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TITLE: A STUDY OF FRACTURE PRESSURIZATION AS A RESULT OF EXPLOSIVE DETONATION

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MASTER

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SOCIETY OF MINING ENGINEERS

Rock Mechanics
in Protection
and Productivity

A STUDY OF FRACTURE PRESSURIZATION AS A RESULT OF EXPLOSIVE DETONATION

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ABSTRACT

This paper describes a number of model tests conducted in plexiglas models to investigate the phenomenon of fracture pressurization. The models were examined with high speed photography while being subjected to explosive loading. At the same time pressure transducers were used to record the pressure in the borehole as a function of time and also along the path of the propagating fracture to measure the pressure at various locations along the fracture as a function of time.

Both propellants and explosives were used to charge the borehole. Air as well as fluid filled boreholes were needed to provide a variety of pressure rise rates. On some tests eddy current displacement gauges measured crack opening displacements as a function of time. As a final check high speed photographs taken during the event were used to visually ascertain the location of the fracture at any given time.

INTRODUCTION

The speed with which fractures created by an explosive detonation are filled with high pressure gases as well as the magnitude of the pressure in the fractures are of great interest. To date no valid data has been presented that sheds light on this very complex event. In the case of fragmentation blasting it has been postulated that the amount of rock breakage that results is very much a function of successful pressurization of the fractures. The exact mechanism of fragmentation is unknown but the current theory is that in a matter of microseconds an intense fracture network is created in the near vicinity of the borehole. At some as yet undetermined time later (tens or hundreds of milliseconds) these fractures are filled with high pressure gases which continue to drive the fractures and jumble the resulting rock fragments. The proper combination of stress waves and gas pressures result in good fragmentation. Once this process is at a certain stage then proper blasting procedures call for a second hole or series of holes to be detonated. Before proper fragmentation blasting can be planned a complete knowledge of the pressurization process, how it is affected by pressure rise rate and at what time it occurs, must be determined.

In other areas of blasting practice it is also important to understand the process of fracture pressurization. In oil and gas well stimulation with explosive and propellant charges it is desired to create multiple fractures which travel from the borehole wall and intersect natural fracture systems within the reservoir in order for the trapped hydrocarbons to flow into the well bore so that they can be taken to the surface. In this application it has been demonstrated that if gases which are created by the explosion do not penetrate into the stress wave created fractures very little production is achieved.

Although sophisticated computer codes exist for predicting well bore fracturing, S. L. McHugh, et al 1978, and rock fragmentation, T. G. Barbour et al 1980 and S. L. McHugh 1980, they have been ineffective since no physical model is available to predict the crack pressurization event. That is, more needs to be known about when the gas pressure gets into the fractures, what is the distribution of pressure along the fracture length, how much of the newly formed fracture is pressurized, and what are the associated crack opening displacements.

This paper describes model testing conducted as a first attempt to determine at what time fractures formed by explosives are pressurized and what pressure magnitudes can be expected within these fractures.

EXPERIMENTAL PROCEDURES

The tests were conducted in thick rectangular blocks of plexiglas with geometry similar to that shown in Figure 1. The 12.7 mm diameter borehole was drilled parallel to the faces of the model as shown in the figure. The borehole was grooved to produce a controlled fracture that would cleave the model in half in the thickness direction. A cylindrical charge (either an explosive or a deflagrating device) about 3 mm in diameter and 12.7 to 38 mm in length was placed in the bottom of the borehole. The borehole was either air filled or filled with an ink water mixture and then tightly stemmed with 54 mm of modeling clay and a 6.4 mm cap plate of lexan bonded over the end. Figure 2 presents a borehole cross section showing the charge and stemming detail. Holes 3.2 mm in diameter were drilled three quarters of the way through the model at various locations. These holes were either air filled or water filled and were capped with 6.4 mm diameter Kistler model 603A or 601H piezoelectric pressure transducers. These transducers as well as one in the stem were used to record pressures in the borehole and in the fracture as it intersected the holes.

