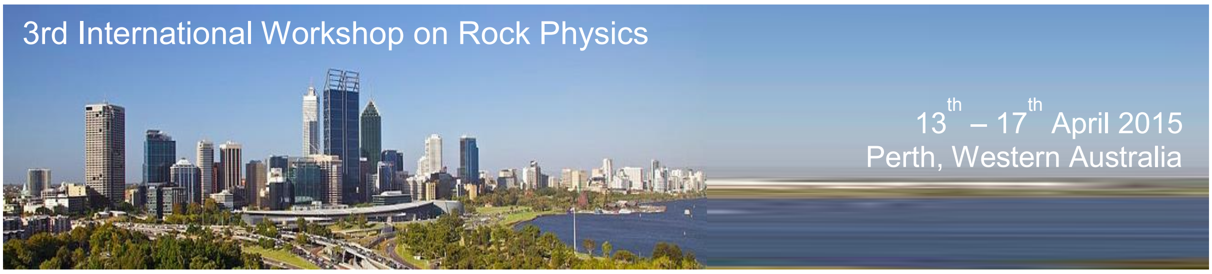

Electrical tortuosity, Kozeny's factor and cementation factor modelled for chalk

Konstantina Katika[a] and Ida L. Fabricius[b].

[a,b]*Department of Civil Engineering, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark; koka@byg.dtu.dk.*

Summary

Based on the electrical properties of chalk from the North Sea and Stevns Klint and on published data, we explore how klinkenberg corrected permeability from experimental data relate to porosity and electrical resistivity. In the current study we use electrical conductivity data of partially water saturated core plugs to determine the cementation factor, m. This value differs from the one Archie used to describe his equation and best describes the formation factor based on experimental data. Based on this m, we determine the formation factor, F, and the tortuosity, τ. We use this value of τ, to calculate permeability based on electrical resistivity data. We also calculate the permeability based on a simple porosity model. Finally, we redefine Kozeny's factor, c, using Carman's model based on tortuosity and the model based on porosity. This resulted in a third modelled permeability, which describes the experimental data in high accuracy.

Introduction

Kozeny's equation relates the porosity, ϕ, the permeability, k, and the specific surface of the pore space of the rock, S, as follows (Kozeny, 1927):

$$k = c\frac{\phi}{S^2}\ . \tag{1}$$

Based on the Carman's model for the tortuous path of flow (Carman, 1937), the tortuosity of a rock plug is a property related to the length of the sample and the apparent flow length of the current through the porous medium and can be described from the actual flow path, L_α, and the length of the sample, L. Carman, used Kozeny's equation and replaced the factor c, by the following expression:

$$c_R = \frac{1}{k_0(L_\alpha/L)^2}\ . \tag{2}$$

where k_0 is a dimensionless factor Carman observed to be close to 2 and $(L_\alpha/L)^2$ is commonly referred as tortuosity, τ (Dullien, F.A.L., 1979).

Mortensen et. al., 2008, created a simple model that connects Kozeny's factor with porosity for chalk:

$$c_\phi = \left(4\cos\left(\frac{1}{3}arccos\left(\phi\frac{8^3}{\pi^3} - 1\right) + \frac{4}{3}\pi\right) + 4\right)^{-1}\ . \tag{3}$$

A few authors have proposed empirical models for tortuosity using electrical conductivity data (eg. Wyllie and Spangler, 1952). Those tortuosity models are based on the resistivity formation factor, F, and porosity of the material, ϕ. In the current study the following equation was used to determine the tortuosity (Cornell and Katz, 1953):

$$\tau = F\,\phi. \tag{4}$$

F is the resistivity formation factor and is defined as the ratio between the resistivity of the saturating fluid, R_w, and the resistivity of the fully brine saturated rock, R_0:

$$F = R_0/R_w\,. \tag{5}$$

In Archie's equation (Archie, 1942) the cementation factor is a factor related to the pore geometry and may be used to determine the saturation in oil reservoirs. It is often assumed equal to 2 for most types of carbonates, but this value may lead to an overestimation of the fluid saturation in chalk (Olsen et. al., 2008). The cementation factor, m, is related to porosity, ϕ, and the formation factor, F, through the following equation:

$$F = 1/(\phi^m). \tag{6}$$

Because the core plugs under investigation were only partially saturated, the following relationship between the degree of water saturation, S_w, ϕ, R_w, and the resistivity of a partially saturated rock, R_t, was used to calculate m:

$$S_w^n = \frac{1}{\phi^m}\frac{R_w}{R_t}\,. \tag{7}$$

n is the saturation exponent and is assumed equal to m according to Olsen et. al., 2008.

