compared to air but this increase was statistically non–significant (Table XIII).

For Westerly granite, the results are summarized in Table XIV and Figure 19. Although, the average specific work of fracture (4.907 ft.lbs/ft^2 for PEO, 4.850 ft.lbs/ft^2 for $AlCl_3$ and 4.628 ft.lbs/ft^2 for $CaCl_2$) was less in all the three ZPC environments when compared to the average in water (5.135 ft.lbs/ft^2); the reduction (10%) was significant only for $CaCL_2$ environment. The average specific work of fracture in water was less than the average in air (5.965 ft.lbs/ft^2). This reduction (14%) was significant (Table XV).

4.3 Discussion of Results

The overall summary of results indicates that the fracture toughness and specific work of fracture are both significantly lower in all the ZPC environments than in water for Sioux quartzite, but the reduction is not consistently significant in all ZPC environments for the other two rocks. The fracture toughness reduction, for example, is significant in PEO and $AlCl_3$ environments for dolomitic limestone but is significant only in $CaCl_2$ solution for Westerly granite.

TABLE XII. SUMMARY OF SPECIFIC WORK OF FRACTURE(R)
RESULTS FOR QUARTZITE

Environment	No. Of Samples	R(lbs.ft/ft^2)		% Red. Compared to Water
		Average	St.Dev	
AIR	5	7.155	0.106	-
DDIW	6	7.77	0.569	-
PEO	5	7.007	0.986	10%
ALCL3	6	6.912	0.702	11%
CACL2	6	6.845	0.531	12%
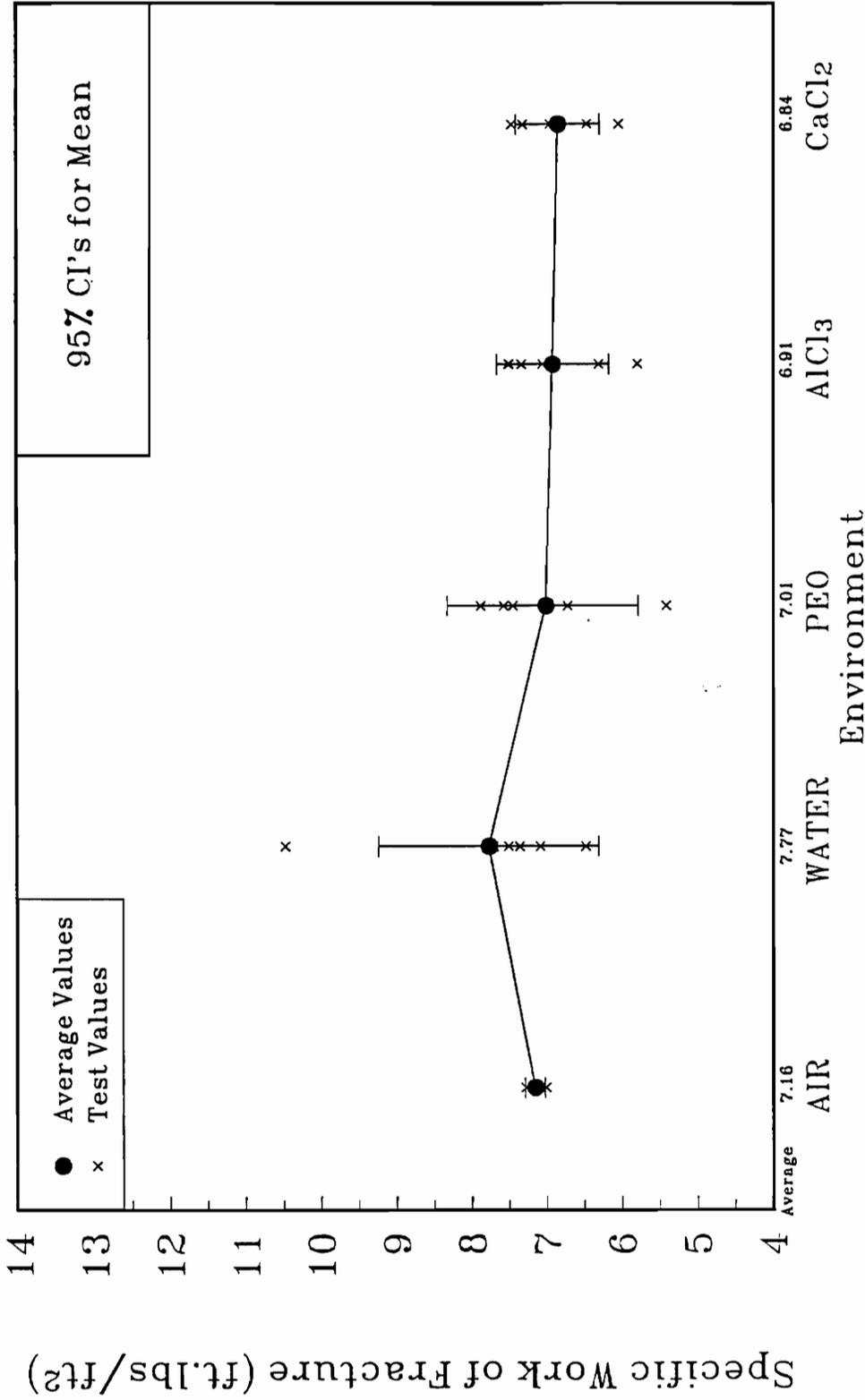
Figure 18. Spec. Work of Frac. Results For Quartzite

Table XIII. T- Test Results of Specefic Work of Fracture Test Data
(Sioux Quartzite)