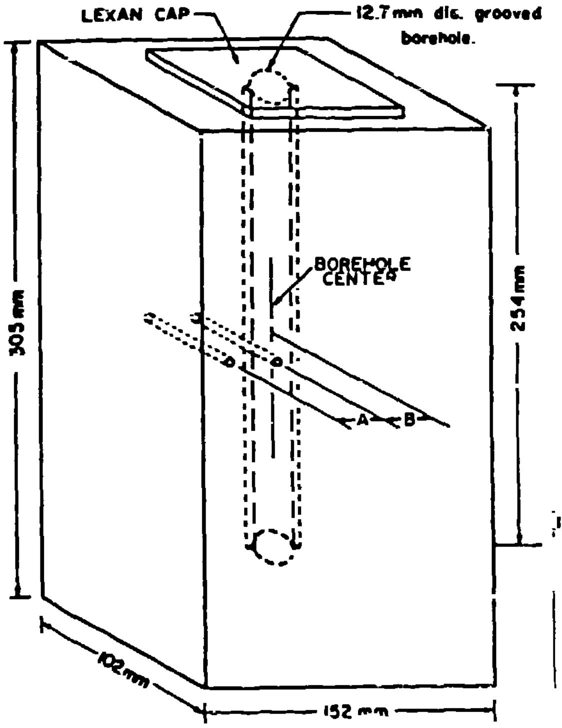

Figure 1 Geometry of models used in investigation.

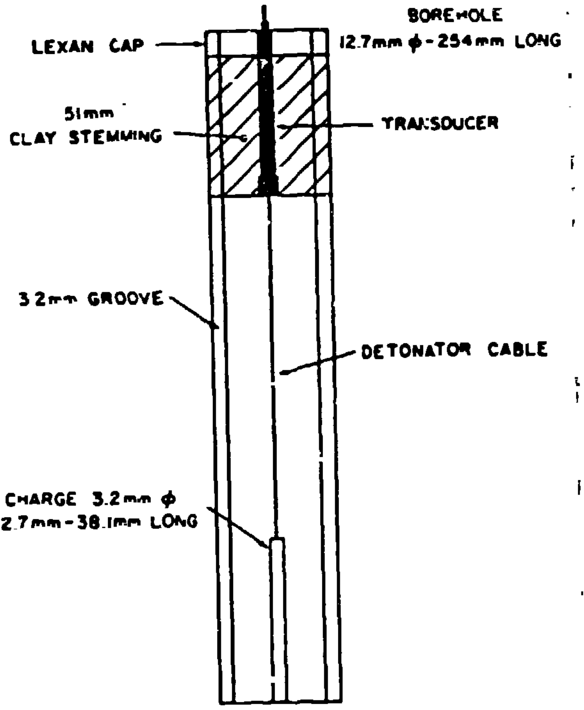

Figure 2 Borehole cross section showing charge location.

The pressure transducers used could record a rise time of 1 microsecond. The 603A has a linear range of 20.69 MPa with a possibility of reading up to 34.48 MPa in conjunction with a calibration curve. The 601H has a capability of recording pressures up to 55 MPa.

In some models an eddy current displacement transducer was used to determine crack opening as the cracks propagated away from the borehole. The charge was detonated and dynamic photoelastic photographs were taken with a Cranz-Schardin multiple spark gap camera as the fractures initiated and propagated. The camera and the technique of dynamic photoelasticity will not be discussed here since it has been described in many previous publications such as W. L. Fourney, et al 1975. The camera takes 16 photographs during the dynamic event at rates up to 850,000 frames per second and allows for the instantaneous location of the stress waves, the fracture fronts, and the detonation products or fluids which originally filled the borehole.

TYPICAL TEST RESULTS

Figure 3 shows three frames from Test 16, the first taken 190 microseconds after detonation, the last 570 microseconds later. In this particular test the borehole was only grooved for half of its length or about 127 mm below the top edge. The PETN charge was 175 mg. Figure 3a shows that no fracture was initiated in the vicinity of the charge at the bottom of the borehole due to the light load and the absence of grooves. At 190 microseconds the stemming area fracture, W. L. Fourney, et al 1981, has grown three-quarters of an inch (14.3 mm) on either side of the borehole and very little detonation products have entered the propagating crack. Figure 3b shows at 342 microseconds some detonation products being emitted through the fracture along the top edge of the model. From the photograph the products do not seem to be very dense and it appears that they are being ejected along most of the crack length. In Figure 3c taken at 760 microseconds the stemming area fracture has nearly cleaved the model in two. Dense smoke is being extruded along the top edge. Also visible is a small amount of smoke that is being emitted from the right and left edges of the model. Notice also from the photographs the very rough appearance of ripple markings of the fracture surfaces. This normally is caused by slight changes in maximum normal stress directions such as would be caused by stress wave reflections from boundaries. The larger the spacing between ripples the higher the crack velocity, A. B. J. Clark, et al 1966.

