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Influence of Discontinuity Length and Density on Permeability of Nigerian Coals

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Abstract: Laboratory investigation was conducted to determine the influence of discontinuity length and density on permeability of Nigeria coal seams to serve the advantage of water infusion in coal seam mining. This study presents the measured equivalent permeability results and its relevance to water infusion in coal seams. The laboratory results indicated that the coals have equivalent permeabilities of 10^{-4} to 10^{-3} m s^{-1} and the permeability coefficient is mainly dominated by the percentage of porosity and the crack number. The laboratory data provide a base for assessment and prediction of water inflow into the seams during coal seams mining.

Key words: Discontinuity length and density, equivalent permeability, water infusion, laboratory investigation

INTRODUCTION

The flow of groundwater through a fractured rock mass critically depends on: the geometry of the fracture system (fracture frequency, distribution and connectivity) and the characteristics of single fractures (Sainath and Harpalani, 2004). Since rock discontinuities control the behavior of rock mass failure, a complete knowledge of the location, orientation, c ontinuity, frequenting and surface properties are essential in characterizing geo-logical properties of rock mass. Various models studies have been carried out to investigate the influence of fracture system geometry on the rock mass hydraulic conductivity (Samaniego and Priest, 1984; Kikuchi *et al.*, 1991; Wei *et al.*, 1995). These studies showed that only a fraction of the fractures are connected and form potential flow paths and random fractures and fractures of low persistence (short length) are often not water bearing and conducting. A numerical study conducted by Wei and others based on rock fracture network simulation (Wei and Hudson, 1988; Wei *et al.*, 1995) suggested that the hydraulic conductivity decreases with depth and is proportional to the depth cubed.

In this study, the author observed that there is need to consider the effect of discontinuity length and density on the permeability of Nigerian coal seams by conducting permeability test on the coal samples subjecting the test to similar insitu conditions. The goal was to relate the finding to water movement in fractures and utilize the generated data in water infusion to solve coal mining problems such as coal dust noting that the presence of coal dust in mines causes a significant number of operational and safety problems during mining that may result in low production and development rates, poor efficiency and high ventilation costs.

DISCONTINUITIES IN ROCKS

Fractures are discontinuous breaks in rock masses. A small volume fraction of fractures in a rock material can produce an appreciable mechanical effect by decreasing its strength and increases its deformability, Olaleye and Jegede (2006). Fractures can be as a result of ground movements. The first cause of cracks in coal is by gravitational effects, that is, an overburden stress and the associated lateral stress developed under conditions of no lateral strain. The second component is the tectonically induced horizontal stresses that, apart from redistribution through creep, should theoretically be proportional to the moduli of the rocks, provided that horizontal strains are approximately equal, as could be expected in extensive sedimentary deposits (Bell, 1992).

Fractures in rocks have been investigated by a number of workers basing their judgments on predictions. Snow (1969) used assumed infinite fracture length to predict the permeability for jointed rock masses. Several other approaches have been introduced to account for the interconnectivity and heterogeneity effects. La Pointer and Hudson (1981) used electrical analog models to study finite fractures and Sagar and Runchal (1982) took into account the finite size of fractures and found that the equivalent permeability of fractured rock depends upon not only the number of fracture groups, number of fractures in each group, fracture dimensions and orientation but also the rock volume considered. They obtained a non-symmetric and nontensorial permeability matrix by summing up the contribution of each fracture that intersects at least one face of the rock cube considered. The fractures that do not intersect any face are not taken into account. In order to apply their theory for a cube of given rock volume, it is important to know

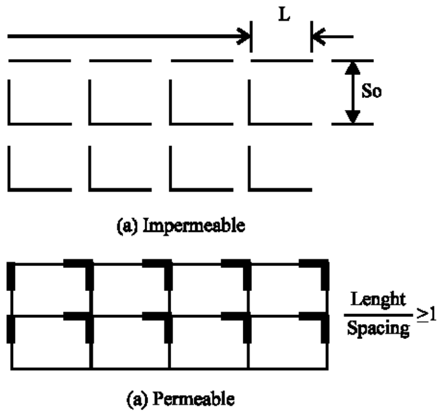

Fig. 1: Permeability threshold of jointed rock mass

how many fractures intersect at least one face of the cube. Neumann (1988) therefore proposed a stochastic continuum approach and used a unified framework to analyze hydraulic test data obtained on different scales, generally on Representative Elementary Volume (REV) scales which is the jointed rock mass volume beyond which there is no substantial variation in permeability.

