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Annual Review of U.S. Progress in Rock Mechanics

Coupled Processes

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Annual Review of U.S. Progress in Rock Mechanics

Coupled Processes

U.S. National Committee for Rock Mechanics
Commission on Engineering and Technical Systems
National Research Council

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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PANEL ON ANNUAL REVIEW OF U.S. PROGRESS IN ROCK MECHANICS

GARY R. OLHOEFT, U.S. Geological Survey, Denver, Colorado
GARY D. CALLAHAN, RE/SPEC Inc., Rapid City, South Dakota
W. DAVID CARRIER, III, Bromwell & Carrier Inc., Lakeland, Florida
DONALD LANGMUIR, Department of Chemistry and Geochemistry, Colorado School of Mines, Golden, Colorado
HAROLD W. OLSEN, U.S. Geological Survey, Denver, Colorado
VASUDEVAN RAJARAM, Consultant, Downers Grove, Illinois
JAY E. RHODERICK, Office of Civilian Waste Management, U.S. Department of Energy, Washington, D.C.

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VIRGINIA M. LYMAN, Administrative Assistant

PREFACE

In 1981, the U.S. National Committee for Rock Mechanics and its Panel on Rock-Mechanics Research Requirements completed a major technology assessment with publication of the report Rock-Mechanics Research Requirements for Resource Recovery, Construction, and Earthquake-Hazard Reduction. As a follow-up to this effort, in 1982, the Committee established a panel which was directed to prepare annual, written assessments of programs and needs in rock mechanics. After approval by the Committee and the National Research Council, the assessment would be published and distributed throughout the rock mechanics community and to program managers and decision-makers in government.

The panel's yearly assessment was to be brief and restricted in scope, and yet emphasize programs applicable to diverse disciplines and problems. The first three reviews were devoted to rock mass characterization, engineering rock mechanics, and rock dynamics. The theme selected for the fourth review is "Coupled Processes."

Although each annual assessment is to be narrow in scope, it is anticipated that the series of reviews will encompass a broad range of rock mechanics themes. The emphasis and organization of these reports are expected to change from year to year, reflecting changes in the priorities of programs and needs in rock mechanics. This year's theme contains an extensive bibliography, something that has not been done before for this subject, and considered appropriate and useful by the panel.

This fourth review was conducted under the leadership of Dr. Gary R. Olhoeft, the chairman of the panel listed previously. The committee would like to give special recognition to Dr. Olhoeft for his efforts in writing and editing much of this report.

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INTRODUCTION

This report, the fourth in a series of annual reports intended to review significant progress in selected areas of rock mechanics, focuses on coupled processes--thermal, mechanical, electrical, hydraulic, and chemical. Coupled processes are those in which a thermodynamic flow (flux) occurs due to the application of an unrelated force (gradient), such as flow of water in response to a thermal or electrical gradient instead of in response to an hydraulic gradient. Frequently, multiple forces and fluxes are involved, such as attenuation of acoustic energy in wet rocks by conversion of the elastic wave into hydraulic viscous fluid flow through fractures or pores and thence into thermal energy by dissipation as heat.

Coupled processes are important in a wide variety of current problems in soil and rock mechanics. Coupled processes can influence the migration of contaminants from nuclear waste repositories (Tsang and Mangold, 1984; Chan et al., 1985; Cook, 1985) and from chemical waste sites (Mackay et al., 1985), stability of soil near foundations (Winterkorn, 1975; Mitchell and Katti, 1981), stress-corrosion cracking and rock/soil strength (Anderson and Grew, 1977; Dunning and Huf, 1983; Ishido and Nishizawa, 1984), absorption of acoustic energy through fluid flow in cracks (Jones, 1986), soil liquifaction (Committee on Earthquake Engineering, 1985), permeability modification in enhanced oil recovery (Donaldson and Chilingarian, 1985), solution mining (Schlitt and Schock, 1979), flotation in mineral processing (Woods, 1981), and the control of density and viscosity in drilling muds (van Olphen, 1977; Chillingarian and Vorbutr, 1981). On larger scales, coupled processes are suspected to be active participants in various aspects of climatic change (Ramage, 1986), landslides (Veder, 1981; Sidle et al., 1985), earthquakes (Dmowska, 1977; Simpson, 1986), and the origin of life (Cairns-Smith, 1985).