AIR vs WATER	N	MEAN	STDEV
AIR	5	7.155	0.106
WATER	6	7.77	0.569
Tobs = -2.60			
Tcrit = 1.83			

WATER vs PEO	N	MEAN	STDEV
WATER	6	7.77	0.569
PEO	5	7.007	0.986
Tobs = 1.61			
Tcrit = 1.83			

WATER vs AlCl3	N	MEAN	STDEV
WATER	6	7.77	0.569
ALCL3	6	6.912	0.702
Tobs = 2.33			
Tcrit = 1.81			

WATER vs CaCl2	N	MEAN	STDEV
WATER	6	7.77	0.569
CACL2	6	6.845	0.531
Tobs = 2.91			
Tcrit = 1.81			

TABLE XIV. SUMMARY OF SPECIFIC WORK OF FRACTURE(R)
RESULTS FOR GRANITE

Environment	No. Of Samples	R(lbs.ft/ft^2)		% Red. Compared to Water
		Average	St.Dev	
AIR	6	5.956	0.593	-14%
DDIW	6	5.135	0.482	-
PEO	6	4.907	0.611	4%
ALCL3	3	4.85	0.071	6%
CACL2	6	4.628	0.439	10%
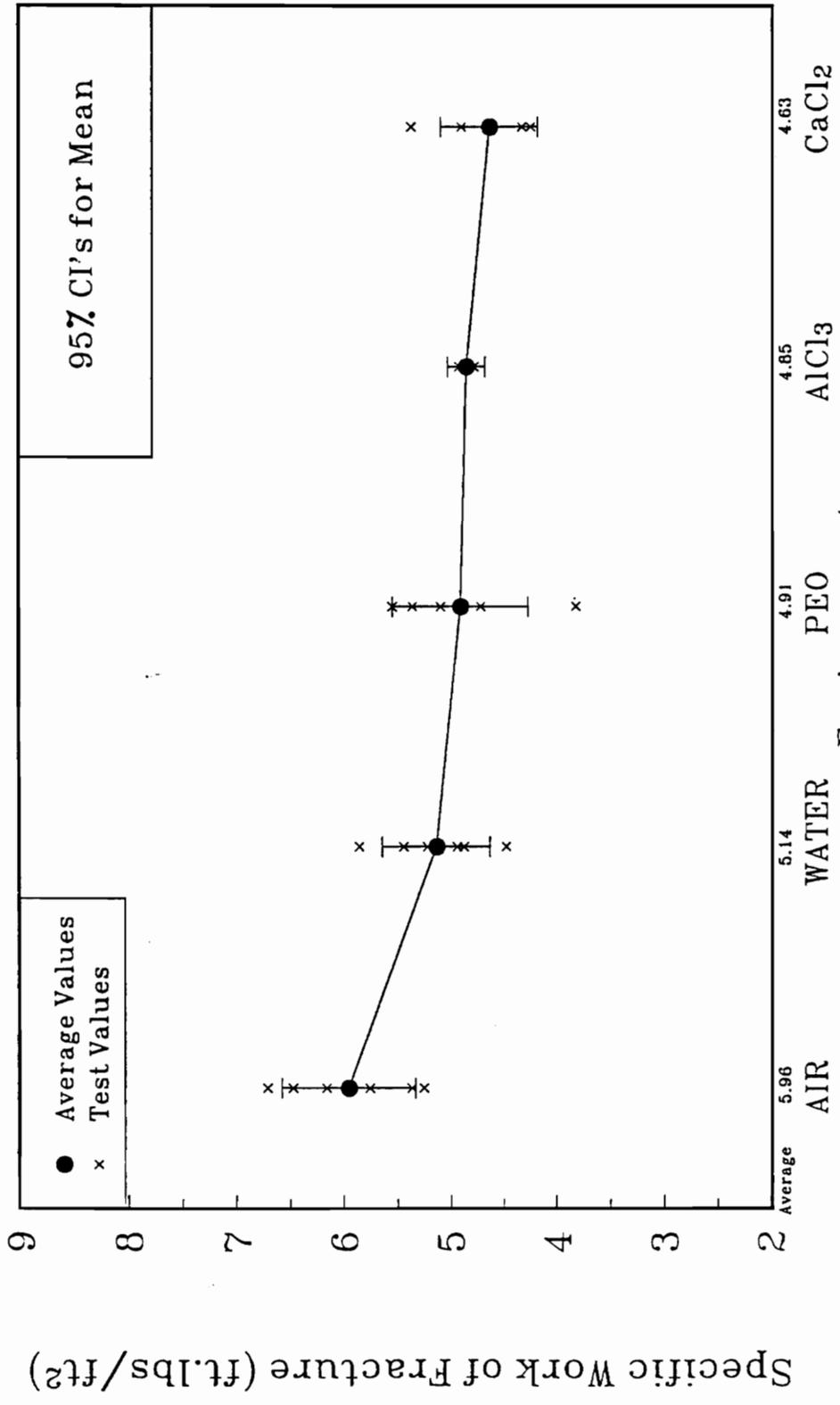
Figure 19. Spec. Work of Frac. Results For Granite

Table XV. T- Test Results of Specefic Work of Fracture Test Data
(Westerly Granite)

AIR vs WATER

	N	MEAN	STDEV
AIR	6	5.956	0.593
WATER	6	5.135	0.482

Tcrit = 1.81 Tobs = 2.63

WATER vs PEO

	N	MEAN	STDEV
WATER	6	5.135	0.482
PEO	6	4.907	0.611

Tcrit = 1.81 0.72

WATER vs AlCl3

	N	MEAN	STDEV
WATER	6	5.135	0.482
ALCL3	6	4.85	0.071

Tcrit = 1.81 Tobs = 0.98

WATER vs CaCl2

	N	MEAN	STDEV
WATER	6	5.135	0.482
CACL2	6	4.628	0.439

Tcrit = 1.81 Tobs = 1.90

The reduction in specific work of fracture is significant only in the $CaCl_2$ environment for granite, but in none of the environments for dolomitic limestone.

