EFFECT OF DRILLING FLUID COMPOSITION ON PENETRATION RATE

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ABSTRACT

A fully instrumented and bench-mounted diamond drilling machine, purpose designed and built, has been used for investigating the effect of aqueous solutions of various chemical compounds when used as drilling fluids. The rocks investigated were andesite, basalt and granite, the chemical compounds were alkylamines, with various hydrocarbon chain lengths, aluminium chloride and dinone.

Rotation speed seems to be one of the major factors affecting the emergence of mechanochemical effects as the results obtained with aluminium chloride clearly indicate. Penetration rate is either unaffected or enhanced by the presence of certain compounds, such as aluminium chloride. On the other hand, penetration rate diminishes when the drilling fluid contains diozone and exhibits an apparently unpredictable behaviour with alkylamine solutions, although it appears that an increase in hydrocarbon chain length usually equates to an increase in penetration rate. Rock texture seems to have a pronounced effect on test repeatability. With hexadecylamine acetate solutions in concentrations ranging from $10^{-5}$ to $5 \cdot 10^{-4}$ mol cm$^{-3}$ and $41.88$ rad s$^{-1}$ rotation speed, 86% increments in penetration rate of andesite were observed, with respect to water, whereas penetration rate decreased in basalt by as much as 60% when a diozone solution was used as drilling fluid. An interpretation of the observed effects is proposed in the light of current knowledge of solid state physics and physical chemistry.

INTRODUCTION

The changes produced in the natural mechanical properties of rocks by the physico-chemical environment are defined "chemo-mechanical effects". Since 1931, when the Russian physico-chemist Rehbinder published the first results of his investigations (Rehbinder, 1931), numerous researchers have been engaged in the study of these chemo-mechanical phenomena. According to Rehbinder, the changes in scratchability of rocks observed after contact with aqueous solutions of certain chemical compounds was to be ascribed to the adsorption of their molecules on the solid surfaces. The physico-chemical
model proposed by Rehbinzer to explain the effects of this adsorption was based on the hypothesis that the observed effects were related to variations of surface energy induced in the solid by this adsorption.

Investigations carried out over last quarter of a century (Westwood et al., 1974 and 1980; Mills and Westwood, 1978) led to the development of a model that takes into account the modifications of the microplastic behaviour of crystalline materials produced by chemical additives as well as the influence of the physico-chemical and operating parameters of the different testing devices used. The mechanisms proposed by the above authors contributed to elucidating several aspects of the chemomechanical phenomena. However, as Westwood et al. (1980) indicated, it is widely acknowledged that chemomechanical phenomena depend on a number of basic mechanisms but so far no satisfactory information is available for any of them.

Hence, the resort to experimental investigation - aimed at identifying further possible factors not yet accounted for in the development of theoretical models - appeared justified. Chemomechanical effects may considerably affect rock-breaking techniques where explosives are not employed, such as drilling, rock excavation with shovels, continuous miners and raise borers and cutting of dimension stones.

Experimental investigations aimed at ascertaining the importance of the Rehbinzer effect in drilling and rock-cutting and breakage processes have been conducted over the past twenty years also by the mining and Mineral Dressing Department of the University of Cagliari (M.H.D.D.U.C.) using laboratory devices as well as full size machines employed in the mining industry (Giuliani and Rossi, 1974; Giuliani et al., 1974; Giuliani and Rossi, 1979; Carta et al., 1980; Rossi and Troisi, 1982; Rossi and Troisi, 1983; 1983b; Rossin and Troisi, 1989; Troisi, 1991).

The present paper reports on the information gathered through tests conducted with a laboratory-scale diamond core-drilling machine and the interpretations drawn therefrom. The machine was of the authors' own design and was built by the M.N.D.D.U.C.

MATERIALS AND METHODS

THE LABORATORY DRILLING MACHINE

A laboratory diamond drilling machine was used to simulate commercial drilling machines.

Fig. 1 is an isometric drawing of this

Fig. 1 - Isometric drawing of laboratory diamond drilling machine.
machine; the control-, adjustment and measuring instruments are not shown. The diamond core bit (1) is mounted on the hollow shaft (2) on top of which the mass (3) is applied. This mass provides the axial load on the bit. Shaft (2) is free to slide along its vertical axis, whereas it is forced to revolve around this axis by the horizontal bar (4) fastened to it by means of a setscrew. The tips of the horizontal arm of bar (4) are provided with two Teflon rollers that are free to revolve around their axes. These rollers impinge on the vertical rods (5) of a "cage", composed of two discs (6) joined by the rods (7). The cage is idle on shaft (2) and is connected to the pulley of the electric motor (10) by means of driving belt (8). When the electric motor is running, the cage revolves and sets in motion bar (4) and shaft (2). In this way the axial movement of shaft (2) is not affected by the driving system. The rotation speed or electric motor (10) can be continuously adjusted by means of a suitable electronic system type Elbrodyn 2500 (Eltronics Antriebstechnik A.G., Schinznach, Switzerland). The rotation speed of the shaft is continuously measured by means of an optical tachometer "Digital Tachometer Mod. 7617.003" (I.S.C., Milan, Italy). Penetration rate of the tool is measured by means of a Kamen Multivit non-contacting device Mod. MD-1200-2S (Kamen Instrumentation Corporation, Colorado Springs, U.S.A.) for measuring the conductive surface motion. Hence, the measuring devices do not affect the performance of the drilling machine.

