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Electrochemical Effects on Rock Drilling

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A strong correlation has been found between drilling performance in rocks and the ζ-potential at the rock/drilling-fluid interface. Maximum drilling performance improvement was observed upon drilling in Westerly granite and Sioux quartzite with drilling fluid containing inorganic salts at concentrations which produce zero ζ-potentials at the drilling fluid/rock interface.

ζ-potentials were measured using a commercial zeta reader. At the rock zero point of charge (ZPC), the ζ-potential is also zero. ZPC concentrations for Sioux quartzite in $AlCl_3$, $ZrCl_4$, $CaCl_2$, and NaCl solutions were determined to be 6.8×10^{-7}, 1.4×10^{-6}, 1.6×10^{-2}, and 2.0×10^{-1} mol/L respectively; while ZPC concentrations for the quartz, feldspar, and biotite components of Westerly granite in $AlCl_3$ were determined to be 7.0×10^{-7}, 2.0×10^{-6}, and 3.0×10^{-6} mol/L, respectively. Solution pH ranged between 5.3 and 6.0.

Drilling tests were conducted on Sioux quartzite with $AlCl_3$, $ZrCl_4$, $CaCl_2$, and NaCl solution concentrations and on Westerly granite with $AlCl_3$ solution concentrations below, at, and above their respective ZPC concentrations using a 16-mm diamond impregnated coring bit. Rotational speed and thrust were 100 rpm and 150 kg, respectively. Each test consisted of drilling as many holes in a 15-cm rock cube as was necessary to progress from a "sharp" state (4.5 mm/min) to a "dull" state (2.0 mm/min).

Plots of penetration improvement versus additive solution concentration, as exemplified by Fig. 1, showed that the greatest penetration improvement was obtained at the ZPC concentration of the additive. (Penetration improvement is the percent change in total penetration for additive drilling over that for drilling with distilled, deionized water obtained upon going from a "sharp" to a "dull" bit state). A smaller peak in performance, at 10^{-5} mol/L, is not clearly understood at this time.

Penetration improvements of 104, 96, 97, and 115 pct were obtained with $AlCl_3$, $ZrCl_4$, $CaCl_2$, and NaCl ZPC concentration solutions, respectively. Increased penetration is ordinarily achieved by increasing thrust or rotational speed of the drill at the expense of bit life. However, drilling of Sioux quartzite with the respective ZPC concentrations of $AlCl_3$, $ZrCl_4$, $CaCl_2$, and NaCl also resulted in maximum bit life extensions (percent increase in time for progressing from the "sharp" to "dull" bit state) of 99, 68, 73, and 76 pct, respectively. For Westerly granite, maximum penetration improvements for 155 and 165 pct and bit life extensions of 109 and 136 pct were obtained at $AlCl_3$ concentrations of 7.0×10^{-7} and 2.0×10^{-6} mol/L, which correspond to the respective ZPC concentrations of the major mineral components, quartz and feldspar.

