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Rock Mechanics Models and Measurements Challenges from Industry

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The effect of the critical path on fluid flow through a fracture

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Abstract: Fluid flow through a fracture or fracture network is controlled by the geometry of the network and by the distribution of voids within each fracture. The critical path, i.e., the path of largest apertures across a fracture, dominates the flow of fluid through the fracture. We have directly quantified the importance of the critical path by using Wood's metal porosimetry and methane flow rate measurements. Filling the critical path with Wood's metal reduced flow rates through the fracture by 70% to 98%. X-ray tomographic scanning and photomicroscopy are used to visualize the void spaces in the fracture.

1 INTRODUCTION

Some of richest known gas reservoirs (14 TcF) are located in coal seams. During the production of methane from coal beds, methane and brine flow through a natural fracture network know as cleats which are the primary hydraulic conductors for the coal. An underlying question about the movement of fluids through a fracture or fracture network is how the fracture void geometry affects the permeability of the fracture. Recent modeling of fluid flow through a single fracture suggests that fluid flow through a fracture is dominated by channel flow (Tsang & Tsang, 1987), by the critical path (Pyrak-Nolte et al., 1988) or by preferential flow paths (Yang et al., 1993). The critical path of a fracture is the path consisting of the largest apertures. Through laboratory experiments and computer-aided visualization, we have investigated the geometry of the cleat network and the critical path in fractures in coal. Saturating the critical path with a non-wetting fluid reduces the wetting phase flow rate. We have also examined the relationship between effective cleat porosity and absolute water permeability by imaging the fracture network in coal.

2 COAL CORES

Table 1 lists the dimensions of the coal samples used in this study. Sample #7-2-3 is a whole drill core from the Pittsburgh seam of the Northern Appalachian Basin, Wetzel County, West Virginia. This sample was used to investigate the geometry of the critical path and the effect of the critical path on fluid flow. Coal cores CC and TT are from Seam #1 of the Sundance Pit at the La Plata coal mine and were cored from blocks of coal. Sample CC was drilled perpendicular to the bedding planes and sample TT was drilled parallel to the bedding planes. Samples CC and TT were used to investigate the geometry of the cleat (fracture) network and the effect of the cleat network on the hydraulic properties of the coal.

Table 1. Sample Dimensions

Sample Number	Diameter (cm)	Length (cm)	Bulk Volume (cm^3)
#7-2-3	5.22	5.01	105.47
CC	8.89	4.41	274
TT	8.89	11.2	694

Table 2. Properties of Wood's Metal (Cerrosafe®)

Components: Bismuth Lead Tin Cadmium	 42.5 % 37.7 % 11.3 % 8.5 %
Melting Temperature Range (°C)	70 - 80
Surface Tension (dynes/cm)	485 ± 17
Contact Angle on Coal	$130^{\circ} \pm 21^{\circ}$
Density (grams/cm^3)	9.46 ± 0.16
Young's Modulus (GPa)	9.7

Table 3. Experimental Parameters and Results on Coal Sample 7-2-3 from the Pittsburgh Seam of the Northern Appalachian Basin, and Coal Samples CC and TT from Seam #1 of the Sundance Pit at the La Plata Coal Mine, San Juan Basin, New Mexico.

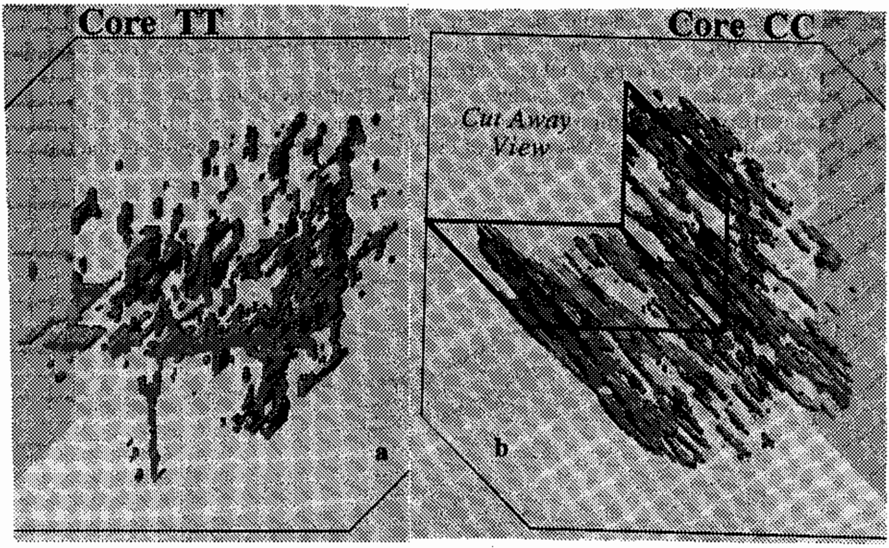
Sample Number	7-2-3	CC	TT
Confining Pressure at Solidification (MPa)	4.5	4.89	5.54
Nitrogen Pressure at Solidification (MPa)	0.41	0.49	0.44
Effective Pressure at Solidification (MPa)	4.09	4.4	5.1
Weight of Wood's Metal Injected (grams)	0.01	2.14	6.19
Connected Void Volume (cm^3)[1]	$0.001 \pm 2\times10^{-5}$	0.22 ± 0.005	0.65 ± 0.013
Effective Cleat Porosity (%)[1]	$0.001 \pm 2\times10^{-5}$	0.082 ± 0.002	0.094±0.002
Minimum Aperture Size Accessed (μm)[2]	1.47 ± 0.7	1.22 ± 0.59	1.37 ± 0.65