Wei *et al.* (1995) considered percolation threshold in the prediction of permeability of jointed rock masses and introduced a discontinuity index which is the product of the discontinuity frequency and length. Percolation threshold is an indication of when a rock mass is permeable. Whether a jointed rock mass is permeable can be studied by percolation theory, Guegueen and Dienes, (1989). Here a very simple approach was used and verified against numerical results. Figure 1 shows rock masses with two orthogonal sets of fractures. The reason why only the rock mass in diagram (b) is permeable is that the Length (L) of fractures is equal to or greater than the spacing (S_o).

$$I_d = \frac{\text{Length}}{\text{Spacing}} = \frac{L}{S_o} = \lambda_o L \geq 1 \quad (1)$$

where I_d is discontinuity index and λ_0 is the discontinuity frequency in the direction normal to the discontinuity set. In two or three-dimensions, according to Hudson and Priest (1983), they are, respectively:

$$\lambda_o = \frac{\lambda_{max}}{\sqrt{2}},\ \lambda_o = \frac{\lambda_{max}}{\sqrt{3}} \quad (2)$$

Therefore, in two dimensions, Eq. 1 becomes

$$I_d = \frac{L}{S_{min}} = \lambda_{max} L \geq \sqrt{2} \quad (3)$$

and in 3 dimensions

$$I_d = \frac{L}{S_{min}} = \lambda_{max} L \geq \sqrt{3} \quad (4)$$

where S_{min} and λ_{max} are minimum and maximum total discontinuity spacing and frequency, respectively.

Coal permeability is a major parameter that requires determination for the application of water infusion in coal seams. However, the key factors influencing coal seam permeability are the distributed features of the pores and cracks. These two parameters have been used by Zhao *et al.* (2002) in the study of the permeability characteristics of China coal seams. Based on the analyses of the test result, they related permeability coefficient, volume stress and pore pressure and fitted it into exponential form to generate permeability coefficient equation.

PERMEABILITY OF COAL MASS

The permeability of a porous substance is the ability of the substance to permit flow of fluid through its network of interconnected pore space. It is obvious that if the pore opening of a rock were not interconnected there would be no permeability. Darcy's equation expresses the linear velocity or rate of fluid flow through a permeable substance. Darcy's Law can therefore fairly accurately represent the movement of groundwater in soils and rocks:

$$Q = AKi \quad (5)$$

where Q is the volume flow rate, m^3/s; A is the cross-sectional area through which the flow takes place, m^2; i is the hydraulic gradient and K is the coefficient of permeability (hydraulic conductivity) having the same limits as velocity, m s^{-1}.

Also the equivalent permeability of water through fissures in rocks is given as:

$$k = \frac{ge^3}{12\mu . b} \quad (6)$$

where k is the equivalent permeability, m s^{-1}; g is the gravitational acceleration (9.81 m s^{-2}); e is the opening of cracks or fissures, mm; b is the spacing between cracks, mm and μ is the coefficient of kinematic viscosity of water (Pa.s).

BRIEF DESCRIPTION OF COAL OCCURENCES IN THE BENUE TROUGH OF NIGERIA

Numerous authors have defined, described and classified coal as rock. According to Bell (1992) coal is a sedimentary rock of organic origin. Essentially, it is