We used equation (7) to determine the cementation factor and the formation factor of the partially saturated plugs using equation (6). Using this F, we calculated τ from equation (4). Additionally we calculated c_ϕ based on our porosity data and equation (3). We were able to redefine Kozeny's and Carman's model for chalk from the North Sea and Stevns Klint using the geometric average of c_R and $1/\tau$ through the following equation:

$$k = \sqrt{\frac{c_\phi}{\tau}}\,\frac{\phi}{S^2}\,. \tag{9}$$

Methods

The porosity of the chalk samples was obtained from a helium porosimeter, and the dry density of the core plugs was obtained from dry weight. The volume of the samples was measured by mercury immersion. The content of carbonate in the solid phase was obtained from titration. The specific surface for each sample was obtained with the nitrogen adsorption (BET) method (Brunauer et al., 1938). Klinkenberg permeability was also obtained for those samples. The core plugs were saturated under vacuum conditions with a variety of brines and the electrical resistance of the samples was measured at unconfined conditions under an axial stress level of 2 MPa. The water resistivity was measured with a water resistivity meter. All petrophysical data are listed in Table 1. Data used from the literature can be found in Megawati, 2008, Olsen et. al., 2008 and Fabricius et. al., 2008.

Results

Figure 1 shows the correlation of *F*, *k*, BET specific surface, vs. porosity for all samples. Figure 1c illustrates how *m* equal to 2 may lead to false estimation of the formation factor, especially in small porosities.

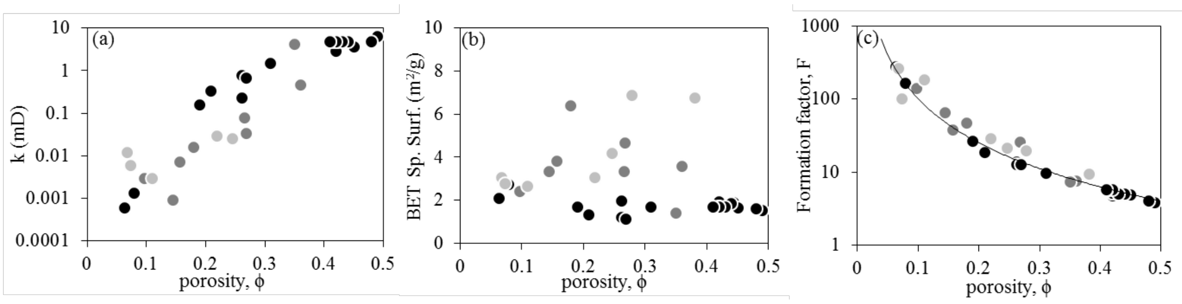

Figure 1. Klinkenberg corrected permeability, k, BET specific surface, and Formation factor, vs. porosity for all samples. In Figure 1c, the solid black line corresponds to values of F, for m equal to 2 based on equation (7).The black dots represent chalk with carbonate content (CC) > 95 %, dark gray dots represent chalk with 95% > CC > 80 % and light gray is for CC < 80%.

By using equation (1) and information on the specific surface and porosity of the samples from Table 1 we calculated twice the permeability based on Kozeny's equation. Once using the c-factor from equation (3) based on porosity and again using the c-factor from equation (2) based on electrical conductivity data; we call them k_ϕ and k_R respectively. Both modelled permeabilities are shown in Figure 2 vs. the measured klinkenberg corrected permeability. In this figure we can see that Carman's model based on tortuosity and Mortensen et. al., 2008, model based on porosity predict similar permeabilities for chalk. Both k_ϕ and k_R seem to overestimate the permeability for the low range of values and underestimate it in high. In the same figure we present the modeled permeability based on equation (9) and the geometric average of c_ϕ and $1/\tau$ that best describes the experimental data on chalk (Figure 2c).

Table 1. Physical properties of the studied samples.

sample	porosity	ρ (g/cm^3)	kl. Perm, mD	Carb. Con., %	BET, m^2/g	Sw	Rw, ohm m	F	m
N-3X-T1	0.35	2.70	4.10	94.8	1.40	0.99	1.55	7.25	1.89
ST-T1	0.44	2.71	4.75	97	1.86	0.97	1.15	4.98	1.96
ST-12	0.42	2.71	4.75	99	1.70	0.94	0.50	4.80	1.82
ST-13	0.42	2.70	4.75	99	1.70	0.94	0.52	5.08	1.88
ST-15	0.41	2.71	4.75	99	1.70	0.94	0.80	5.45	1.91
ST-16	0.42	2.71	4.75	99	1.70	0.94	0.76	5.09	1.89
ST-19	0.43	2.70	4.75	99	1.70	0.95	0.66	4.94	1.90
ST-21	0.42	2.71	4.75	99	1.70	0.98	0.68	5.74	2.01
ST-22	0.41	2.71	4.75	99	1.70	0.96	0.44	5.54	1.92
ST-23	0.41	2.70	4.75	99	1.70	0.96	0.46	5.74	1.96
M-1X 12H	0.26	2.71	0.82	98	0.97	1.00	4.24	15.14	2.00
M-1X 13H	0.25	2.71	0.68	98	0.97	1.00	4.68	16.71	2.01
M-1X 6H	0.28	2.71	1.35	99	1.00	0.98	4.21	13.87	2.05
M-1X 8H	0.26	2.71	1.02	99	1.03	0.99	4.35	14.92	2.02
M-1X 10H	0.26	2.71	1.05	99	0.97	0.99	4.59	15.73	2.03

