

Letters

Influence of chemomechanically active fluids on diamond wear during hard rock drilling

The use of additives to the fluids circulated during diamond drilling of hard rocks has been studied for over three decades [1–10], but the mechanisms by which such additions influence drilling behaviour are not clearly understood. Indeed, the results of the various studies sometimes appear to be in conflict.

Recently, Westwood *et al.* [5–7, 11] suggested that certain surface-active additives can alter the mechanical properties of the surface layer of a rock, and thereby influence the behaviour of a bit drilling into that rock by means of the chemo-mechanical effect (CME). They noted that one useful criterion for optimizing such an influence was that the environment should reduce the ζ -potential* of the rock surface to zero [5]. They observed that when $\zeta \approx 0$ the rate of drilling (\dot{D}) after 200 sec, $\dot{D}(200)$, was maximized; the value of this parameter was sometimes several times greater than that produced in tests under water, for which $\zeta \neq 0$. It was not fully appreciated in these earlier studies, however, just how sensitive $\dot{D}(200)$ was to bit load, rotational speed, and other factors that influence diamond wear. Thus, although measurements of $\dot{D}(200)$ are certainly a convenient laboratory-scale indicator of the potential value of CME's in drilling, when scaling up to field conditions, new factors become important, and these can sometimes be overriding. Moreover, it has long been known that surface active additives can affect bit life [1, 3, 4, 11]. But, the mechanisms by which they do so have not been addressed in any detail.

According to current understanding, there appear to be several mechanisms by which an additive could affect the rate of penetration of

a diamond-impregnated bit into a hard rock. Two speculative mechanisms of relevance to chemo-mechanically active additives are: (I) as proposed earlier [5–7, 11], the additive could facilitate rock fracture and disintegration via changes in rock surficial mechanical properties; and (II) by influencing the hardness and frictional behaviour of the rock's surface, the additive could change the diamond-rock interaction, reduce the rate of diamond wear[†], and thereby enhance the instantaneous penetration rate of the bit at any particular time (e.g. 200 sec) after starting a hole with a freshly dressed bit.

In this contribution, data are presented that support the latter possibility, namely that chemo-mechanically active fluids reduce the wear rate of diamonds in diamond-coring bits, so enhance drilling rates, primarily via their action on those properties of the rock that control its frictional behaviour, e.g. hardness. The implications of this conclusion are discussed with especial regard to recent observations and comments by Cooper and Berlie [9] and Engelman *et al.* [10].

The precision drill used in this work was that described previously [6, 7, 11], but the drilling system was modified by replacing the puddling conditions of previous studies with a pressurized fluid-flow system which permitted through-the-bit flushing. Tap water was used as the circulating fluid, and dodecyltrimethyl ammonium bromide (DTAB) was the additive. Two reservoirs permitted rapid switching between water and the active fluid.

The data to be presented was obtained by drilling into Westerly granite with 0.6 cm and 0.95 cm o.d. diamond-impregnated coring bits rotating at 2000 and 5000 r.p.m. under thrusts of 40 N and 60 N, respectively. The fluid flow rate was $\sim 100 \text{ cm}^3 \text{ min}^{-1}$ in both cases. These drilling conditions were such that redressing or "sharpening"

* For a review of the concept of ζ -potential, see [12]. Briefly, it is a measure of the charge on the surface of a solid when it is immersed in an electrolyte.

† Note that a reduction in the rate of bit wear by direct action on the diamonds is not likely. Various arguments have been presented against this view [11], but perhaps the most convincing of these is based on observations that environmental compositions that beneficially influence bit penetration into one substance can be detrimental when drilling another [11]. It is concluded, then, that this possibility cannot provide the basis for any generic explanation for the effects that are of interest in this paper.

of these bits did *not* occur during the test. Bits were redressed at appropriate times (see below) by drilling a few shallow holes into a silicon carbide dressing stick.

Two simple test procedures can be used to assess which of the two possible mechanisms mentioned previously is more likely to be responsible for chemomechanical effects in drilling rocks with diamond bits. The first procedure involves drilling the rock using a water environment for some small fraction of the bit life, then changing the cutting environment to the more active fluid without altering any other experimental variable. If rock disintegration efficiency (mechanism I) is the parameter most affected by chemomechanically active fluids – such as a 10^{-3} mol l⁻¹ DTAB solution which produces $\zeta = 0$ for Westerly granite [7] – then, a prompt change should be apparent in the slope of a plot of penetration distance versus time. Fig. 1a reveals, however, that when the freshly dressed 0.6 cm o.d. coring bit is drilled into Westerly granite, no such change in slope occurs, even when the cycle of fluid change is repeated several times.