A computer sketch of the fracture formation from frame to frame for Test 16 along with velocities computed for the fracture are given in Figure 4. The velocity of the stem area fracture appears to be erratic — especially after the free boundary has been reached.

Pressures measured at three locations during the test are given in Figure 5. Figure 5a is the pressure measured at the stem, Figure 5b the pressure in the propagating crack 25 mm from the center of the borehole, and Figure 5c the pressure measured 50.8 mm from the borehole center. As observed from Figure 3 all three transducers were located in the area of the stem. The pressure in the borehole at the stem peaked at about 160 microseconds after detonation at 9.3 MPa. The pressures measured in the crack were extremely low — about .76 MPa at the nearest station and only .3 MPa at the other station. The pressure started to build at about 240 microseconds after detonation at the transducer located 25.4 mm from the borehole and at about 425 microseconds at the other location.

RESULTS FROM TEST SERIES

The pressure behavior exhibited in Figure 5 from Test 16 were not observed in all cases. Figure 6 gives results from a similar test - Test 11. Figure 6a gives the pressure time history recorded at the stem location while 6b gives the pressure recorded in the fracture

Figure 3 High speed photographs showing crack growth in Test 16.
a) 190 μs, b) 342 μs, c) 760 μs.

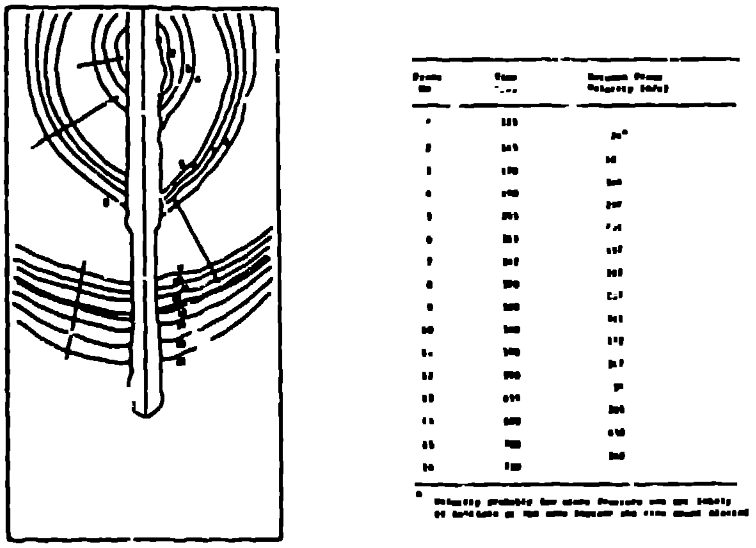

Figure 4 Fracture growth obtained from all 16 frames during Test 16.

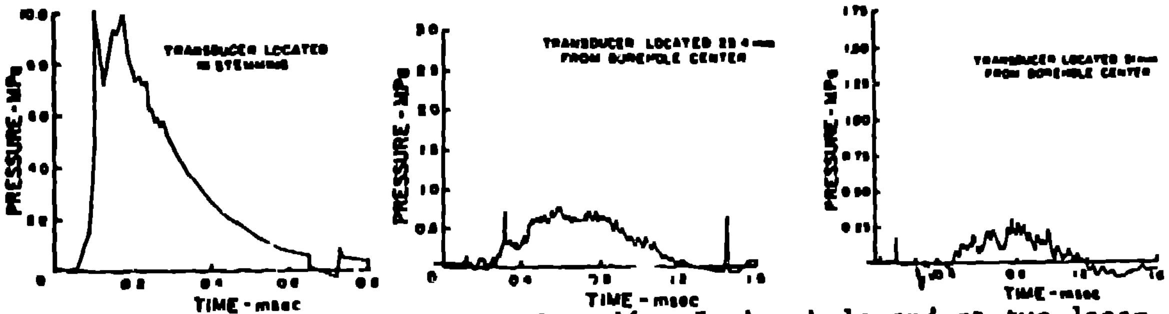

Figure 5 Pressures measured in Test 16. In borehole and at two locations within the fracture.