The comparison of air versus water shows that there is no reduction either in fracture toughness or in specific work of fracture for Sioux quartzite. For dolomitic limestone, although the fracture toughness reduces from air to water, the specific work of fracture increases. For Westerly granite, the fracture toughness and specific work of fracture both decrease from air to water.

One thing that can be inferred from this trend in results is that ZPC effect is consistent and more pronounced in a rock which is monominerallic, i.e. quartzite. It appears that in the case of the other two rocks the chemical reactions at the crack tip, rather than the pure ZPC effect, may be the deciding factor in determining the effectiveness of a particular environment.

The reduction in fracture toughness with the simultaneous increase in the specific work of fracture from air to aqueous environments, in the case of dolomitic limestone, is somewhat intriguing. There could be several possible reasons for such behavior. The relatively high porosity of this rock may have played a role in pre—conditioning the rock ahead of the propagating crack in aqueous environments. Under such conditions there might be more pronounced microcracking ahead of the crack tip, or crack propagation might be accompanied by grain boundary dislocation and branching at the microscopic level. In such a case, fracture toughness may be less because of the reduced resistance of the rock to crack initiation, but the crack may still consume more energy due to microcracking, fracture branching or grain boundary dislocation.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study was conducted to evaluate the effect of zero point of charge environment on rock fracture behavior. The material parameters selected for this characterization were fracture toughness and specific work of fracture. Both of these properties describe the resistance which a material offers to crack extension.

Semi—circular bend specimens of dolomitic limestone, Sioux quartzite, and Westerly granite were tested in air, water, and aqueous solutions of polyethylene oxide, aluminum chloride, and calcium chloride, each at zero point of charge condition e, the concentration at which the adsorbed environment neutralizes the rock sur.   charge. At least six replicate tests were done for each of the 15 rock—environment combinations. The results were statistically analyzed to compare the mean values obtained in each of the three ZPC environments with the mean in water. The means in air and water were also compared.

The comparison of mean values obtained in each of the ZPC environments with the mean values in water shows that:

i   In Sioux quartzite, each of the three ZPC environments produced significant reductions in fracture toughness (up to 9%) and specific work of fracture (up to 12%).

ii   In Westerly granite, only the ZPC solution of $CaCl_2$ gave significant reduction in fracture toughness (8%) and specific work of fracture (10%).

iii   In dolomitic limestone, the ZPC solutions of PEO and $AlCl_3$ yielded significant reductions in fracture toughness (23% and 16% respectively), but no reduction in specific work of fracture.

66

From these findings it can be concluded that the ZPC environment do enhance tensile fracturing in certain rock—environment combinations.

The comparison of mean values in air with the means in water shows that:

i   In Sioux quartzite, there is no significant effect of water on either of the parameters tested.

ii   In Westerly granite, water significantly reduces fracture toughness (17%) and specific work of fracture (14%).

iii   In dolomitic limestone, the reduction in fracture toughness (10%) is accompanied by an increase in specific work of fracture (27%).

The decrease in fracture toughness with the simultaneous increase in specific work of fracture observed in dolomitic limestone indicates the possibility of increased microcracking in aqueous environments.

The information yielded by this study may be used in the application of ZPC phenomenon in rock fragmentation processes such as rock cutting, hydraulic fracturing, and comminution. Although the parameters studied, i.e., fracture toughness and specific work of fracture, are not the only strength properties which describe the rock behavior in a given process, yet these may be more relevant than the other strength measures, especially in the modeling of rock fragmentation where relatively few dominant cracks are involved.

5.2 Recommendations

The rock—environment combinations in which significant reductions have been found should be studied for fatigue characteristics and crack propagation rates for complete fracture characterization. For these cases, the adsorption kinematics should also be studied by testing under different displacement rates.

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APPENDIX A

FRACTURE TOUGHNESS RESULTS FOR DOLOMITIC LIMESTONE

Table A-I. FRACTURE TOUGHNESS TEST RESULTS FOR DOLOMITE

(ENVIRONMENT - AIR)

Specimen #	Thickness t (in)	Radius r (in)	Notch a (in)	a/r	Crit. Load (lbs)	Sigma (psi)	Ki	Kic (psi*sqrt in)
B3-C4-S2-08	0.970	1.955	1.245	0.637	238	62.752	9.938	1233
B3-C3-S3-28	0.910	1.950	1.260	0.646	212	59.735	10.263	1220
B3-C1-S1-31	0.990	1.965	1.260	0.641	238	61.172	10.750	1308
B3-C5-S3-45	0.920	1.960	1.260	0.643	212	58.784	10.150	1187
B3-C5-S1-57	0.950	1.960	1.250	0.638	232	62.299	9.975	1231
B2-C2-S3-65	1.050	1.970	1.250	0.635	230	55.596	9.850	1085
						AVERAGE Kic =		1211

Table A-II. FRACTURE TOUGHNESS TEST RESULTS FOR DOLOMITE

(ENVIRONMENT - WATER)