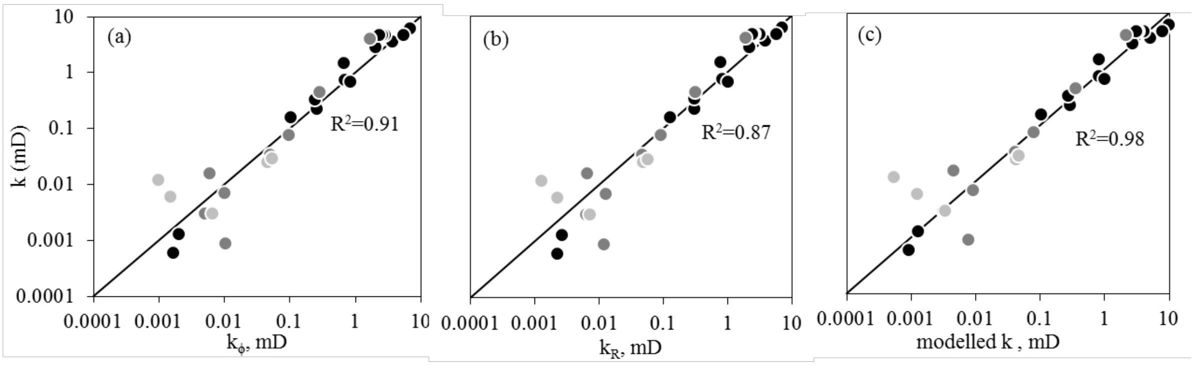

Figure 2. Measured vs. modelled permeability. Modelled permeability in Figure 2c was calculated from the geometric average of c_ϕ and $1/\tau$. The black dots represent chalk with high carbonate content and the ligher the gray shade, the less the amount of carbonate based on figure 1.

Conclusions

Both permeabilities modelled from porosity and resistivity data, k_ϕ and k_R, underestimate the permeability in high values while overestimate it for low values of *k*. Permeability modelled from the geometric average of Kozeny's factor, as calculated from porosity data, and tortuosity from electrical resistivity data, best describes the permeability of our experimental and published data from the North Sea and Stevns Klint in a big range of measured permeabilities. A correction in the cementation factor is required for core plugs that are not fully water saturated. The correct value of *m* can be used to calculate *F* that is later used to model permeability based on resistivity and porosity data.

References

Archie, G. E., 1942, The electrical resistivity log as an aid to determining some reservoir characteristics: Transactions of the American Institute of Mining and Metallurgical Engineers, 146, 54–62.

Brunauer, S., Emmett, P. H., and Teller, E., 1938, Adsorption of gases in multimolecular layers: Journal of the American Chemical Society, 60(2), 309-319.

Carman P.C., 1937, Fluid Flow Through Granular Beds, Transt. Chem. Eng. London, 15, 155-166.

Cornell, D. and Katz D.L., 1953, Flow of Gases Through Consolidated Porous Media, Ind. And Eng. Chem. 45, 2145.

Dullien, F.A.L., 1979. Porous Media, Fluid Transport and Pore Structure. Academic Press, New York.

Fabricius, I. L., Gommesen, L., Krogsbøll, A., and Olsen, D., 2008, Chalk porosity and sonic velocity versus burial depth: Influence of fluid pressure, hydrocarbons, and mineralogy: AAPG Bulletin, 92(2), 201-223.

Kozeny, J., 1927, Über kapillare Leitung des Wassers im Boden: Sitzungsberichte der Wiener Akademie der Wissenschaften, 136, 271–306.

Megawati, 2008, Electrical properties of brine saturated rocks, Master thesis, Department of Environment and Resources, Technical University of Denmark.

Mortensen, J., F. Engstrøm, and I. Lind, 1998, The relation among porosity, permeability, and specific surface of chalk from Gorm field, Danish North Sea: SPE Reservoir Evaluation & Engineering, 3, 245–251.

Olsen, C., Hongdul, T., and Fabricius, I. L., 2008c, Prediction of Archie's cementation factor from porosity and permeability through specific surface: Geophysics, 73(2), E81-E87.

Wyllie, M. R. J., and Spangler, 1952, Application or electrical resistivity measurements to problems of fluid flow in porous media: Bull. Amer. Assoc. Petr. Geologists, 36, 359-403.