In the second test, freshly dressed bits are drilled into the rock until they wear out using: (1) water, and (2) the 10^{-3} mol l⁻¹ DTAB solution. Then, the penetration versus time curves are compared. If the active fluid does reduce diamond wear, then the penetration versus time curve obtained using this fluid should lie above that obtained using water. The curves in Fig. 1b show this to be the case.*

The results from these two types of tests†, when considered together, lead us to conclude that when rocks are drilled with diamond bits, chemomechanically active additives function primarily to reduce wear of the diamonds so that they cut faster for longer‡.

One implication of this conclusion, also pointed out by Cooper and Berlie [9] (but for different reasons that will be discussed later), is that to properly discern the influence of chemomechan-

ically active fluids on penetration rates, the behaviour of the diamond bits should be followed over significant portions of their lives. Otherwise significant environmental effects are not likely to be observed. For example, values of the rate of drilling after 25 sec taken from Fig. 1b would be essentially the same for both environments.

This point is especially relevant for drilling in the field with bits designed to drill several hundred feet with the same diamonds. These bits will not readily reveal environmentally-induced differences in penetration rates from data that are averaged over distances of a few feet or so. That is, if a comparison is made of penetration rates measured over a small fraction (i.e., <5%) of the diamond life in active versus passive fluids, the chemomechanical influence probably will be too small to be detected.

This may explain the absence of observable chemomechanical effects in the work of Cooper and Berlie [9] who drilled marble, and of Engelmann *et al.* [10] who drilled soft, non-abrasive minerals such as microcline, marble, and serpentine. Presumably, the lives of the diamonds in the bits they used were sufficiently long in comparison to the distances drilled that little or no wear occurred. Thus, no chemomechanical influence was revealed, whether it existed or not. Environmentally-induced reductions in mean penetration rates of such bits will not be apparent unless they are averaged over distances comparable to the life of the diamonds.

On the other hand, when Engelmann *et al.* [10] drilled into quartz crystals, in which the life of the diamonds in their 0.31 cm o.d. bit was presumably quite short, fluids producing $\zeta = 0$ on that mineral did indeed provide marked increases in the average drilling rate.

Of course, the comparative drilling of holes 10 cm or more in diameter and many metres in depth into hard rocks is extremely expensive, and this could serve as a negative incentive to the development of optimized cutting fluids for field-

* Incidentally, under the experimental conditions employed to derive the data of Fig. 1b, $D(200)$ is about three times greater in the active fluid than in water, confirming earlier data [6].

† Essentially similar results, to be published later [13], have also been obtained using bits of various sizes (from 0.6 cm o.d. to ~ 6.0 cm o.d.) and types (surface set and diamond-impregnated coring bits), drilling into a variety of rocks (including sandstones and porphyrys) under thrusts ranging from 18 to 28 000 N, bit rotational speeds between 50 and 5000 r.p.m., and fluid flow rates from zero (puddling conditions) up to 601 min⁻¹.

‡ It should be noted, however, that this conclusion may not be applicable to other types of drilling (such as rotary-percussive) or to other materials whose drilling characteristics are different from those of hard rocks.

scale use. Fortunately, an analytical approach can be used to reduce this potential expense. Tsoutrelis [14], and later the present authors [15], observed that diamond bit penetration rate, $\dot{D}(t)$, is approximately linearly dependent on the distance drilled, $D(t)$. Specifically,

$$\dot{D}(t) = \dot{D}(0) - wD(t) \quad (1)$$

where t is time, $\dot{D}(0)$ is the drilling rate at $t = 0$, and w is a measure of the rate of wear of the diamonds – namely the slope of a plot of $\dot{D}(t)$ versus $D(t)$. This equation permits an operator to estimate the life of the bit diamonds, L , without having to drill until the diamonds are worn out. By measuring $\dot{D}(0)$ and estimating w from measurements of $\dot{D}(t)$ over the first 5 to 10% of the bit life, L can be calculated immediately from the relation

$$L = \dot{D}(0)/w \quad (2)$$

Data from rock drilling experiments analysed according to Equations 1 and 2 are quite revealing. In Fig. 2, for instance, the data indicate that w for a 0.95 cm diamond-impregnated coring bit (drilling into Westerly granite at 5000 r.p.m. under a thrust of 60 N) is approximately four times less when a $10^{-3} \text{ mol l}^{-1}$ DTAB solution is used than when water is used. Also, $\dot{D}(0)$ is not significantly different for the two fluids, confirming the data in Fig. 1b. Consequently, L is about four times greater in the active environment than in water.