Specimen #	Thickness t (in)	Radius r (in)	Notch a (in)	a/r	Crit. Load (lbs)	Sigma (psi)	Ki	Kic (psi*sqrt in)
B1-C3-S4-01	0.960	1.920	1.230	0.641	200	54.253	10.075	1074
B2-C2-S2-04	1.025	1.940	1.250	0.644	210	52.804	10.175	1065
B3-C5-S2-22	0.970	1.960	1.260	0.643	194	51.020	10.150	1030
B1-C2-S3-38	1.000	1.965	1.270	0.646	196	49.873	10.263	1022
B3-C3-S1-88	1.035	1.950	1.255	0.644	234	57.971	10.175	1171
B3-C4-S1-94	0.990	1.960	1.260	0.643	220	56.689	10.150	1145
							AVERAGE Kic =	1085

Table A-III. FRACTURE TOUGHNESS TEST RESULTS FOR DOLOMITE

(ENVIRONMENT - PEO)

Specimen #	Thickness t (in)	Radius r (in)	Notch a (in)	a/r	Crit. Load (lbs)	Sigma (psi)	Ki	Kic (psi*sqrt in)
B3-C6-S1-44	0.980	1.960	1.260	0.643	174	45.294	10.150	915
B2-C2-S1-64	1.000	1.960	1.250	0.638	180	45.918	9.975	908
B2-C3-S4-66	0.960	1.965	1.265	0.644	176	46.650	10.175	946
B2-C3-S1-81	1.010	1.950	1.250	0.641	184	46.712	10.075	933
B3-C6-S4-90	0.890	1.960	1.255	0.640	174	49.874	10.025	993
							AVREAGE Kic =	939

Table A-IV. FRACTURE TOUGHNESS TEST RESULTS FOR DOLOMITE

(ENVIRONMENT - ALCL3)

Specimen #	Thickness t (in)	Radius r (in)	Notch a (in)	a/r	Crit. Load (lbs)	Sigma (psi)	Ki	Kic (psi*sqrt in)
B3-C6-S3-25	0.950	1.960	1.255	0.640	194	52.095	10.025	1037
B1-C2-S1-39	0.970	1.950	1.250	0.641	160	42.294	10.075	844
B1-C1-S2-47	0.995	1.970	1.265	0.642	154	39.283	10.100	791
B2-C3-S3-72	1.000	1.950	1.240	0.636	198	50.769	9.900	992
B3-C7-S1-89	0.950	1.940	1.240	0.639	172	46.663	10.000	921
B3-C1-S2-92	0.905	1.965	1.265	0.644	158	44.424	10.175	901
							AVERAGE Kic =	914

Table A-V. FRACTURE TOUGHNESS TEST RESULTS FOR DOLOMITE

(ENVIRONMENT - CACL2)

Specimen #	Thickness t (in)	Radius r (in)	Notch a (in)	a/r	Crit. Load (lbs)	Sigma (psi)	Ki	Kic (psi*sqrt in)
B3-C6-S1-24	0.980	1.960	1.260	0.643	174	45.294	10.150	915
B3-C5-S1-35	0.960	1.970	1.270	0.645	220	58.164	10.225	1188
B3-C4-S2-61	0.970	1.960	1.260	0.643	214	56.280	10.150	1137
B2-C3-S2-70	0.970	1.960	1.250	0.638	196	51.546	9.975	1019
B3-C1-S4-77	0.960	1.960	1.260	0.643	198	52.615	10.150	1063
B3-C6-S3-91	0.950	1.960	1.260	0.643	186	49.946	10.150	1009
							AVERAGE Kic =	1055

APPENDIX B

FRACTURE TOUGHNESS RESULTS FOR SIOUX QUARTZITE

Table B-I. FRACTURE TOUGHNESS TEST RESULTS FOR QUARTZITE

(ENVIRONMENT - AIR)

Specimen #	Thickness t (in)	Radius r (in)	Notch a (in)	a/r	Crit. Load (lbs)	Sigma (psi)	Ki	Kic (psi*sqrt in)
B2-C3-S4-05	0.995	1.970	1.385	0.703	162	41.323	12.513	1079
B2-C5-S3-18	1.040	1.915	1.350	0.705	174	43.683	12.600	1134
B2-C5-S3-28	1.045	1.960	1.375	0.702	173	42.232	12.463	1094
B1-C7-S1-33	1.030	1.970	1.390	0.706	174	42.876	12.638	1132
B2-C5-S1-35	1.055	1.960	1.350	0.689	180	43.525	11.950	1071
B1-C5-S3-40	1.010	1.945	1.310	0.674	202	51.414	11.338	1183
							AVERAGE Kic =	1115

Table B-II. FRACTURE TOUGHNESS TEST RESULTS FOR QUARTZITE

(ENVIRONMENT - WATER)

Specimen #	Thickness t (in)	Radius r (in)	Notch a (in)	a/r	Crit. Load (lbs)	Sigma (psi)	Ki	Kic (psi*sqrt in)
B2-C5-S1-02	1.050	1.960	1.350	0.689	184	44.704	11.950	1100
B2-C2-S2-08	1.000	1.950	1.345	0.690	170	43.590	11.950	1071
B1-C6-S3-48	1.060	1.970	1.320	0.670	198	47.409	12.400	1197
B1-C6-S1-52	1.065	1.970	1.325	0.673	202	48.140	12.513	1229
B1-C4-S4-68	0.985	1.960	1.360	0.694	169	43.769	12.150	1099
B1-C2-S1-91	0.980	1.980	1.375	0.694	168	43.290	12.150	1093
							AVERAGE Kic =	1132

Table B-III. FRACTURE TOUGHNESS TEST RESULTS FOR QUARTZITE

(ENVIRONMENT - PEO)