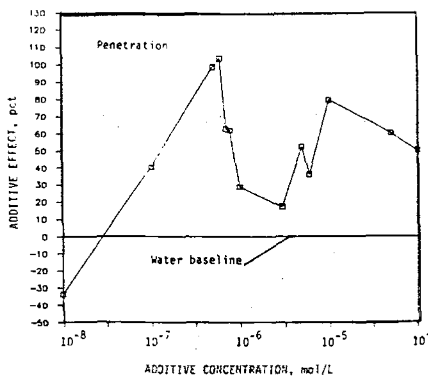

Figure 1. Sioux quartzite drilling results for $AlCl_3$ solutions

These drilling results indicate that ZPC-concentration solutions condition the mineral surfaces of the rock in such a way to facilitate rock breakage. A model based on correlations between the electrical double layer (EDL) profiled in the rock interfacial layer and Lippmann's electrocapillarity (LEC) is proposed to account for the observed phenomena. Figures 2 and 3 give theoretical LEC and EDL curves for a solid in an aqueous medium with salt addition. With no salt addition, the effective thickness of the diffuse double layer is large (curve A, Fig. 3) and the ζ-potential is highly negative. The corresponding rock surface condition is represented by point A, Fig. 2. In dilute salt solutions, the ζ-potential is less negative (curve B, Fig. 3) and the rock surface condition is represented by point B, Fig. 2. With large salt concentrations, the double layer is compressed since becomes large and the rock surface condition is represented by point C in the LEC curve. Charge reversal in the EDL occurs at relatively high electrolyte ionic strengths. Curve C, Fig. 3, represents the corresponding positive ζ-potential profile. At an intermediate salt concentration where the intrinsic rock surface charge is exactly balanced by the charge on the outer Helmholtz plane, the potential profile is represented by curve z, the corresponding rock surface condition at the ZPC. Thus at the ZPC concentration, the rock interfacial tension is maximized and drilling enhancement is also maximized, possibly because the rock is weaker in tension than in compression.

It can be shown that rock interfacial tension is a monotonal function of rock stress. Equating the work done to create new surface to the stress energy, one (1) obtains

$$\gamma = \int_0^\infty \frac{\theta}{2}\, dx \qquad [1]$$

where γ is the surface energy, θ is the stress (applied force per unit area), and x is the separation distance. For ionic lattices one obtains

$$\gamma = Y \frac{r_0}{\Pi^2} \qquad [2]$$

where Y is the rock elastic constant (Young's Modulus) and r_0 is the interatomic distance. Although rocks are more complex than simple ionic lattices, a maximum in the rock surface tension, γ, will still result in a maximum chemically induced stress, θ_c.

Drilling penetration rate is proportional to the total stress applied to the rock, θ_t, which is comprised of the mechanical stress applied by the drill, θ_m, plus the chemically induced stress, θ_c, i.e. $\theta_t = \theta_m + \theta_c$. An increase in θ_c induced by ZPC concentrations of chemical additives will give a proportional increase in θ_c, and hence in the penetration rate. On either side of the ZPC, the interfacial tension is reduced, θ_c is reduced and the magnitude of the penetration improvement decreases as confirmed by the data in figure 1 where departure from the $AlCl_3$ ZPC concentration results in less penetration improvement.

Surface tension reducers are efficient (2) in chemical crack propagation. However, when drilling is regarded as activated cracking that involves the catastrophic growth of microcracks into more destructive ones, it is then possible that the interfacial tension, or surface energy, must first go up to a critical tension before a rock fragment separates with a lowering of interfacial tension. This distinction between the kinetic process of drilling and the thermodynamic state of crack formation can explain why an increase in interfacial tension can facilitate drilling rate by lowering the energy barrier for rock fragmentation.

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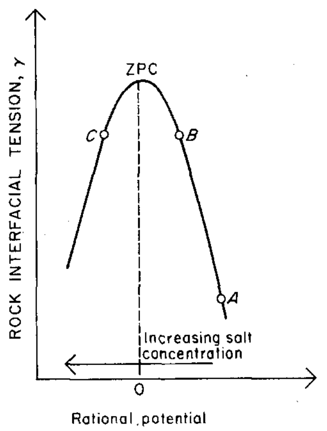

Figure 2. Theoretical LEC Plot

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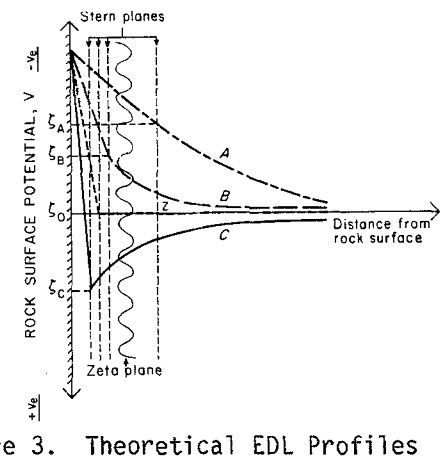

Figure 3. Theoretical EDL Profiles