This report summarizes the status of coupled-process research and the application of knowledge about coupled processes to a variety of problems in rock mechanics. Coupled processes in soils are also discussed, as soils are sometimes considered weak rocks and much of the research into coupled processes in soils can also be indicative of similar problems in rocks.

Naturally occurring coupled processes are frequently difficult to investigate as they are not simple pair-couplings, but multiple couplings tied to the ambient conditions in open thermodynamic systems. A thermocouple measures temperature by the simple pair-coupling of thermoelectric effects. Osmosis, however, may involve fluid flow under coupling from electric, thermal, and chemical forces. Further, since reaction rates and transport coefficients are functions of temperature, it might be said that any such chemically coupled process must in fact be thermochemically coupled. Thus, investigation of natural coupled processes requires complicated interdisciplinary research. Despite incomplete understanding of their occurrence, coupled processes are becoming more widely recognized as the source of practical problems such as swelling clays which cause $7 billion in property damage every year (Civil Engineering, 1986), or the migration of radioactive and other hazardous wastes.

BACKGROUND

Equations of change for systems are typically given in terms of the fluxes of mass, momentum and energy. To obtain workable expressions for the equations, we have to be able to replace the fluxes by expressions that contain transport properties and the gradients of the concentration, pressure, electrical potential, velocity, and temperature. The familiar, uncoupled processes are: Darcy's Law relating fluid flow to hydraulic head (gradient); Fourier's Law relating heat flow to thermal gradient; Ohm's Law relating charge flow (electric current) to electric field gradient; Fick's Law relating flow (diffusion) of matter to concentration gradient; and Newton's Law relating shearing force to velocity gradient. These and similar constitutive relations linearly relate a flow to a conjugated force. When the uncoupled flows associated with these potentials are driven by different potentials as in the off-diagonal entries below, they represent coupled flows. Table 1 lists coupled processes and their related gradients.

Table 1 Gradients, Flows and Related Coupled Processes*

Gradient:	Hydraulic Head	Temperature	Electric Field	Chemical Concentration
Flow:				
Fluid	hydraulic conduction (Darcy's Law)	thermo-osmosis	electro-osmosis	chemico-osmosis
Heat	isothermal heat thermal filtration	thermal conduction (Fourier's Law)	Peltier effect	Dufour effect
Electric Charge	streaming current	Seebeck effect	electrical conduction (Ohm's Law)	diffusion and membrane potentials
Ions	streaming current ultra filtration or reverse osmosis	Soret effect	electro-phoresis	diffusion (Fick's Law)

*The off-diagonal entries in the table are simple pair-coupled processes (Mitchell, 1976).

Onsager (1931) demonstrated that these constitutive equations are not independent. Using irreversible, nonequilibrium thermodynamics, he derived reciprocal relationships that relate forces and fluxes linearly through phenomenological coefficients. If an electric field is applied to a wet rock, both an electric charge flow and a water fluid flow result. The charge flow results from the conjugated force described by Ohm's Law. The fluid flow results from the nonconjugated force described by Onsager's reciprocal relations and is said to be a coupled process--an electrokinetic effect. These effects are reciprocal in that a hydraulic gradient force may drive a fluid flow and an electrical current flow. This flow of electrical current through a finite conductivity liquid produces the voltage drop known as the streaming potential. Other examples of paired-coupled processes include electrophoresis and sedimentation potential, Seebeck/Peltier thermoelectric effects, Soret/Dufour thermal-diffusion effects, and dissolution/precipitation chemical-mechanical effects.

Within the Onsager relations are described the coupling between electrical, thermal, mechanical, hydraulic, and chemical forces. Magnetic forces add complications that we will not consider here and which are not very influential in natural near-surface earth science systems (though coupled magnetic processes such as the Hall and magneto-optic effects are very important technologically). Further introduction to coupled processes may be found in De Groot and Mazur (1962) and Baer (1972). Some of the processes and examples discussed below do not fit the classic Onsager definition of coupled process. An example is mineral flotation, where chemistry and other processes couple to make minerals float to allow metallurgical separation; but making minerals float does not necessarily control chemistry.

It should be noted that rock and soil materials are generally anisotropic, which increases the complexity of describing coupled processes. Along with the main diagonals themselves, like fluid conductivity, the off-diagonal effects are likely to be quite anisotropic, and therefore not describable by a single coefficient. Similarly, the heterogeneity of underground materials complicates the study of coupled processes, since problems associated with scale and representative volumes arise. It is difficult to discuss these processes individually as they are coupled in several different ways. As a consequence, the following descriptions contain some redundancy.