Specimen #	Thickness t (in)	Radius r (in)	Notch a (in)	a/r	Crit. Load (lbs)	Sigma (psi)	Ki	Kic (psi*sqrt in)
B1-C7-S3-21	1.050	1.950	1.360	0.697	172	42.002	12.263	1065
B2-C4-S4-29	1.020	1.960	1.305	0.666	199	49.770	11.025	1111
B1-C6-S3-49	1.055	1.955	1.310	0.670	203	49.212	11.188	1117
B1-C6-S2-55	1.045	1.950	1.355	0.695	140	34.352	12.188	864
B1-C5-S1-74	1.010	1.975	1.380	0.699	163	40.857	12.350	1051
B1-C5-S3-75	1.010	1.960	1.370	0.699	146	36.876	12.350	945
							AVERAGE Kic =	1025

Table B-IV. FRACTURE TOUGHNESS TEST RESULTS FOR QUARTZITE

(ENVIRONMENT - ALCL3)

Specimen #	Thickness t (in)	Radius r (in)	Notch a (in)	a/r	Crit. Load (lbs)	Sigma (psi)	Ki	Kic (psi*sqrt in)
B2-C3-S3-30	1.040	1.955	1.350	0.691	172	42.298	12.025	1047
B2-C3-S3-34	1.040	1.960	1.330	0.679	200	49.058	11.550	1158
B1-C1-S3-38	1.030	1.960	1.340	0.684	154	38.141	11.750	920
B1-C5-S2-60	0.995	1.965	1.370	0.697	160	40.917	12.263	1041
??-??-??-72	0.920	1.950	1.315	0.674	176	49.052	11.338	1130
B1-C2-S3-94	0.895	1.980	1.455	0.735	112	31.601	13.825	934
							AVERAGE Kic =	1038

Table B-V. FRACTURE TOUGHNESS TEST RESULTS FOR QUARTZITE

(ENVIRONMENT - CACL2)

Specimen #	Thickness t (in)	Radius r (in)	Notch a (in)	a/r	Crit. Load (lbs)	Sigma (psi)	Ki	Kic (psi*sqrt in)
B2-C1-S1-19	1.060	1.980	1.325	0.669	172	40.976	11.138	931
B2-C1-S3-31	1.020	1.960	1.385	0.707	165	41.267	12.675	1091
B2-C4-S3-50	0.985	1.960	1.290	0.658	192	49.725	10.713	1072
B1-C5-S1-51	1.020	1.960	1.325	0.676	168	42.017	11.425	979
B1-C3-S1-77	0.945	1.910	1.320	0.691	162	44.877	12.025	1099
B1-C5-S1-99	1.015	1.955	1.370	0.701	170	42.836	12.425	1104
							AVERAGE Kic =	1046

APPENDIX C

FRACTURE TOUGHNESS RESULTS FOR WESTERLY GRANITE

Table C-I. FRACTURE TOUGHNESS TEST RESULTS FOR GRANITE

(ENVIRONMENT - AIR)

Specimen #	Thickness t (in)	Radius r (in)	Notch a (in)	a/r	Crit. Load (lbs)	Sigma (psi)	Ki	Kic (psi*sqrt in)
B2-C5-S1-21	1.050	1.975	1.265	0.641	168	40.506	10.075	814
B2-C9-S2-43	1.030	1.980	1.330	0.672	140	34.324	11.260	790
B2-C6-S2-51	1.025	1.970	1.290	0.655	154	38.133	10.600	814
B2-C10-S2-68	1.035	1.990	1.230	0.618	180	43.697	9.300	799
B2-C2-S2-84	1.050	1.960	1.255	0.640	172	41.788	10.025	832
B2-C1-S3-87	1.100	1.960	1.260	0.643	166	38.497	10.150	777
							AVERAGE Kic =	804

Table C-II. FRACTURE TOUGHNESS TEST RESULTS FOR GRANITE

(ENVIRONMENT - WATER)

Specimen #	Thickness t (in)	Radius r (in)	Notch a (in)	a/r	Crit. Load (lbs)	Sigma (psi)	Ki	Kic (psi*sqrt in)
B2-C4-S2-02	1.050	1.930	1.265	0.655	126	31.088	10.600	657
B1-C2-S4-33	1.080	1.950	1.240	0.636	148	35.138	9.900	687
B1-C2-S2-37	1.050	1.950	1.250	0.641	120	29.304	10.075	585
B2-C2-S1-63	1.005	1.960	1.275	0.651	120	30.460	10.450	637
B2-C7-S5-75	1.050	1.950	1.250	0.641	158	38.584	10.075	770
B1-C1-S2-86	0.990	1.940	1.240	0.639	132	34.364	10.000	678
							AVERAGE Kic =	669

Table C-III. FRACTURE TOUGHNESS TEST RESULTS FOR GRANITE

(ENVIRONMENT - PEO)

Specimen #	Thickness t (in)	Radius r (in)	Notch a (in)	a/r	Crit. Load (lbs)	Sigma (psi)	Ki	Kic (psi*sqrt in)
B2-C5-S3-24	1.050	1.990	1.310	0.658	124	29.672	10.713	645
B1-C2-S3-32	1.080	1.950	1.330	0.682	116	27.540	11.675	657
B1-C2-S3-34	1.060	1.960	1.260	0.643	148	35.618	10.150	719
B2-C6-S4-49	1.030	1.980	1.320	0.667	114	27.949	11.025	627
B2-C6-S1-52	0.970	1.990	1.265	0.636	132	34.192	9.900	675
B2-C7-S4-77	1.010	2.000	1.250	0.625	130	32.178	9.525	607
						AVERAGE Kic =		655