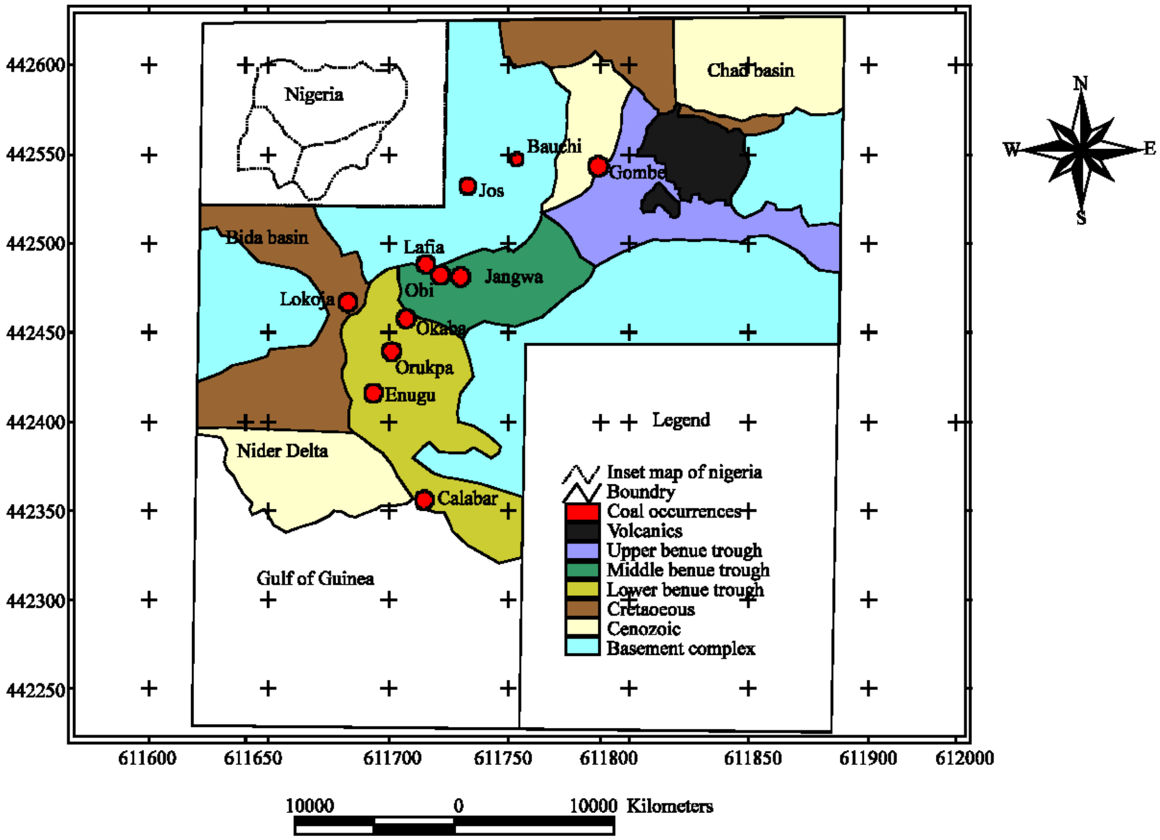

Fig. 2: Area of major coal occurrences in the Benue Trough of Nigeria showing the study locations

sediment, organoclastic in nature, composed of lithified plant remains, which has the important distinction of being a combustible material (Thomas, 1992). The geology and stratigraphic descriptions of sediments in the Benue Trough of Nigeria have been generally discussed and widely reviewed by many authors amongst who are Obaje and Abaa (1996), Omoda and Ike (1996). Obaje (2000) observed that although minor lignite and sub-bituminous coal deposit have been reported for the Sokoto Basin of northwestern Nigeria (Kogbe, 1976), the middle Niger (Bida) Basin (Adeleye, 1976) and the Dahoney Embayment (Reyment, 1965), the major coal resources of Nigeria occur within the Benue Trough, (Fig. 2). Sub-bituminous coal is distributed within the coal measures of the Maastrichtian Manu and Nsukka Formations in the lower Benue Trough (Akande *et al*., 1992a) and in the Campanian Maastichtian Gombe Sandstone Formation in the upper Benue Trough. The coal in the lower Benue outcrop mainly in Enugu area where four mines: Onyeama, Okpara, Okaba and Orukpa are being worked.

LABORATORY INVESTIGATION

Laboratory investigations were carried out to measure the permeability of the coal seams at different locations and depth in the mines taking into consideration the discontinuity length and density of the coals. The coal samples were taken from four coal mines presently worked in Nigeria. The study areas are located along Enugu escarpment in the Southeastern Nigeria, which encompasses the Nigerian coalfield. They are Okpara (182.42 m deep) and Onyeama (221.70 m deep) underground coal mines in Enugu State, Okaba (20m deep) and Orukpa (10.20 m deep) surface coal mines in Kogi and Benue States, respectively. Representative coal samples used for discontinuity and permeability measurements were obtained from different locations in the mines. The size of the samples used in the experiment was cuboids measuring about 110×110 mm and cut smooth in the laboratory with the use of Laboratory Rock Cutting Machine. The cut surfaces of these samples were subsequently ground with different sizes of abrasive papers ranging from coarse to fine grids on Laboratory Rock Grinding Machine. These surfaces were then polished using Polishing Machine to allow for examination of fractures in the samples through petrography.

The geometry of the fracture system (fracture frequency, distribution and connectivity) under different scale was determined in accordance with Zhao *et al.* (2002). A square (100×100 mm) was delineated on the plane surface of the coal sample. This square was designated L_0 (initial fractal scale) and the number of the fracture traces cutting through the square were counted and recorded. The next step involved the division of the square into a grid with side length $L_1 = L_0/2$ making 4 squares. The number of the fractures cutting through the 2^2 squares were counted and recorded. The length and the aperture of each crack were also measured with Venier caliper and Brinnel microscope, respectively and recorded. The data obtained were used in the numerical analysis of the discontinuity coefficient of the coals.