COUPLED PROCESSES

ELECTRICAL COUPLING

Probably the most extensively studied and best understood of coupled processes are those involving electrical forces and flows. Thermoelectric effects are exploited in thermocouples to measure temperature (Nye, 1957). Electrokinetic effects are exploited in electrophoresis methods of chemical analysis and biological cell separations (Anderson and Eyring, 1970). Electromechanical effects are exploited through piezoelectric crystals as in acoustic transducers used to monitor seismic energy (Nye, 1957), in direct electromagnetic detection of breaking rock (Nitsan, 1977) and earthquake "lights" (Lockner and others, 1983, 1985). The movement of electrons through a conductor results in electrical energy being converted into thermal energy in a process called Joule heating. Temperature dependence of the thermal and electrical properties of the material leads to a nonlinear, coupled problem involving the electric field and heat conduction equations. This type of coupling is particularly important in electrical devices (Robertson, 1985), but of minimal importance in earth-science problems.

In the earth sciences, the coupling of electrical and other forces are used to control the physical properties of drilling muds (van Olphen, 1977; Chilingarian and Vorbutr, 1981), to control minerals processing through flotation (Woods, 1981), to locate mineral and geothermal resources through spontaneous polarization exploration geophysics (Corwin and Hoover, 1979; Sill, 1982; Corry, 1985), among other things. Frequently, multiple coupling occurs, such as in mineral flotation where an electrical-chemical-hydraulic-mechanical coupling exists.

A gradient of electrical potential may drive the movements of fluids through osmosis in soils. The basic physics underlying electro-osmosis is not fully understood, though at least four theories have been developed (Mitchell, 1976; Banerjee and Vitayasupakorn, 1984). For soils, the most satisfactory theory appears to be that of Helmholtz (1879) and Smoluchowski (1914). They showed analytically that the coefficient of electro-osmotic permeability should be directly proportional to the porosity of the soil, but independent of the size of the pore openings. This has been confirmed by measurements on a number of soils, in which it has been found that this coefficient is more or less independent of soil type, but is strongly affected by the pore water electrolyte concentration (Gray and Mitchell, 1967; Mitchell, 1976; Wan and Mitchell, 1976).

Mitchell (1976) has shown that electro-osmosis is most effective in poorly compacted materials of low cation exchange capacity, whereas chemico-osmosis is more effective in densely compacted materials of high cation exchange capacity. Thermo-osmosis is relatively ineffective in materials of any type. The significance of these laboratory data is limited in two fundamental aspects. Adequate data are lacking for undisturbed samples which are required to simulate the natural structure of argillaceous materials. Data are also lacking for systems that simulate natural causes of osmosis. In nature, the causes of osmosis are substantially more complex than the simple solute-concentration and electrical-potential gradients used in laboratory studies. The causes include not only solute-concentration, but also complex solute-composition gradients. They also include the geochemical conditions and reactions that generate electrical-potential gradients in nature. The studies to date have also concentrated mostly on soils, with little research into the effects in either clean or altered rocks.

Thus, it appears that either chemico-osmosis or electro-osmosis can be effective in a wide range of natural environments. However, the natural causes of, and some controls on, these mechanisms have yet to be clarified in either soil or rock. From an engineering viewpoint, natural sources of electrical-potential gradients, such as chemical reactions involving weathering, are of particular interest because the efficiency of electro-osmosis is relatively high in poorly consolidated materials of low cation exchange capacity (such as those in rocks and often associated with geochemical processes in near-surface soil environments).

Osmosis has been recognized as a possible cause of anomalous pore-fluid pressure that facilitates overthrust faulting (Hanshaw and Zen, 1965); influences the mechanics of groundwater systems (Greenberg et al., 1973; Marine, 1974; Marine and Fritz, 1981; Olsen, 1972); and activates landslides (Veder, 1981). It may be contributing to anomalies in the consolidation state and pore pressure of the Pierre Shale (Fleming et al., 1970; Neuzil and Pollack, 1983). It may be the cause of non-Darcy flow behavior in argillaceous materials (Bolt and Groenvelt, 1969; Olsen, 1985).