Table C-IV. FRACTURE TOUGHNESS TEST RESULTS FOR GRANITE

(ENVIRONMENT - ALCL3)

Specimen #	Thickness t (in)	Radius r (in)	Notch a (in)	a/r	Crit. Load (lbs)	Sigma (psi)	Ki	Kic (psi*sqrt in)
B2-C -S5-22	1.040	1.970	1.275	0.647	126	30.750	10.300	634
B2-C8-S2-54	1.000	1.970	1.230	0.624	145	36.802	9.505	688
B2-C6-S1-48	0.980	1.950	1.250	0.641	136	35.583	10.075	710
B2-C7-S1-71	1.030	1.990	1.240	0.623	148	36.103	9.488	676
B2-C5-S2-80	1.020	1.990	1.270	0.638	132	32.516	9.975	648
B2-C9-S1-95	1.010	1.990	1.370	0.688	106	26.369	11.900	651
							AVERAGE Kic =	668

Table C-V. FRACTURE TOUGHNESS TEST RESULTS FOR GRANITE

(ENVIRONMENT - CACL2)

Specimen #	Thickness t (in)	Radius r (in)	Notch a (in)	a/r	Crit. Load (lbs)	Sigma (psi)	Ki	Kic (psi*sqrt in)
B2-C3-S4-08	1.000	1.960	1.280	0.653	106	27.041	10.513	570
B1-C1-S3-28	0.950	1.970	1.280	0.650	106	28.320	10.375	589
B1-C2-S2-31	1.050	1.950	1.250	0.641	132	32.234	10.075	644
B2-C2-S4-62	1.060	1.920	1.250	0.651	120	29.481	10.450	611
B2-C7-S3-72	1.020	1.980	1.310	0.662	120	29.709	10.863	655
B2-C8-S5-79	1.030	1.950	1.270	0.651	120	29.873	10.450	624
							AVERAGE Kic =	615

APPENDIX D

SPECIFIC WORK OF FRACTURE RESULTS FOR DOLOMITIC
LIMESTONE

Table D-I. SPECIFIC WORK OF FRACTURE - DOLOMITE

(ENVIRONMENT - AIR)

Specimen #	Thickness t (in)	Radius R (in)	Notch a (in)	Ligament b(in)	Ligament Area (ft^2)	W (ft.lbs)	R (ft.lbs/ft^2)
B3-C4-S2-08	0.970	1.955	1.245	0.710	0.00478	0.0163	3.408
B3-C3-S3-28	0.910	1.950	1.260	0.690	0.00436	0.0144	3.302
B3-C1-S1-31	0.990	1.965	1.260	0.705	0.00485	0.0168	3.466
B3-C5-S3-45	0.920	1.960	1.260	0.700	0.00447	0.0125	2.795
B3-C5-S1-57	0.950	1.960	1.250	0.710	0.00468	0.0197	4.206
B2-C2-S3-65	1.050	1.970	1.250	0.720	0.00525	0.0135	2.571
						AVERAGE R =	3.291

Table D-II. SPECIFIC WORK OF FRACTURE - DOLOMITE

(ENVIRONMENT - WATER)

Specimen #	Thickness t (in)	Radius R (in)	Notch a (in)	Ligament b(in)	Ligament Area (ft^2)	W (ft.lbs)	R (ft.lbs/ft^2)
B1-C3-S4-01	0.960	1.920	1.230	0.690	0.00460	0.0200	4.348
B2-C2-S2-04	1.025	1.940	1.250	0.690	0.00491	0.0168	3.421
B3-C5-S2-22	0.970	1.960	1.260	0.700	0.00472	0.0204	4.326
B1-C2-S3-38	1.000	1.965	1.270	0.695	0.00483	0.0184	3.812
B3-C3-S1-88	1.035	1.950	1.255	0.695	0.00500	0.0291	5.825
B3-C4-S1-94	0.990	1.960	1.260	0.700	0.00481	0.0260	5.403
						AVERAGE R =	4.523

Table D-III. SPECIFIC WORK OF FRACTURE - DOLOMITE

(ENVIRONMENT - PEO)

Specimen #	Thickness t (in)	Radius R (in)	Notch a (in)	Ligament b(in)	Ligament Area (ft^2)	W (ft.lbs)	R (ft.lbs/ft^2)
B3-C6-S1-44	0.980	1.960	1.260	0.700	0.00476	0.0174	3.652
B2-C2-S1-64	1.000	1.960	1.250	0.710	0.00493	0.0213	4.320
B2-C3-S4-66	0.960	1.965	1.265	0.700	0.00467	0.0201	4.307
B2-C3-S1-81	1.010	1.950	1.250	0.700	0.00491	0.0254	5.173
B3-C6-S4-90	0.890	1.960	1.255	0.705	0.00436	0.0197	4.521
						AVERAGE R =	4.395

Table D-IV. SPECIFIC WORK OF FRACTURE - DOLOMITE

(ENVIRONMENT - ALCL3)

Specimen #	Thickness t (in)	Radius R (in)	Notch a (in)	Ligament b(in)	Ligament Area (ft^2)	W (ft.lbs)	R (ft.lbs/ft^2)
B3-C6-S3-25	0.950	1.960	1.250	0.710	0.00468	0.0196	4.184
B1-C2-S1-39	0.970	1.950	1.250	0.700	0.00472	0.0192	4.072
B1-C1-S2-47	0.995	1.970	1.265	0.705	0.00487	0.0218	4.475
B2-C3-S3-72	1.000	1.950	1.240	0.710	0.00493	0.0211	4.279
B3-C7-S1-89	0.950	1.940	1.240	0.700	0.00462	0.0208	4.504
B3-C1-S2-92	0.905	1.965	1.265	0.700	0.00440	0.0180	4.092
						AVERAGE R =	4.268