[1] Error from deviations in the density of Wood's metal

[2] Error from deviations in the surface tension and the contact angle of Wood's metal

3 WOOD'S METAL INJECTION

A Wood's metal injection technique (Pyrak-Nolte et al., 1987; Pyrak-Nolte, 1990) is used to measure the effective cleat porosity of a coal core and capture the geometry of the cleat network. The properties of Wood's metal are listed in Table 2. In this technique a low melting point metal is injected into a sample subjected to a confining pressure. The sample is heated to 95 °C and molten metal is injected into the sample using a pressure generator. A nitrogen backpressure is applied during the injection process and maintained during cooling of the sample. After injection, the sample is allowed to cool and the metal to solidify. Gravimetric data and pressure data are used to determine the volume of voids injected, the effective cleat porosity, and the minimum aperture penetrated by the metal. The geometry of the injected flow paths are examined using X-ray tomography (CT) and photomicroscopy. The pressures used during injection of the samples and the results of the metal injection experiment are given in Table 3.



Figures 1 & 2. Three dimensional reconstruction of the cleat networks in coal core TT (a) and coal core CC (b).

4 GEOMETRY OF THE CLEAT NETWORK

The three-dimensional geometry of the cleat or cleat network is reconstructed from the two-dimensional x-ray tomographic (CT) data. The reconstructed fracture networks for coal cores TT and CC are shown in Figures 1 & 2. The fracture network in core TT which was oriented parallel to the bedding planes, and is dominated by a bedding plane fracture which is the horizontal fracture in the Figure 1. The observed fractures in core TT are planar and rectilinear in shape. The fractures in core CC are curvi-linear and show the tortuosity of the cleat network. The geometry of flow paths in the cleats in these coal cores are anisotropic as observed by comparing the reconstructed fracture networks in Figure 1 and Figure 2. The disconnected voids observed in the Figures are a result of the coarse spacing of the CT scans. The scans were taken every 12 mm and 5 mm for cores TT and CC, respectively.

5 GEOMETRY OF THE CRITICAL PATH

Coal core #7-2-3 was injected while subjected to a high confining pressure (4.5 MPa) to examine the geometry of the critical path of the fracture. The critical path of the fracture is the path of largest apertures across the fracture. Figure 3 shows the three-dimensional reconstruction of the cleat in coal core #7-2-3 based on two dimensional CT data. For this sample, the reconstruction shows a single vertical cleat and shows the spatial relationship between the cleat and a bedding plane with high density minerals (Horizontal structure in Figure 3).

Figure 4 is a composite map of the Wood's metal-filled void spaces (represented by black) in the fracture based on photomicroscopy of the metal casts in the fracture. The white regions of the map represent coal to coal contact or inaccessible voids. The direction of metal injection into the core is noted in Figure 4. A swatch of large voids is located in the center of the fracture and is oriented perpendicular to the direction of metal injection. The disconnected void spaces in the map can be a result of (a) the resolution of the composite map (~ 70 microns); or (b) the solidification pressure of the Wood's metal, if it is lower than the Wood's metal pressure during injection so that the Wood's metal retreats from the small connective pathways between portions of the flow paths.