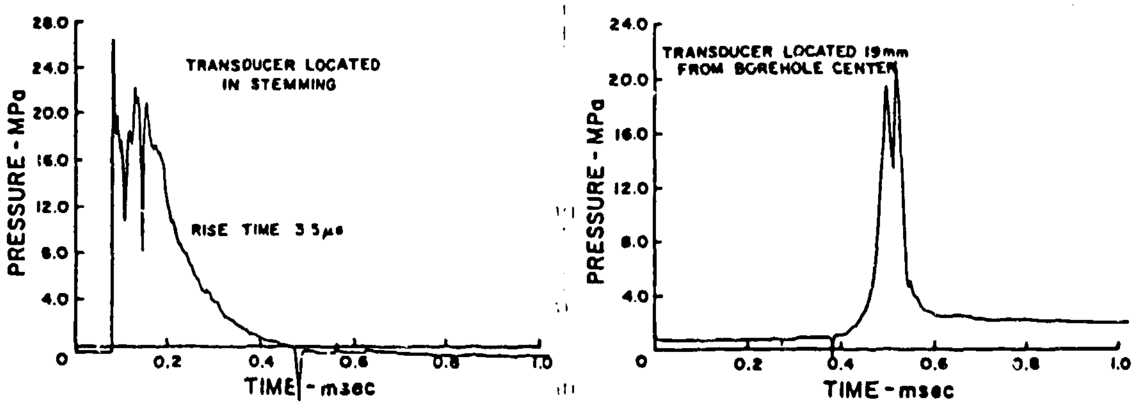

Figure 6 Pressures within the borehole and within the fracture in Test 11.

12.7 mm from the borehole wall. In this case the pressure recorded in the fracture was nearly equal to the pressure recorded in the borehole but the time lag was 150 μs longer than with Test 16 even though the transducer was located 8 mm closer to the edge of the borehole and the charge was 43% larger.

Some of the discrepencies obtained in pressure records can be explained by looking at Figure 7 which shows three frames from a model which was tested with the borehole filled with a water ink mixture. This mixture was used to make the flow into the fracture more visible. It is of course realized that the behavior of the mixture within the fracture will not be identical to the flow of a gas but it will permit trends to be observed.

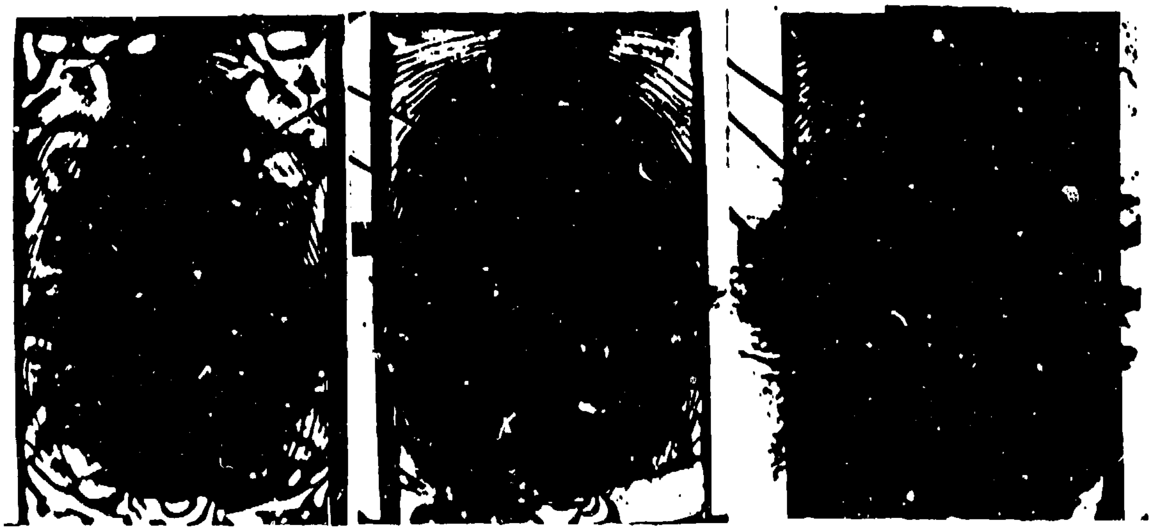

Figure 7 Flow of water into growing fractures createdby explosive loading. a) 530 μs, b) 710 μs, c) 1010 μs.