Electro-osmosis is being exploited in applied practical situations. As a construction technique, one procedure is to install vertical metal rods in a saturated soil layer in a hexagonal pattern of cathodes and anodes (Mitchell and Katti, 1981). When a direct current voltage potential is applied across the soil, the cations in the pore fluid (such as Na^+) migrate toward the negatively charged cathode. The movement of cations in turn drags water molecules in the same direction. The result is a dewatering, or consolidation, occurring in the vicinity of the anode. Electro-osmosis has been used successfully to consolidate and stabilize a number of soil deposits (Casagrande, 1949, 1952, 1959; Tamez and Flamand, 1959; Casagrande et al., 1961; Eide and Eggestad, 1963; Esrig, 1964; Esrig and Gemeinhardt, 1967; Fetzer, 1967; Bjerrum et al., 1967; and Nichols and Herbst, 1967).

Electro-osmosis has also been used for electrochemical injection, in which a chemical stabilizer is introduced at either the anode or the cathode, depending upon the charge, and flows into the soil pores in response to the electrical gradient (Pilot, 1977; Mitchell and Katti, 1981). This technique has been used to strengthen various soils including expansive or

welling clay (O'Bannon et al., 1976). Electro-osmosis has also been used to remove heavy metals and pesticides in a field test on dredged material (Segall et al., 1960). As a result, the Environmental Protection Agency is considering it as a possible site-remediation technique for hazardous wastes.

CHEMICAL COUPLING

It has already been noted that chemical reactions are thermochemically coupled in the sense that a temperature must be defined to describe the system. Except for solid state diffusion at high temperatures and for radioactive decay, most chemical reactions in subsurface environments involve fluid transport of reactants and/or products. Thus, in water saturated rocks, chemical processes are hydrochemically, as well as thermochemically coupled.

Chemical processes that affect the properties of earth material are heterogeneous, and include solid phase precipitation/dissolution, solute adsoption/desorption, osmosis, gas dissolution/exsolution, ion exchange, deritufication, and filtration and settling of suspended particulate matter. These processes can lead to major changes in the hydrologic, mechanical, and thermal properties of rock. Such chemical processes usually take place in thermodynamically open systems (Stumm and Morgan, 1981), which include fluxes of chemical substance and/or gradients in other system properties such as temperature, pressure, or electrical field. Thus, such processes cannot be fully understood unless they are modelled using the principles of irreversible thermodynamics and kinetics, and include the coupling of other forces and fluxes.

As an example of a chemically coupled process, consider calcite and gypsum which tend to precipitate from groundwater in fractures adjacent to heat sources, whereas quartz-fracture filling occurs some distance away from heat sources. Moore et al. (1983) and Morrow et al. (1985, 1986) found that passing water through granite along a thermal gradient from 250° C to 100° C reduced the hydraulic conductivity by a factor of 3 to 70 times. This reflected leaching of the rock at the higher temperatures and precipitation of the silicate phases, closing off porosity at the lower temperatures.

Adsorption/desorption reactions produce another important coupled process: the Na^{+}/Ca^{++} exchange onto montmorillonite clays (Yariv and Cross, 1979). Exchange of Na^{+} for Ca^{++} on montmorillonite leads to expansion of the clay lattice by two or more times. This chemically induced mechanical expansion and the accompanying reduction in permeability can ruin agricultural soils, and do damage to overlying foundations and pavements. This same effect is considered desirable in compacted clay liners used to isolate hazardous waste as the swelling of the sodic clay decreases the permeability of the liner to provide a barrier to waste migration into the groundwater aquifer. It is also one of the effects used in controlling the viscosity and density of drilling-muds (van Olphen, 1977). Adsorption of organic polymers can frequently produce the reverse effect, increasing permeability (Anderson et al., 1982) of a clay barrier.

The migration of dissolved substances in groundwater will reflect the bulk movement of water in relatively permeable rocks such as sandstones, gravels, and extensively fractured crystalline rocks (Freeze and Cherry, 1979). However, when bulk groundwater flow is through intact crystalline rocks, groundwater flow rates will be extremely slow, and the migration of dissolved substances may be via diffusive transport (driven by concentration gradients), or coupled thermal transport (driven by temperature gradients: the Soret effect, [Lerman, 1979; Petit et al., 1986]), or thermal- or electro-osmosis as discussed above.

