INTRODUCTION

The fracture behavior of concrete is often attributed to a fracture process zone. This fracture process zone manifests itself in the form of nonlinear stress-strain behavior, post peak strain softening, size effect, and numerous toughening mechanisms. Features of the fracture process zone include arrays of microcracks, aggregate interlocking, crack bridging, and grain boundary sliding friction. From a material modeling standpoint, properties of the fracture process zone must be known in order to accurately predict the response of the material to stress. Since the fracture process zone characteristics are critical to material properties, a better understanding of those characteristics will lead to a better understanding of overall performance.

In order to investigate some of the microstructural phenomena which make up the fracture process zone, an experimental program using quantitative acoustic emission techniques was conducted. The specific goals of the program were to evaluate microcrack properties through the deconvolution of recorded AE waveforms, and to examine the relationship between the recovered microcrack properties and the overall fracture properties of the material. Toward this end a series of plain (unreinforced) beam specimens were tested in three point bending under closed-loop control. The microcracking was monitored using an array of acoustic emission transducers. The AE events were analyzed using quantitative techniques as described below. Microcrack characteristics determined through the quantitative AE analysis were compared with bulk material properties such as load-deformation response and fracture toughness.

QUANTITATIVE ACOUSTIC EMISSION

The quantitative AE approach used in this study is the same as that presented by Hsu et al [1], in which the source characteristics may be deduced through a knowledge of the propagation medium and the measurement system characteristics. This approach may be
written as:
\[ V(t) = T(t) * \left[ G(t) * M(t) \right] \]  
(1)

where \( V(t) \) is the measured voltage transient, \( T(t) \) is the response function of the measurement system, \( G(t) \) is the elastodynamic Green’s function for the material, and \( M(t) \) is a function representing the acoustic source. "*" denotes a convolution integral. The basic premise here is that if \( T(t) \) and \( G(t) \) are known a priori, the AE source function may be determined from the measured voltage transient through a series of deconvolutions.

The AE (microcrack) source is represented by a seismic moment tensor which equates the microcrack discontinuity with a set of equivalent body forces. This equivalence may be written [2]:

\[ M_y = C_{ijkl} b_k n_i \Delta A \]  
(2)

Here \( b_k n_i \Delta A \) is discontinuity with area, \( \Delta A \), and slip direction, \( b_k \). The plane of the discontinuity has a normal vector \( n_i \). \( C_{ijkl} \) is the elastic stiffness tensor, and \( M_y \) is the seismic moment tensor. For isotropic materials eq. (2) can be simplified to:

\[ M_y = \left[ \lambda b_k n_i \delta_{ik} + \mu (b_i n_j + b_j n_i) \right] \Delta A \]  
(3)

where \( \lambda \) and \( \mu \) are the Lamé constants. Microcrack parameters of orientation, volume and slip angle can be determined from the principal values and principal directions of \( M_y \). If the principal values of \( M_y \) are denoted by \( M^{(1)} \), \( M^{(2)} \), and \( M^{(3)} \), and the principal directions are denoted by \( x^{(1)} \), \( x^{(2)} \), and \( x^{(3)} \) then the microcrack orientation, volume and slip angle can be defined by [3]:

\[ n_i = \frac{1}{2(b_k b_k)^{1/2}} (x_i^{(1)} - x_i^{(3)}) \]  
(4)

\[ V = b_k n_i \Delta A = \frac{M^{(1)} + M^{(2)} + M^{(3)}}{3\lambda + 2\mu} \]  
(5)

\[ \cos \alpha = \frac{b_k n_i}{(b_k b_k)^{1/2}} = \frac{2\mu M^{(2)}}{\lambda (M^{(1)} - M^{(3)})} \]  
(6)

where \( n \) is a vector normal to the crack plane, \( V \) is the microcrack volume, and \( \alpha \) is the angle between \( n \) and the direction of motion between the two faces of the microcrack, \( b_k \). Using this designation, and angle of \( \alpha \) close to 0° indicates mode I (tensile) microcracking, whereas an angle of \( \alpha \) close to 90° indicates mode II (shear) microcracking. Thus, through the use of equations (4)-(6), a microcrack may be uniquely characterized in terms of its volume, orientation, and slip angle.