Table D-V. SPECIFIC WORK OF FRACTURE - DOLOMITE

(ENVIRONMENT - CACL2)

Specimen #	Thickness t (in)	Radius R (in)	Notch a (in)	Ligament b(in)	Ligament Area (ft^2)	W (ft.lbs)	R (ft.lbs/ft^2)
B3-C6-S1-24	0.980	1.960	1.260	0.700	0.00476	0.0174	3.652
B3-C5-S1-35	0.960	1.970	1.270	0.700	0.00467	0.0257	5.507
B3-C4-S2-61	0.970	1.960	1.260	0.700	0.00472	0.0195	4.135
B2-C3-S2-70	0.970	1.960	1.250	0.710	0.00478	0.0201	4.203
B3-C1-S4-77	0.960	1.960	1.260	0.700	0.00467	0.0179	3.836
B3-C6-S3-91	0.950	1.960	1.260	0.700	0.00462	0.0215	4.656
					AVERAGE R =		4.332

APPENDIX E

SPECIFIC WORK OF FRACTURE RESULTS FOR SIOUX QUARTZITE

Table E-I. SPECIFIC WORK OF FRACTURE - QUARTZITE

(ENVIRONMENT - AIR)

Specimen #	Thickness t (in)	Radius R (in)	Notch a (in)	Ligament b (in)	Ligament Area (ft^2)	W (ft.lbs)	R (ft.lbs/ft^2)
B2-C3-S4-05	0.995	1.970	1.385	0.585	0.00404	0.0283	7.001
B2-C5-S3-18	1.040	1.915	1.350	0.565	0.00408	0.0290	7.107
B2-C5-S3-28	1.045	1.960	1.375	0.585	0.00425	0.0309	7.279
B1-C7-S1-33	1.030	1.970	1.390	0.580	0.00415	0.0299	7.207
B2-C5-S1-35	1.055	1.960	1.350	0.610	0.00447	0.0321	7.183
					AVERAGE R =		7.155

Table E-II. SPECIFIC WORK OF FRACTURE - QUARTZITE

(ENVIRONMENT - WATER)

Specimen #	Thickness t (in)	Radius R (in)	Notch a (in)	Ligament b(in)	Ligament Area (ft^2)	W (ft.lbs)	R (ft.lbs/ft^2)
B2-C5-S1-02	1.050	1.960	1.350	0.610	0.00445	0.0334	7.509
B2-C2-S2-08	1.000	1.950	1.345	0.605	0.00420	0.0324	7.712
B1-C6-S3-48	1.060	1.970	1.320	0.650	0.00478	0.0339	7.085
B1-C6-S1-52	1.065	1.970	1.325	0.645	0.00477	0.0309	6.478
B1-C4-S4-68	0.985	1.960	1.360	0.600	0.00410	0.0430	10.477
B1-C2-S1-91	0.980	1.980	1.375	0.605	0.00412	0.0303	7.359
					AVERAGE R =		7.770

Table E-III. SPECIFIC WORK OF FRACTURE - QUARTZITE

(ENVIRONMENT - PEO)

Specimen #	Thickness t (in)	Radius R (in)	Notch a (in)	Ligament b(in)	Ligament Area (ft^2)	W (ft.lbs)	R (ft.lbs/ft^2)
B1-C7-S3-21	1.050	1.950	1.360	0.590	0.00430	0.0289	6.718
B1-C6-S3-49	1.055	1.955	1.310	0.645	0.00473	0.0352	7.449
B1-C6-S2-55	1.045	1.950	1.355	0.595	0.00432	0.0327	7.573
B1-C5-S1-74	1.010	1.975	1.380	0.595	0.00417	0.0226	5.415
B1-C5-S3-75	1.010	1.960	1.370	0.590	0.00414	0.0326	7.878
						AVERAGE R =	7.007

Table E-IV. SPECIFIC WORK OF FRACTURE - QUARTZITE

(ENVIRONMENT - ALCL3)

Specimen #	Thickness t (in)	Radius R (in)	Notch a (in)	Ligament b(in)	Ligament Area (ft^2)	W (ft.lbs)	R (ft.lbs/ft^2)
B2-C3-S3-30	1.040	1.955	1.350	0.605	0.00437	0.0320	7.324
B2-C3-S3-34	1.040	1.960	1.330	0.630	0.00455	0.0341	7.495
B1-C1-S3-38	1.030	1.960	1.340	0.620	0.00443	0.0333	7.509
B1-C5-S2-60	0.995	1.965	1.370	0.595	0.00411	0.0259	6.300
72	0.920	1.950	1.315	0.635	0.00406	0.0286	7.050
B1-C2-S3-94	0.895	1.980	1.455	0.525	0.00326	0.0189	5.792
					AVERAGE R =		6.911

Table E-V. SPECIFIC WORK OF FRACTURE - QUARTZITE

(ENVIRONMENT - CACL2)