Experimental ion diffusivities measured for Cs, Sr, and I in clay packing and granite (Birgersson and Neretnieks, 1982) have been found to be much faster than for the same ions in granite alone (Skagius and Neretnieks, 1982). Rasmuson and Neretnieks (1983) suggest that this may reflect migration of the ions by pore diffusion and by surface diffusion of the sorbed ions. In a study of CsCl migration through compacted bentonite, Soudek et al. (1984) observed that the diffusion rate of Cs was enhanced over its rate in bulk solution by a mechanism the authors describe as surface diffusion. In contrast, compaction of the bentonite led to a reduction in the transport rate of Cl ions, probably because of strong Donnan ion exclusion (Bressler, 1973).

Measurements of electrical conductivity versus temperature show surface diffusion becomes more important than volume diffusion with increasing temperature (Olhoeft, 1980; Ucok, 1979). Similar measurements also show surface diffusion to become more important with decreasing salinity of pore water (Hunter and Wright, 1971; Ucok, 1979; Waxman and Smits, 1968). This surface versus volume diffusivity process could be termed a process of coupled temperature, chemistry and texture (or pore morphology). Surface diffusivity and other processes are also modified by coupled chemical reactions, particularly inorganic processes modified by organic processes (de Silva and Toth, 1964; Anderson et al., 1982). Organic chemical processes can modify inorganic chemical transport by chelating and complexing the inorganics into forms that are more water soluble or by directly interfering with adsorption processes that would otherwise take the inorganics out of solution by cation exchange.

Johns (1979, 1982) has reviewed the catalytic activity of clays in petroleum maturation and diagenesis in sedimentary rocks. Such could be called a coupled process as it involves migration (transport) of petroleum-generating fluids near clay surfaces which catalyze chemical reactions to produce petroleum. The use of surfactants and other chemical modifiers in enhanced oil recovery (EOR) operations is another example of coupled processes. Most chemicals added during EOR are used to modify surface properties of clays to alter reservoir-rock permeability and fluid flow, allowing greater mobility of the petroleum (Donaldson and Chilingarian, 1985).

THERMAL COUPLING

Thermal coupling has already been mentioned in all of the other sections as temperature is required to specify the physical and chemical state of most properties. Temperature also couples directly, as in the Peltier thermoelectric effect in thermocouples. However, most thermal coupling

occurs due to a temperature gradient (as in the Soret effect) or to changes in temperature (as in stresses induced by thermal expansion).

Thermomechanical coupling is a major consideration in numerous geological situations. For example, thermomechanical effects are major considerations in compressed air energy storage (Gnirk et al., 1979), in-situ coal gasification (Advani and Lin, 1976; Smith and Smoot, 1981), geothermal energy (Demuth and Harlow, 1980; and Nayfeh et al., 1975), liquid natural gas storage (Lindblom, 1977), oil shale retorting (Galloway, 1979; Chan and Cook, 1979), weapons research (Nilson, 1981), and radioactive waste isolation (Werme, 1986; Noorishad et al., 1984; Hart and St. John, 1986; Heuze, 1983; Callahan, 1981; Gnirk and McClain, 1980).

Multiple couplings have been investigated for problems related to the isolation of radioactive waste (Hart and St. John, 1986; Tsang, 1987; Chan et al., 1985; Tsang and Mangold, 1984; Noorishad et al., 1984; Gnirk et al., 1980; Callahan and Gnirk, 1979). Most of these problems have been concerned with thermal-mechanical-hydraulic couplings.

In a geologic radioactive waste repository, the waste heats the surrounding rock, creating a temperature gradient and thermal stresses from thermal expansion of the rock and the fluids in the pores. Mechanical stresses are induced when openings are made in the rock, primarily affecting a shell around the opening, about one or two opening-diameters into the rock mass. However, the effect of thermal stresses penetrates further into the rock mass and depends upon (among other factors) the thermal conductivity and thermal expansion coefficient of the rock mass. The coupled effect of these mechanical and thermal stresses is to increase the overall hydraulic conductivity of the rock mass. This is due to the fact that although the stress increase will tend to decrease the permeability in the volume of the heated rock, the compensatory decrease in stress outside the heated volume will increase permeability (Cook, 1985). These thermomechanical-coupling effects have been studied in the laboratory on cores (Reda, 1985), by large scale testing in simulated environments (Cramer et al., 1983), and by in-situ testing at depth (Birgersson and Neretnieks, 1982). Mathematical modeling is also being performed using simplified assumptions to unravel the coupling of the various inter-related physical and chemical phenomena expected or observed around radioactive waste repositories (Noorishad et al., 1984; Hinton et al., 1981; Swift and Burton, 1984; Heuze et al., 1985; Elsworth and Goodman, 1985; Chan et al., 1985; Hart and St. John, 1986; Whitaker, 1986; Lewis et al., 1986).