The moment tensor components are determined through an inversion of equation (1)

The theoretical basis for equation (1) is an integral solution of the differential equation of motion in an elastic solid. The far field displacement \( u_i \) in an elastic medium at point \( x \), due to a transient dipole body force \( M_{ik} \), acting at point \( \xi \) can be written [2]:

\[ u_i(x,t) = \int_{-\infty}^{\infty} G_{i\lambda}(x, \xi, t-\tau) M_{\lambda k}(\xi, \tau) d\tau \]  
(7)

where \( G_{i\lambda} \) is the elastodynamic Green’s function (2nd kind) for the medium. If equation (7) is convolved with the impulse response function for the AE transducer, the result is equation
(1). Thus, if the Green's function for the medium, and the transducer response function are known, then moment tensor representing a microcrack can be determined through an inversion of equation (7) at a number of locations.

A nonlinear least-squares approach was developed for the required multichannel inversion [4]. The multichannel inversion produces the nine moment tensor components. The moment tensor is then rotated to its principal axes. Finally, the microcrack parameters (orientation, volume and slip angle) are evaluated using equations (4) through (6).

EXPERIMENTAL PROGRAM

A series of three point bend specimens of varying composition were prepared for this program. The specimens were designated as follows: coarse mortar, fine mortar, plain cement paste, and DSP cement paste. The fine mortar had a maximum aggregate size of 1 mm, and the coarse mortar had a maximum aggregate size of 5 mm. The results of previous experiments showed that the "coarse mortar" represents a practical limit of quantitative AE analysis of microcracking in cement-based materials [5]. The proportion of aggregate in the mortars was 2 parts aggregate to 1 part cement. The DSP cement paste is a portland cement-based material with a very low water-cement ratio, and a relatively large fraction of added silica fume. After the constituents are thoroughly mixed, a vacuum is applied to minimize the amount of entrapped air. The result is a material with a very dense microstructure (as compared to conventional cement-based materials). All specimens were tested in a closed-loop, servo-hydraulic load frame. The experimental setup is illustrated in Figure 1. Details of the experiments are presented in [6]. Specimens of two different size and geometry were tested: larger unnotched beams and smaller notched beams.

The components of the AE measurement system are also illustrated in Figure 1. A LeCroy modular transient recorder system was used to acquire the AE waveforms. A LabVIEW-based application was developed to record the signals and to control the LeCroy system. Eight channels of AE data was recorded for all tests. 16 and 32 megasamples per second were the sampling rates for the large and small specimens respectively.

Two different types of transducers were used: micro80 AE transducers from Physical Acoustics Corp (PAC), model CA-1135 position transducers (PIN) from Dynasen Inc. Each of the transducers were calibrated against a glass capillary reference signal. The PIN transducers were found to have a more broadbanded displacement response than the

Figure 1. Experimental setup.
PAC transducers. However, the PAC transducers were much more sensitive up to about 250 kHz [5]. The PAC transducers were used on the larger specimens because of their better sensitivity.

EXPERIMENTAL RESULTS

The cumulative AE event counts are plotted along with the loads for the two paste specimens in Figures 2 and 3. The event counts shown in these figures illustrate an interesting characteristic of the AE properties of cement-based materials. This characteristic is that the rate of AE activity appears to increase just prior to the ultimate load. In the cement paste specimen (Fig 2), the increase in event rate occurs at the peak load. The specimen also shows linear prepeak behavior. In the DSP specimen (Figure 3) the event rate jump occurs at
about 86% of the peak. There is a notable nonlinear prepeak region in this specimen. Li and Shah [7] attributed this jump in the AE event rate to the localization of microcracking into a single critical crack. In their specimens of mortar and concrete the jump occurred typically at about 80% of the peak load. Ohtsu [8] attributed the AE event rate increase to the formation of the fracture process zone. He also suggested that a linear elastic fracture mechanics (LEFM) approach could be applied to concrete if the load for evaluating fracture toughness was taken as the load where the AE event rate jumps and the fracture process zone forms.