A comparison of the composite map (Figure 3) of the Wood's metal-filled void spaces and the three dimensional reconstruction of the void space (Figure 4) suggests that the

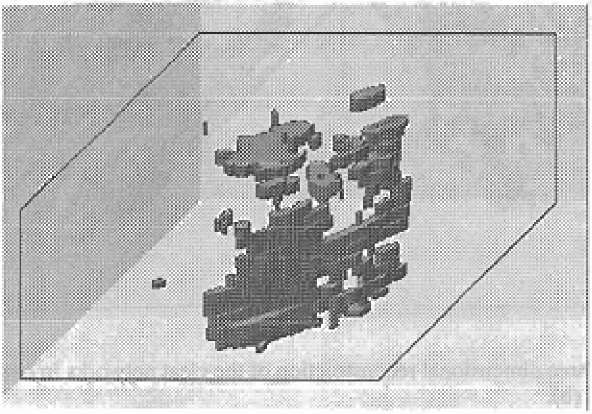


Figure 3. Three dimensional reconstruction of a fracture in coal sample #7-2-3. Horizontail plane features is a region of minerals with high density.

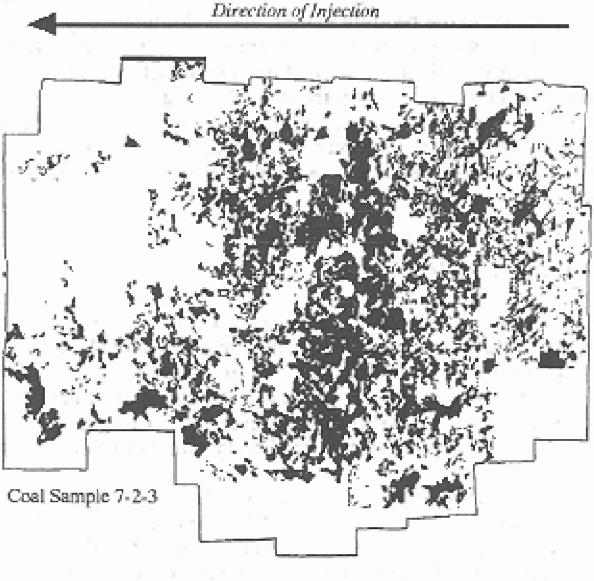


Figure 4. Composite image of the void space in a single cleat in coal sample #7-2-3. Black represents the void spaces. Notice preferential flow path is perpendicular to the direction of the metal injection.

three dimensional reconstruction gives the gross outline of the flow paths. However, the CT scans for this sample were taken every three millimeters while the structure in the composite map is observed to vary on length scales much smaller than that. The three-dimensional reconstruction would be improved by using a smaller spacing between scans.

6 PERMEABILITY-POROSITY PARADOX

Two service laboratories made measurements of absolute water permeability and porosity on samples CC and TT from the San Juan Basin in New Mexico (Pyrak-Nolte, 1992). Each laboratory used the unsteady-state method where the coal core is saturated with brine that is subsequently displaced with humidified helium. The volumes of helium and brine produced are recorded and used in models to determine the relative permeability of the sample (Gash, 1991; Gash et al., 1992). The effective cleat porosity and absolute water permeability are shown in Figure 5. Core CC was oriented perpendicular to the bedding planes (parallel to the face cleats) and core TT was oriented parallel to the bedding planes. Contrary to expectation, the core with the higher permeability (TT) had the smaller porosity (Figure 5).

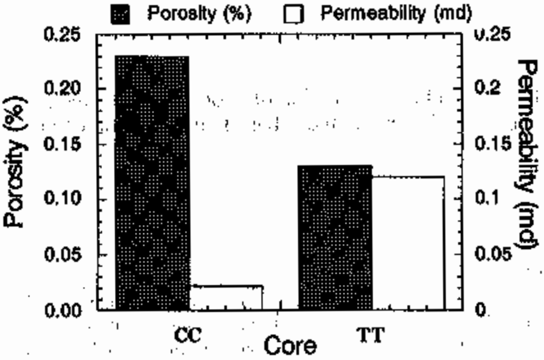


Figure 5. Porosity and absolute water permeability for coal cores CC and TT from the San Juan Basin.

This apparent paradox in the permeability and porosity relationship for these two coal cores was resolved using information from the geometry of the cleats obtained from the Wood' metal injection experiments. The ratio of the effective cleat porosity determined from the Wood's metal method to the effective cleat porosity determined from unsteady-state method gives the fraction of cleat porosity with apertures greater than two microns. This ratio revealed that 36 % of the fracture network porosity in coal core CC consisted of apertures greater than 2 microns. For coal core TT, 76 % of the fracture network porosity consisted of apertures greater than 2 microns. While coal core CC had a higher porosity than coal core TT, the porosity was mainly from small apertures (< 2 microns) which support less flow. Thus, the permeability is controlled by the geometry and interconnectedness of the void spaces within the cleat network structure. Three-dimensional reconstructions (Figures 1 & 2) of the x-ray tomographic images of the fractures illustrate the anisotropy in the fracture network in coal.