The effect of rock mass heating on the travel time for fluids through rock is of critical importance in assessing the performance of geologic repositories. The Nuclear Regulatory Commission has published a draft Technical Position on the disturbed zone around a geologic repository. The disturbed zone is created by a coupling of thermal and mechanical stresses, and hence an understanding of this complexity is important to defining the extent of the disturbed zone.

An interesting and complex coupled phenomenon in radioactive waste isolation involves that of brine movement in salt deposits. The first significant evidence of brine movement occurred during the Project Salt Vault field demonstration (Bradshaw and McClain, 1971). The first laboratory and theoretical studies (Anthony and Cline, 1971) revealed that brine

inclusions migrate up the thermal gradient toward the heat source establishing a thermal-chemical coupling. In some instances, however, gas-liquid inclusions can migrate down the temperature gradient (Pigford, 1982). Later, intragranular brine migration caused by Soret-Dufour thermal-diffusion effects was coupled with pressure-driven brine existing in the interconnected porosity (Ratigan, 1984) to further explain brine movement.

At present, the mechanical coupling to the Darcian flow components is thought to be important (Olander, 1982). The porosity associated with grain boundaries and microcracks affects the salt permeability and the ability to store intergranular water. Therefore, the impact of salt-stress and microcrack healing under stress should have a strong influence on brine movement. However, this influence is presently unquantified and represents a contemporary research area. This topic has been investigated and documented in draft at a recent workshop conducted by the Salt Repository Project at the University of California, Berkeley in 1985.

MECHANICAL COUPLING

The mechanical behavior of rock has been studied in the laboratory and in the field for decades (Jaeger and Cook, 1969). Coupled processes in geomechanics were recently summarized by Cook (1985). Fluid conductivity of fractures is dependent upon the effective stress normal to the fracture plane and is therefore affected by the pore fluid pressure within it. Under some conditions, shear displacement between the two surfaces may result in major changes in the geometry of the void, and hence conductivity (Senseny et al., 1983). The effective normal stress across fractures is expected to change as a result of the redistribution of stresses around excavations, thermally induced stresses, and pore pressures (Cook, 1985).

Thermomechanical coupling is often described by the theory of thermoelasticity (Boley and Weiner, 1960; Nowacki, 1962; Fung, 1965). For most applications, the uncoupled, quasi-static theory of thermoelasticity is used and is described by the Duhamel-Neumann law (Sokolnikoff, 1956) which couples the mechanical and thermal fields in a material. This form of the theory degenerates the problem into separate problems of heat transfer and thermoelasticity forming a one-way coupling. Inherent in this decoupling are the assumptions that the mechanical coupling term in the energy equation and the inertia term in the equation of motion can be omitted. These two assumptions mean that the temperature change in an elastic material is small because of adiabatic straining and that the stress changes caused by acceleration of a body during heating are negligible. Fortunately, these two assumptions are acceptable for most geological applications without introducing significant errors.

The near-field around an excavation consists of loosened rock that is stabilized with supports. This loosened rock zone can be reliably measured with instrumentation, and several researchers have established the extent of this zone in various rock types. However, the extent of the near-field lying between the loosened rock zone and the undisturbed rock is difficult to quantify since mechanical-thermal-hydraulic coupling is involved.

Mechanical coupling through the piezoelectric effect is also postulated to cause electrical charge accumulation and effects sometimes called earthquake "lights" (Corwin and Morrison, 1977; Fitterman, 1978; Lockner et al., 1983, 1985). The piezoelectric effect also produces electromagnetic emissions from crushing rock (Nitsan, 1977) that has been exploited for exploration and mine safety (Sobolev et al., 1984).

Acoustic energy passing through water-saturated porous rocks moves fluid in cracks, hydraulically converting propagating elastic energy into thermal energy (Jones, 1986). This appears as an inelastic loss mechanism to absorb acoustic energy. As it involves the coupling of mechanical elastic forces to fluid flows, it is a coupled process.