DISCONTINUITY LENGTH AND DENSITY

Table 1 shows the result of the mapped fractures on cuboids sample surfaces of the coals investigated. Statistical results confirmed that the value of domain of the fractal dimension, D is $2 \le D \le 7$. This result confirms Zhao *et al*. (2002) conclusion that the crack number in a coal mass is increasing with a decreasing observing scale. The result also shows that the discontinuity index, λ, is 1.7 which suggests that the coal seams are permeable. This observation is similar to Hudson and Priest (1983). In Okaba and Orukpa coals, the fracture densities and fracture lengths are greater than that of Okpara and Onyeama coals. Fracture length and fracture density have a strong influence on permeability according to Wei *et al*. (1995). Hence, the Okpara and Onyeama coals with shorter fracture lengths and lower fracture densities have lower permeabilities than Okaba and Orukpa coals with longer fracture lengths and higher fracture densities. It is also observed that fracture opening (aperture) also affect permeability. The higher the values of these parameters, the greater the permeability, that is, the permeability of the coal depends upon not only on the number of fractures but also on the fracture dimension and orientation. The measured equivalent permeability of the Nigerian coal seams with visible cracks ranged from 10^{-4} to 10^{-3} m s^{-1} and it increased with increasing number of cracks. Permeability is closely related to porosity as indicated in Figure 3. The porosities of the coals are 2.46, 1.78, 1.90 and 2.66% for Okaba, Okpara, Onyeama and Orukpa coals, respectively with corresponding permeabilities of 6.83E-3, 3.13E-4, 4.85E-4 and 6.48E-3 m s^{-1}. Figure 3 is the relations between porosity, fracture density and permeability of the coals. The greater the porosity and fracture density, the greater the value of the permeability.

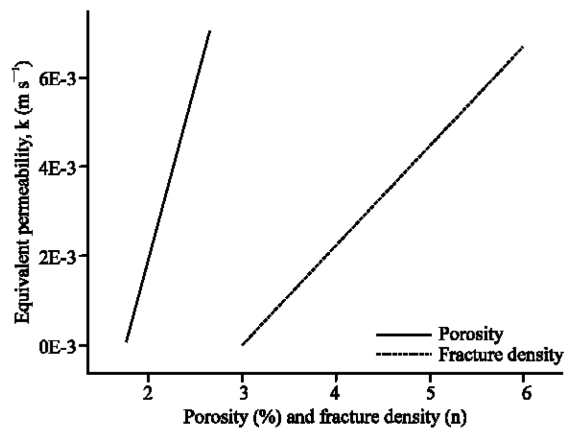

Fig. 3: Relations between porosity, fracture density and permeability of the coals

Table 1: Mapped fractures on cuboids sample surfaces of the coal samples

			Crack (100×100 mm surface area)			
Sample location	Sample identification	Crack density	Mean aperture (mm)	Mean length, l (mm)	Mean spacing, b (mm)	Equivalent permeability, k (m s^{-1})
Okaba	OK-M-A	4	0.5825	50.00	22.00	7.18E-3
	OK-M-B	5	0.4360	70.00	18.00	3.83E-3
	OK-M-C	7	0.5228	55.43	12.14	9.48E-3
Okpara	OKP-M-D	3	0.2233	46.67	48.00	1.80E-4
	OKP-M-E	2	0.2700	42.00	52.50	3.04E-4
	OKP-M-F	4	0.2650	56.50	34.75	4.55E-4
Onyeama	ON-M-G	4	0.2950	45.00	47.25	4.62E-4
	ON-M-H	3	0.2233	46.67	50.00	1.72E-4
	ON-M-I	6	0.2600	47.00	19.33	8.21E-4
Orukpa	OR-M-J	5	0.5200	62.40	22.00	5.17E-3
	OR-M-K	6	0.5333	58.67	19.33	6.24E-3
	OR-M-L	7	0.5571	60.00	16.20	8.03E-3

CONCLUSION

The research has been able to show that permeability can be considered as an intrinsic property of rock capable of being affected by the rock discontinuities. The fracture form and number in a coal mass are important factors affecting permeability. The geotechnical information is expected to play an important role in the implementation of engineering practice and management of water infusion in coal seam mining in Nigeria.

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