Specimen #	Thickness t (in)	Radius R (in)	Notch a (in)	Ligament b(in)	Ligament Area (ft^2)	W (ft.lbs)	R (ft.lbs/ft^2)
B2-C1-S1-19	1.060	1.980	1.350	0.630	0.00464	0.0339	7.310
B2-C1-S3-31	1.020	1.960	1.385	0.575	0.00407	0.0304	7.464
B2-C4-S3-50	0.985	1.960	1.290	0.670	0.00458	0.0296	6.459
B1-C5-S1-51	1.020	1.960	1.325	0.635	0.00450	0.0308	6.848
B1-C3-S1-77	0.945	1.910	1.320	0.590	0.00387	0.0269	6.948
B2-C1-S1-92	1.015	1.955	1.370	0.585	0.00412	0.0249	6.039
						AVERAGE R =	6.844

APPENDIX F

SPECIFIC WORK OF FRACTURE RESULTS FOR WESTERLY GRANITE

Table F-I. SPECIFIC WORK OF FRACTURE - GRANITE

(ENVIRONMENT - AIR)

Specimen #	Thickness t (in)	Radius R (in)	Notch a (in)	Ligament b(in)	Ligament Area (ft^2)	W (ft.lbs)	R (ft.lbs/ft^2)
B2-C5-S1-21	1.050	1.975	1.265	0.710	0.00518	0.0319	6.162
B2-C9-S2-43	1.030	1.980	1.330	0.650	0.00465	0.0301	6.474
B2-C6-S2-51	1.025	1.970	1.290	0.680	0.00484	0.0325	6.714
B2-C10-S2-68	1.035	1.990	1.230	0.760	0.00546	0.0287	5.254
B2-C2-S2-84	1.050	1.960	1.255	0.705	0.00514	0.0276	5.369
B2-C1-S3-87	1.100	1.960	1.260	0.700	0.00535	0.0308	5.760
						AVERAGE R =	5.956

Table F-II. SPECIFIC WORK OF FRACTURE - GRANITE

(ENVIRONMENT - WATER)

Specimen #	Thickness t (in)	Radius R (in)	Notch a (in)	Ligament b(in)	Ligament Area (ft^2)	W (ft.lbs)	R (ft.lbs/ft^2)
B2-C4-S2-02	1.050	1.930	1.265	0.665	0.00485	0.0253	5.218
B1-C2-S4-33	1.080	1.950	1.240	0.710	0.00533	0.0263	4.939
B1-C2-S2-37	1.050	1.950	1.250	0.700	0.00510	0.0249	4.878
B2-C2-S1-63	1.005	1.960	1.275	0.685	0.00478	0.0214	4.476
B2-C7-S5-75	1.050	1.950	1.250	0.700	0.00510	0.0299	5.858
B1-C1-S2-86	0.990	1.940	1.240	0.700	0.00481	0.0262	5.444
						AVERAGE R =	5.136

Table F-III. SPECIFIC WORK OF FRACTURE - GRANITE

(ENVIRONMENT - PEO)

Specimen #	Thickness t (in)	Radius R (in)	Notch a (in)	Ligament b(in)	Ligament Area (ft^2)	W (ft.lbs)	R (ft.lbs/ft^2)
B2-C5-S3-24	1.050	1.990	1.310	0.680	0.00496	0.0234	4.719
B1-C2-S3-32	1.080	1.950	1.330	0.620	0.00465	0.0237	5.097
B1-C2-S3-34	1.060	1.960	1.260	0.700	0.00515	0.0197	3.823
B2-C6-S4-49	1.030	1.980	1.320	0.660	0.00472	0.0253	5.359
B2-C6-S1-52	0.970	1.990	1.265	0.725	0.00488	0.0239	4.894
B2-C6-S4-77	1.010	2.000	1.250	0.750	0.00526	0.0292	5.551
						AVERAGE R =	4.907

Table F-IV. SPECIFIC WORK OF FRACTURE - GRANITE

(ENVIRONMENT - ALCL3)

Specimen #	Thickness t (in)	Radius R (in)	Notch a (in)	Ligament b(in)	Ligament Area (ft^2)	W (ft.lbs)	R (ft.lbs/ft^2)
B2-C1-S5-22	1.040	1.970	1.275	0.695	0.00502	0.0240	4.781
B2-C7-S1-71	1.030	1.990	1.240	0.750	0.00536	0.0260	4.847
B2-C5-S2-80	1.020	1.990	1.270	0.720	0.00510	0.0251	4.922
					AVERAGE R =		4.850

Table F-V. SPECIFIC WORK OF FRACTURE - GRANITE

(ENVIRONMENT - CACL2)

Specimen #	Thickness t (in)	Radius R (in)	Notch a (in)	Ligament b(in)	Ligament Area (ft^2)	W (ft.lbs)	R (ft.lbs/ft^2)
B2-C3-S4-08	1.000	1.960	1.280	0.680	0.00472	0.0200	4.235
B1-C1-S3-28	0.950	1.970	1.280	0.690	0.00455	0.0211	4.635
B1-C2-S2-31	1.050	1.950	1.250	0.700	0.00510	0.0274	5.368
B2-C2-S4-62	1.060	1.980	1.310	0.670	0.00493	0.0213	4.319
B2-C7-S3-72	1.020	1.980	1.310	0.670	0.00475	0.0205	4.320
B2-C8-S5-79	1.030	1.950	1.270	0.680	0.00486	0.0238	4.893
						AVERAGE R =	4.628

VITA

Muhammad Akram was born on November 27, 1953 in Gujrat, Pakistan. He graduated from Sir Syed Degree College Gujrat in 1972. He attended Engineering University Lahore, Pakistan from 1973–1978 where he received a B.Sc. in Mining Engineering. He worked as Assistant Mining Engineer and as Assistant Director in the Industries Department of Punjab Government from 1978–1982. He has been employed as an Assistant Professor in the Department of Mining Engineering, Engineering University Lahore, since 1982.