Cooper and Berlie [9] also reported the results of their studies on the influence of n -alcohols on diamond-impregnated-bit drilling of a Bohus granite, via plots similar to those in Fig. 2. They observed that, when 1 cm o.d. bits were used under their testing conditions, all of the alcohols (except methanol) significantly *increased* instantaneous drilling rates. They concluded, in part, that “when measurements of performance are made over a significant fraction of the bit life, differences in average rate of penetration are likely to be found, but they can just as well be attributed to a change in the rate of wear of the bit as to any hardening or softening of the rock being drilled.” Now, we certainly concur that the *particular* effects which Cooper and Berlie [9] observed when drilling into granite (their Fig. 3) probably are *not* attributable to any chemo-mechanical hardening or softening of the rock, but it is our view that when the *drilling conditions*

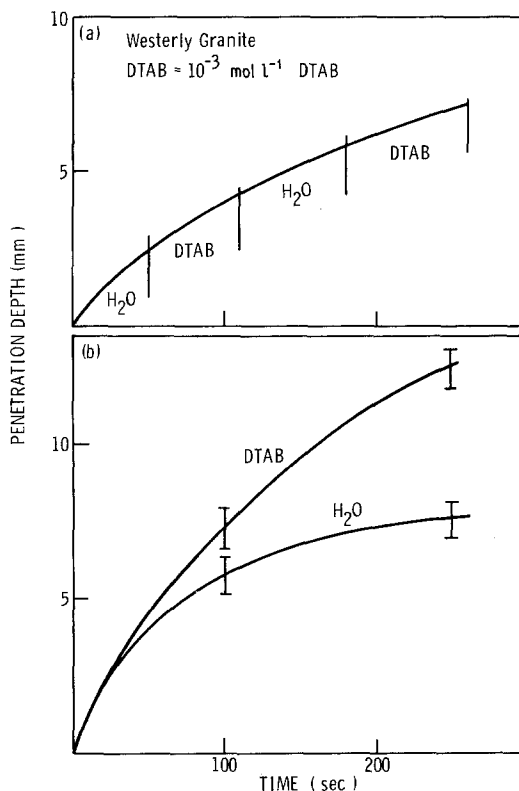


Figure 1 (a) Penetration versus time data for a 0.6 cm o.d. diamond-impregnated bit rotating at 2000 r.p.m. under a thrust of 40 N into Westerly granite. Note that on changing from water to a $10^{-3} \text{ mol l}^{-1}$ DTAB environment, no significant change in slope occurs. (b) Penetration versus time curves for freshly redressed bits drilling into Westerly granite under water or $10^{-3} \text{ mol l}^{-1}$ DTAB.

are appropriate, effects directly attributable to environmentally-induced variations in the hardness of the rock can be observed, and are significant (see Fig. 2). We now wish to amplify and clarify this point.

One obvious difference between the results of Cooper and Berlie [9] for water versus n -alcohol environments (their Fig. 3) and those reported here for water versus a $10^{-3} \text{ mol l}^{-1}$ DTAB environment (Fig. 2) is that, in the present work, the penetration rate, $\dot{D}(t)$, was not immediately influenced by changing from water to the more active environment. In contrast, Cooper and Berlie's data reveal that changing the circulating fluid from water to any of the alcohols (except methanol) produced an immediate and irregular *increase* in penetration rate, behaviour which suggests to us that the n -alcohols induced a re-

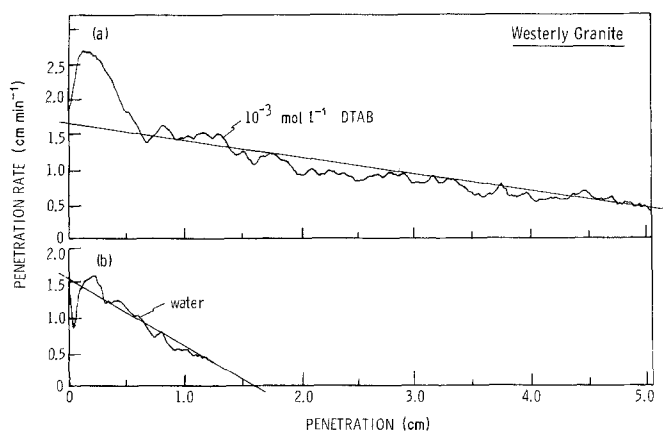


Figure 2 Penetration rate versus penetration distance data for Westerly granite drilled with a 0.95 cm o.d. diamond-impregnated core bit under (a) 10^{-3} M aqueous DTAB and (b) water. The thrust was 60 N, and the bit rotation speed 5000 r.p.m.