7 EFFECT OF THE CRITICAL PATH ON FLOW RATES

Flow measurements were made on coal sample #7-2-3 using methane for a range of confining pressures (0.69 MPa - 4.2 MPa) and a range of pore pressures (0.069 MPa - 0.34 MPa) prior to injection of the sample with Wood's metal. Figure 6 shows that the pre-injection flow rates of methane through the sample (for pore pressures of 0.14 MPa and 0.28 MPa) decrease with increasing confining pressure and increase with increasing pore pressure.

To determine the effect of the critical path on flow through a fracture, coal sample #7-2-3 was injected with Wood's metal while subjected to a stress of 4.5 MPa. The total volume of Wood's metal injected was 0.001% of the total bulk volume of the sample. Apertures as small as 3 microns were penetrated with the metal. Photomicroscopy of the sample has shown that flow paths through the fracture have variable apertures and appear to be spatially correlated. After injection, methane flow rate measurements were made. Figure 6 shows the effect of filling the critical path with a non-wetting phase on the flow rates of the wetting phase (methane). The flow rate is markedly decreased and flow does not occur for confining pressures greater than 2.1 MPa. For purposes of comparison, the ratio of the post-injection flow rate to pre-injection flow rate was taken and is shown in Figure 7 as a function of confining pressure. The post-injection flow rates are observed to be much lower, and were determined to be 70% to 98% lower than the pre-injection flow rates. In addition, the ratio of pre- to post-injection flow rates decreases with increasing stress.

Figure 1. Three dimensional reconstruction of Wood's metal flow paths through a fracture in coal sample 7-2-3. The image is based on two-dimensional x-ray tomographic scans.

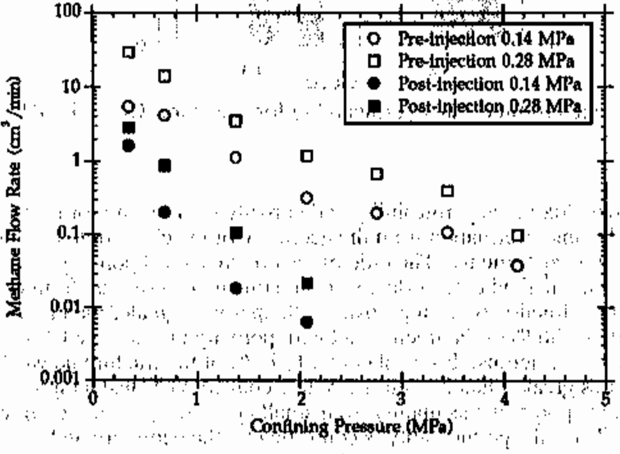


Figure 6. Methane flow rates through coal sample #7-2-3 for pore pressures of 0.14 MPa and 0.28 MPa prior to and after injection of the sample with Wood's metal.

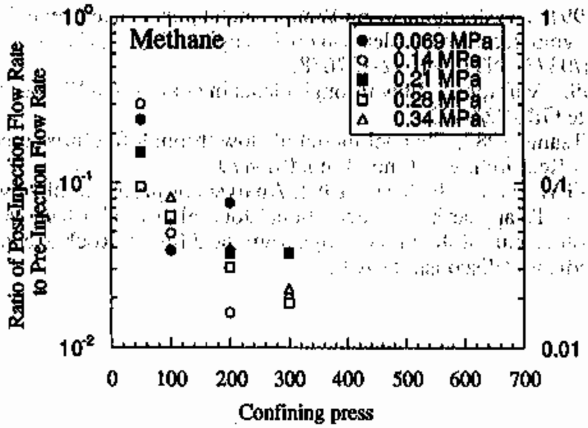


Figure 7. Ratio of post-injection flow rates to pre-injection flows for pore pressures ranging from 0.069 MPa to 0.34 MPa for coal sample #7-2-3.

8 CONCLUSIONS

The dramatic reduction in flow rates is a direct result of obstructing the critical path. The data show that if the critical path of the fracture is saturated with a non-wetting fluid the wetting phase flow rate is greatly reduced. In addition, the effect on the flow rate is not constant as the stress is increased. The reduction in flow rate increases with increasing stress until no flow occurs. These experimental results are significant because they illustrate the dominance of the critical path on fluid flow through a fracture.

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