The duration of each test is set by means of a digital timer Mod. H3CA-A (Omron, Inc., U.S.A.). The tool is an impregnated diamond bit 18 mm in outer diameter. The test conditions (axial load, rotation speed and duration) may thus be easily and accurately changed. The flushing fluid flow rate is adjusted to the desired value by means of an adjustable speed peristaltic pump. With this laboratory set up, the actual field drilling operation can thus be simulated economically and safely.

THE ROCK SPECIMENS

Testing was conducted on granite, andesite and basalt obtained from Sardinian quarries. Andesite exhibits a pronounced porphyry structure with a microcrystalline matrix and abundance of plagioclase phenocrysts, often zoned and phenoic (amphiboles and pyroxenes). The basalt is olivine, amphibole with hypocrystalline porphyric structure and interstitial-type matrix, and is highly porous. Granite has the characteristics of a leucogranite and appears as a medium-coarse-grained epigranular rock with rare melanocratic inclusions.

Microscopic examination reveals profound weathering in basalt and andesite, whereas granite is little altered.

THE ADDITIVES

The flushing fluid was always the carrier of the additives and consisted of solutions of the desired concentrations in distilled water. Except where otherwise specified, the solutions pH was always the natural one.

The additives used were alkylamines (supplied by Ljiljeholmens Stearinfabrik A.B., Stockholm), diwax and aluminium chloride (both supplied by Farnitalia Carlo Erba,
The water miscibility of dioxane (1,4-dioxane, \( \text{C}_2\text{H}_2\text{O}_2 \cdot \text{C}_2\text{H}_2 \)) in all the ratios allowed to compare the behaviour of the different types of rocks versus water-to-dioxane ratios in the range from zero to one, all other experimental conditions being equal.

**METHODS**

The flushing fluid flow-rate was always adjusted to 1 cm\(^3\) s\(^{-1}\). The length of the tests was timed so as to keep constant the total number of revolutions (2400) effected by the diamond bit: 360 s at 41.88 rad s\(^{-1}\), 180 s at 83.77 rad s\(^{-1}\), 120 s at 125.6 rad s\(^{-1}\), and 90 s at 167.55 rad s\(^{-1}\).

The axial load acting on the bit was maintained constant at 20,822 N, corresponding to a pressure on the rock of 117.26 kPa.

Each test was repeated 5 times and the arithmetic mean of the five values of bit penetration was taken as the experimental result in the corresponding operating conditions. For each value the standard deviation was also calculated.

**RESULTS**

The influence of the flushing fluid composition was expressed in terms of the ratio of groove depth \( P' \) attained in the presence of the additive to groove depth \( P_0' \) attained with water alone as the flushing fluid, all other conditions being equal.

**TESTS WITH ALKYLAMINE**

Among the alkylamine acetates added to the flushing fluid, hexadecylamine acetate produced the most pronounced effects on all three rocks with a maximum increase in penetration depth of 46\% compared to water at 41.88 rad s\(^{-1}\) on andesite. A marked decrease in penetration was observed in basalt at all rotation speeds. The behaviour of granite was between the two, as shown by Figure 2.

![Figure 2](image)

**Fig. 2** - Groove depth increments at different hexadecylamine acetate concentrations referred to those obtained in distilled water at 41.88 rad/s bit speed.

When amine is added to the flushing fluid, the rotation speed of the bit and the concentration considerably affect the process. The chemomechanical effect exhibits the same trend for all the rocks at increasing rotation speed. The hydrocarbon chain length - for which an optimum value seems to exist (16 carbon atoms in the case of the present investigation) - is also a determining factor.

**TESTS WITH DIOXANE**

The presence of dioxane in the flushing fluid results in smaller bit penetration compared to water for all rock types.

With 100% dioxane as flushing fluid, bit penetration referred to water attains a minimum value for all the rocks tested.
Figure 3 shows typical results for basalt, in which there was a reduction in penetration of 70%. Rotation speed only appears to exert a minor influence in these operating conditions.