The mechanical movement of charged particles produces a coupled process from the electrokinetic effect called sedimentation potential--Dorn effect (Davies and Rideal, 1963). The settling of clay particles in drilling muds produces a sedimentation-potential that biases wireline logging measurements of electrical properties.

HYDRAULIC COUPLING

The presence of water produces alteration (Fyfe et al., 1978), hydrolytic weakening (Ishido and Nishizawa, 1984), stress corrosion cracking (Wiederhorn, 1967; Cerepanov, 1981), and changes in rock strength (Colback and Wiid, 1965; Street and Wang, 1966; Simpson and Fergus, 1968; Dunning and Huf, 1983). Elevated temperatures may produce water (and other volatiles) from the thermal decomposition of hydrated minerals (Fyfe et al., 1978). The presence of the freed water of decomposition would produce some changes while the movement of the water from the location of the dehydrating minerals in response to other forces (osmotic, chemical, electrical..) would produce other changes. The addition of water to otherwise dry systems, particularly at elevated temperatures, produces accelerated weathering and alteration of the mineralogy to hydrous phases such as amphiboles, clays and zeolites. These changes are frequently accompanied by volume changes in the minerals, due to changes in bulk density from the anhydrous to hydrous phase, and corresponding increases in stress in the surrounding unaltered rock. Hydrous minerals growing inside pre-existing porosity can significantly decrease the pore sizes and rock permeability.

Certain soils are known to swell under wet conditions and shrink under dry conditions. These soils generally contain a significant fraction of clay minerals (see also Chemical Coupling above). This hydromechanical coupling and consequent volume change can severely damage structures, pavements, pipelines, and foundations (Winterkorn, 1975). As a result, the study of expansive soils has become a significant subsection of geotechnical engineering, with its own series of international conferences (College Station, 1965, 1969; Haifa, 1973; Denver, 1980). Expansive clays have been identified as causing more property damage in the United States than other more obvious natural hazards such as floods, earthquakes, and hurricanes. The annual cost of repairs due to expansive clays is estimated to be greater than $7 billion (Civil Engineering, 1986).

The movement of water causes streaming potentials through electrokinetic effects (discussed above), and can cause erosion, piping, and hydraulic fracturing (Sherard and Decker, 1977; Zoback and Haimson, 1983) which are also strongly influenced by the state of stress and chemistry in the soil or rock. Movement of water may also result in the triggering of earthquakes from pressurization of wells and filling of reservoirs (Healy et al., 1968; Raleigh et al., 1964, 1968; Simpson, 1986).

When chemical concentration gradients exist across semi-permeable clay or shale beds, the membrane (semi-permeable barrier) will restrict the motion of charged particles but allow the movement of neutral particles across the barrier. When there is a salinity difference across such a barrier, chemical osmosis will drive water molecules across the barrier from low to high salinity (Letey and Kemper, 1969; Kharaka and Berry, 1973; Marine, 1981; Graf, 1982; Fritz, 1986). In the case where clay or zeolite packing material surrounds nuclear or other waste material, osmotic pressure may lead to hydraulic gradients either towards or away from the waste depending on the salinity differences of groundwaters at the waste and in the surrounding country rock (and in the thermal gradient) (Hanshaw, 1972; Greenberg et al., 1973; Apps et al., 1982; Carnahan, 1985).

DISCUSSION

This report has briefly introduced the interdisciplinary scope of coupled processes and a few of their impacts on rock mechanics problems. Owing to the interdisciplinary nature of coupled processes, research investigations are very difficult, and compounded by their complex occurrence in nature. Only the simplest pairs of coupled processes have been adequately studied, and generally these have been selected for their technological utility (such as thermocouples). Many of the most interesting problems in coupled processes are not simple pairs, such as the multiple couples occurring in transport of wastes through soils and fractured rock systems. A few laboratories in the United States are studying triple systems such as thermomechanically driven hydraulic flow through fractured rock. None are studying the most complex systems where thermal, mechanical, hydraulic, electrical, and chemical forces and fluxes are all coupled. To complicate these systems still further, many terrestrial processes such as waste migration, uranium sedimentary roll front deposition, and petroleum maturation also include the coupled effects of biological activity.

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