dressing of their bits. In other words, some property of the alcohols caused the *matrix* of the bit to be worn away more rapidly than when water was used, and fresh sharp diamonds were continually exposed. Since wear of the bit under such conditions is no longer controlled by the wear of the diamonds *per se*, any chemomechanical influence of the alcohols on this factor would be masked. Thus, under the conditions used by Cooper and Berlie, *n*-alcohols certainly beneficially influenced drilling rate, probably by introducing repeated or continuous bit redressing, i.e., increasing the availability of sharp diamonds. And although penetration rates were enhanced by the *n*-alcohols, it is not unlikely that the total life of their impregnated bits would actually be shortened. In contrast, the present experiments were conducted under conditions in which chemomechanically active fluids influenced the rate of wear of, essentially, a constant number of exposed diamonds. Redressing did not occur. Clearly, the two testing conditions were different.

Although it is not clear why Cooper and Berlie's bits shifted to a self-sharpening mode in the alcohols, one possibility is that such behaviour might be associated with the much lower heat transfer coefficients of these environments, which can be 3 to 20 times less than that of water.* Another possibility is lower chip removal

efficiency,† which could also be > 20 times less than that for water under the constant pressure flow conditions used by Cooper and Berlie.‡

Because of their different testing conditions (light loads, shallow holes, puddling of the fluid), neither heat transfer nor chip removal were critical factors in the earlier studies on the drilling of Westerly granite in *n*-alcohols reported by Westwood *et al.* [5-7]. Consequently, in those studies, a true chemomechanical influence of the *n*-alcohols was more clearly revealed. And in this study, although relatively high loads were used, and initial penetration rates on the order of cm min^{-1} were achieved, because additions of small concentrations of surfactants do *not* significantly alter the heat transfer or chip removal characteristics of water, we propose that the observed reductions in diamond wear can be properly attributed to chemomechanical effects.

Finally, it is appropriate to consider the manner in which chemomechanically active fluids could influence diamond wear. Our present view is that, when $\zeta = 0$, the hardness of the rock surface is maximized, and so the coefficient of ploughing friction between the individual diamonds and the rock is at a minimum [20]. Consequently, the heat *generated* locally is also minimal, and the diamonds run cooler. Since temperature is considered to be a prime factor in determining the

* These values are computed by inserting known values of density, viscosity, and heat conductivity of the alcohols [16] into standard heat transfer equations for laminar flow [17].

† These values were computed by inserting known values of density and viscosity for the alcohols into Stoke's Law for the slip velocity of particles in a fluid [18].

‡ Incidentally, a related effect was observed during grinding studies of Al_2O_3 under *n*-alcohols [19]. In that work, hydrodynamic lubrication of the alumina workpiece by the viscous (cf. water) alcohols masked observation of any chemomechanical effect.

wear of diamond bits [3], they will wear less during drilling in solutions which produce $\zeta = 0$. As a result, they will stay sharp longer, enhancing both penetration rates and penetration.

The bit-wear reduction mechanism will be valid only if the diamonds "fail" due to blunting of their points by wear – not if they fail by massive fracture, which could result in resharping. It should also be emphasized that the mechanism suggested does not depend on any improved cooling capacity of the water by the additive, as has been suggested previously [3], because the heat transfer coefficients of water are not significantly influenced by the small concentrations of surfactants used. The essence of the present hypothesis is that chemomechanically active media actually reduce the *amount* of heat generated at the rock-bit interface.

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J. J. MILLS
A. R. C. WESTWOOD
Martin Marietta Laboratories
Baltimore
Maryland, USA

Comments on "Influence of chemomechanically active fluids on diamond wear during hard rock drilling"

We were very pleased to hear of the work of Mills and Westwood, and to learn that they have confirmed the findings reported by us in an earlier letter to this journal [1]. We should like to make a few brief comments in further clarification of our views.

The effect of the environment on the rate of wear of the diamonds may now be accepted as an important, and sometimes overriding effect. How this occurs is, in our view, still not clear. In all probability, it is related to the heat generated at the cutting points by friction between rock and diamond. Mills and Westwood argue that the quantity of heat generated, and hence the wear of the diamonds, depends upon the coefficient of ploughing friction between the