The locations of the AE sources were evaluated according to the methods described in Landis et al [9]. The source locations evaluated in the fine mortar specimens are shown at four different stages in Figures 4 and 5 respectively. In each of these figures the initial AE source locations are distributed over a relatively wide area in the zone of maximum tensile stress. Prior to peak load, the AE events tend to localize into a zone close to the observed surface crack. Nearly all subsequent AE events are confined to this narrow band.

The recovered slip angles for each specimen are shown in Figure 6. The slip angle, $\alpha$ was defined as the angle between a vector normal to the microcrack plane, and a vector representing the direction of crack motion of one face relative to the other. The majority of the microcrack slip angles recovered for the two mortar specimens tend to be relatively close to 90°, indicating a dominance of shear microfracture modes. There is a significant difference in the slip angles of the paste specimens. Both show much larger crack opening components (smaller slip angles). Although the shear component in both of these is still fairly high (a majority of normal paste events had slip angles in the 70° to 75° range while the DSP had the most events in the 65° to 70° range), it seems clear that the nature of the

Figure 6. Histograms of the slip angles recovered for the different specimens tested.
microcracking is different in the fine versus the coarse-grained materials.

A plot of the recovered microcrack volumes and the corresponding load is shown in Figure 7 for the coarse mortar specimen. Figure 8 shows the slip angles and load history. It can be seen in these figures that there are likely different modes of microfracture at different points on the loading cycle. This could represent microcracking in different material phases. Microcracks occurring early in the loading cycle have often been attributed to primarily matrix-aggregate interface cracks. As load approaches the peak the microcracking also includes the matrix phase [10]. If it is assumed that matrix cracking consists of a higher energy release than interface cracking, then Figure 7 shows that there is primarily matrix cracking around the peak load, whereas the strain softening region could primarily be interface cracking. If this is the case, then from Figure 8 it could be concluded that the matrix cracking is predominantly mixed mode, whereas the interface cracking is primarily shear. This theory could be supplemented by the fact that both cement paste specimens showed primarily mixed mode microcracking.

The fracture toughness of the materials tested was measured using the two parameter fracture model [11]. Tests on the DSP and cement paste specimens were conducted as a part...
of this experimental program. Fracture toughness values for the fine and coarse mortar specimens were taken from published tests of comparable materials [12]. The measured critical effective crack length \( a_e \) was compared to the average slip angle \( \alpha \) measured in each specimen. These two values are plotted in Figure 9. Although there are not enough data points for a statistically significant relationship, but the figure shows a possible relationship between the average microcrack slip angle and the critical effective crack length.

CONCLUSIONS

It is apparent from the results of this investigation that quantitative AE analysis yields a wealth of information about microcracking and microfracture processes. The AE event rate, the source locations, and the microcrack parameters all can be synthesized to aid in the understanding of microcracking and its role in mechanical behavior. In this paper, the rate of AE activity was shown to correspond to nonlinearities in the load-CMOD curves. The mortar specimens showed a much higher shear component microfracture component than did the paste specimens. The progression microcrack characteristics along the load cycle for the specimens illustrates that interface cracks could likely be the source of the high shear component microcracks. It was also shown that there is a potential relationship between average microcrack slip angle and the critical effective crack length of the material. If the shear microcracks are attributed to grain boundary sliding and other frictional mechanisms, then the much of the increase in fracture toughness (as indicated by the critical effective crack length) of the coarse-grained materials over the fine-grained materials can be attributed to these energy absorbing mechanisms. In summary, the results of the tests conducted as a part of this research program can be used to infer properties of the fracture process zone as well as the specific characteristics of individual microcracks. The properties of the microcracks can ultimately be linked to the overall fracture behavior of the materials.

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REFERENCES