Note in Figure 7a that the fracture front at 530 μs is well advanced compared to the fluid front. In particular the fracture has already exited the sides of the model. Notice also that the fluid front is extremely irregular with parts of the fluid front at some locations being at least 25 mm ahead of the trailing front (see point A for example). This becomes more extreme in Frame 5 shown as Figure 7b at 710 μs. In Figure 7c taken at 1010 μs where the ink colored water is exiting the sides of the model some areas are being jetted out as much as 50 mm in advance of adjacent points (see point B for example). Limited crack opening displacement doesn't appear to be a problem as evidenced by Figure 8 which shows the output from an eddy current transducer from a similar test - Test 20. It appears from the displacements recorded that the crack opened to about one tenth of a mm within about 100 μs of the crack reaching the transducer.

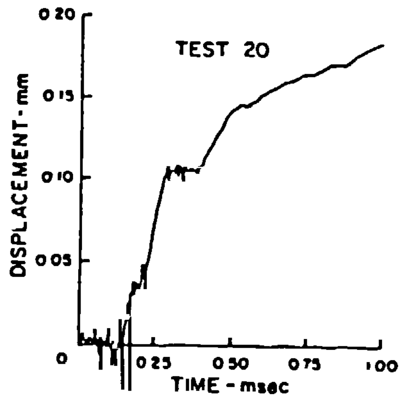

Figure 8 Crack opening displacement as a function of time - Test 20.

Results from tests conducted with propellants as the charge resulted in a much more predictable behavior. Figure 9 for example shows a photograph from such a test taken at 500 μs. Note from the figure that the fracture front is still well advanced of the fluid front but that the fluid front is much less erratic. Notice that the fluid front is smoother even upon being ejected from the sides of the partially fractured model. Figure 10 presents the pressure data obtained for the model shown in Figure 9. About 36% of the pressure value read at the stem was recorded in the fracture and the fracture pressurization occurred after about a 250 μs delay. This was observed to be repetitive for all the models loaded with propellant charges.

CONCLUSIONS

The tests conducted revealed that for air filled borehole, pressures recorded in the fractures were not very repeatable from test to test. The means for this erratic behavior could be explained by the very irregular flows observed in the fractures (for ink water mixture) when the models were charges with explosives. Propellant charges on the other hand resulted in fluid flows into the fracture which were very smooth. The pressures recorded within the fractures were also quite repeatable for the propellant charges.

Figure 9 Flow of water into growing fractures created by propellant loading.

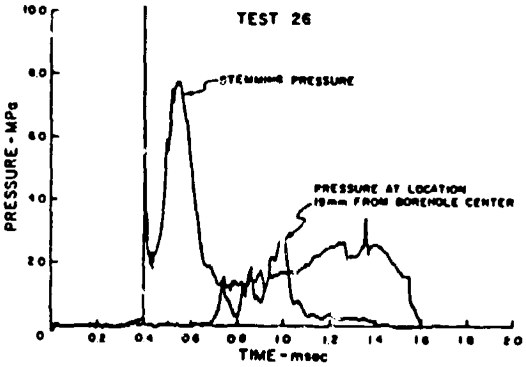

Figure 10 Pressures recoupled in the borehole and propagating crack after propellant loading.

Explosive charges necessary to fracture the models which had fluid filled boreholes were about one fourth that required for the air filled models. On the other hand, the amount of propellant necessary to fracture models with fluid filled boreholes was about five times the amount of explosive charges necessary under the same condition.

The fracture front velocities recorded in the propellant charged models was only about 80% of the fracture front velocities in the explosively loaded models. For the explosively loaded fluid filled models the ratio of the fluid front velocity to the fracture front velocity was about .8. For the fluid filled borehole models which were charged with propellants this ratio was about 0.6. The total number of tests conducted within the study was approximately 30. The results reported should be considered preliminary and more testing should be conducted to better define the pressure distribution within propagating fractures.

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