Fig. 3 - Groove depth increments referred to those obtained in distilled water vs. diameter concentrations at different bit speeds. Rock: basalt.

TESTS WITH ALUMINIUM CHLORIDE

The presence of aluminium chloride in the flushing fluid produces considerable changes in the strength of granite and basalt, whereas it does not seem to have any effect on andesite (Fig. 4, 5 and 6). In the speed range from 83 to 130 rad.s⁻¹, the higher aluminium chloride concentrations produced considerable chemomechanical effects in granite and basalt: the increments in bit penetration compared to water were 90% in granite and 70% in basalt.

Fig. 4 - Groove depth increments at different AlCl₃ concentrations referred to those obtained in distilled water at different bit rotation speeds. Rock: granite.

Fig. 5 - Groove depth increments at different AlCl₃ concentrations referred to those obtained in distilled water at different bit rotation speeds. Rock: basalt.

COMMENTS AND CONCLUSIONS

The influence of the physico-chemical environment on the strength exhibited by rocks to breakage is a well documented
phenomenon that is confirmed by the results of the present work. However, considerable amount of work done on the subject, especially with reference to drilling techniques (Rehlinger et al., 1948; Watson and Engelmann, 1985) has so far provided a wealth of uncorrelatable data.

The detailed critical reviews discussed in earlier papers (Giuliani and Rossi, 1974; Rossi and Trois, 1982) on the effect of environment on rock strength, showed that the lower rock drilling strength observed in the presence of surfactant solutions was attributed to the decrease in surface energy produced in the rook by the adsorption of surfactant molecules (Rehlinger, 1931); according Westwood and Goldschmidt (1970), Westwood and Latanision (1972) and Mills and Westwood (1972), the additives contained in the flushing fluid exert a dual effect: by adsorbing on the rock they probably alter the mobility of dislocations in proximity of the crystalline surfaces and, therefore, modify the creep regime of nearby matter; in addition, it is suggested that they reduce the friction between bit and rock. According to the model proposed by McMillan and Westwood (1974), the chemical adsorption of molecules of chemical compounds alters the electrostatic potential of the solid region located near the surface resulting in a localized redistribution of the electronic and/or ionic charge carriers. In the case of ionic or covalent crystals the charge carriers are electrons and the above authors suggested that their redistribution changes the band structure and that the electrons occupy dislocations and point defects in the region close to the surface. The electrostatic interactions between moving dislocations near the solid surface, between dislocations and point defects and between dislocations and crystal lattice are thus altered. Since the mobility of dislocations in ionic and covalent solids depends on such interactions, this would explain the sensitivity to the environment of crystalline rocks surface hardness.

Water, being a protic liquid, can donate OH ions to solid surfaces while dioxane, being aprotic, cannot. It is therefore very likely that a localized redistribution of charge carriers occurs on a solid surface wetted by water. This charge redistribution alters the resistance of the rock to bit penetration as confirmed by experimental results. Dioxane can not, obviously, donate charges to the solid surfaces with which it comes into contact. Since in these conditions dislocation mobilities in proximity of solid surfaces are not altered, then no local embrittlement takes place, so the solid offers a very high resistance to the bit action.

The formation of silanol groups caused by the reaction of positively charged silicon atoms - located on the surfaces of silicate rocks - with water, probably favours a strong adsorption of Al^{3+} ions attracted by the hydrated silicate groups. This adsorption appears to contribute to the change in charge distribution on solid surfaces, thus immobilizing the dislocations, resulting in embrittlement of the material.

The increment in groove depth observed
in granite when using a flushing fluid of aluminium chloride solutions compares very favourably with that obtained on the same type of rock in the same environmental conditions with wire cutting and an abrasive pulp (Giuliani and Rossi, 1979) (Fig. 7).

Fig. 7 - Groove depth increments at different AlCl₃ concentrations referred to those obtained in distilled water. Rock: granite. Cutting process: wire and abrasive pulp.

The results obtained with dioxane provide evidence that water itself brings about a marked reduction in rock strength owing to the ions deriving from its dissociation.

An explanation of the alteration in rock strength observed when a solution of a surfactant like hexadecylamine acetate is used as flushing fluid appears somewhat more difficult. A mechanism similar to the one suggested to explain the action of aluminium chloride cannot be ruled out: in this case, the positively charged amine groups probably play the same role as the Al³⁺ ions.

The data presented in this work point to the possibility of a contribution of bit rotary speed to the chemomechanical effect as a whole: it is reasonable to assume that for every type of flushing fluid and of material an optimum bit rotary speed exists which enhances the chemomechanical effect. However, more exhaustive research is needed to elucidate this influence.

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REFERENCES


