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Pressure Grouting of Fractured Bedrock to Control Acid Mine Drainage

S. A. Effner, G. D. Vandersluis, and V. Straskraba

Hydro-Geo Consultants, Inc.
165 South Union Boulevard, Suite 400,
Lakewood, Colorado 80228, U.S.A.

ABSTRACT

Pressure grouting techniques can be used to control the flow of acid mine drainage (AMD) in fractured bedrock below leachate collector systems. In the Western United states, waste rock from open pit mines is commonly placed in the upper reaches of ephemeral drainages. In many cases, this material is acid generating and remedial measures must be implemented to control the migration of acidic leachate emanating from the pile. Leachate collection systems can effectively capture AMD flowing on the surface or in shallow alluvium, but in many cases, additional measures must be implemented to prevent the flow of AMD in fractured bedrock below the interceptor system. A general framework for the design and implementation of a grouting program to control acid mine drainage is presented in the following paper.

INTRODUCTION

Acid drainage is a common problem at many mines in the United States including many coal, gold, and base-metal mines. Acidification of mine waters and resulting increase in heavy metal concentrations is caused by pyrite oxidation, and can affect ground water in, and adjacent to mines or mining wastes (Nicholson, 1988, and Bierens de Haan, 1991). Because the potential exists for acid mine drainage (AMD) to contaminate ground water resources it is often necessary to implement measures to control the flow of AMD in bedrock adjacent to acid generating sources. With the recent advent of large-scale open pit mining for precious metals, more attention is being focused on the potential for waste rock piles to generate low pH water. Waste rock from open-pit mines is commonly placed in the upper reaches of ephemeral drainages. In many cases, this material is pyritic, and oxidized water infiltrating into the pile can generate acid drainage which may contaminate ground water. Leachate interceptor or collection systems installed downgradient from AMD generating waste rock piles can prevent or control the migration of low pH waters in surface waters and shallow ground water. Typically, leachate collector systems are composed of some type of interceptor dam or wall underlain by a french drain system. The effectiveness of these types of AMD collection systems depend in part, on their ability to prevent the flow of AMD in joints and fractures in shallow bedrock. In many situations, grout curtains can be used to reduce the permeability of shallow bedrock and to control the flow of AMD in ground water.

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Although grouting techniques have been widely used in mining practices to control the flow of ground water during mining and shaft sinking, only recently has this technology been applied to the control and abatement of acid mine drainage. Because of the corrosive nature of acid mine drainage, special attention must be given to the design of the grouting program and the selection of the grout formulation. The following discussion is intended to provide a general framework for the design of a grouting program to control the flow of acid mine drainage in fractured bedrock.

DESIGN OF GROUTING PROGRAMS TO CONTROL ACID MINE DRAINAGE

Grouting is the processes of injecting a cement or similar material into fractures and joints in bedrock to reduce permeability or increase the strength of the rock mass. The design and implementation of grouting programs will vary depending on site specific characteristics, but in general, all grouting programs share a few features in common. An effective grouting program to control acid mine drainage should include the following components:

- A review of the existing geologic information;
- A study of fracture patterns and joints in bedrock;
- A hydrogeologic study to determine permeability;
- A pilot hole drilling program;
- Evaluation and selection of potential grouts and admixtures; and,
- Design and Implementation of the grouting program.

In the following sections, each of these components will be considered.

Review of the Existing Data

A review of the existing geologic information is important to the successful installation of an acid drainage interceptor system. This review should include information about the regional geologic setting, structural and stratigraphic features present at the site, previous hydrogeologic studies, and the geochemistries of ground water, bedrock, and acid mine drainage. At most mines, a wealth of geologic information exists from mine development maps and exploration boreholes. In many cases, information from previous hydrogeologic studies and monitor wells are available which can be used to determine the hydraulic characteristics and geologic properties of alluvium and shallow bedrock at the site. At this point, information gaps should be identified which need to be filled before a remedial grouting program to control the migration of AMD in fractured bedrock can be implemented.

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Fracture and Joint Study

Joint and fracture patterns in the immediate area of the grout curtain should be mapped and studied to determine continuity, width, orientation, and spacing. Detailed maps of joints and fractures can be constructed using information from outcrops, oriented drill core, or rock faces exposed during mining. In general, the strike, dip, length, and general character of the fractures or joints should be mapped, and a rose diagram or hemispherical plot prepared to determine the dominant structural orientation. In areas covered by shallow alluvium, the alluvial cover will be excavated before construction of the interceptor system and fractures and joints should be mapped after the bedrock surface has been exposed. Typically, several hundred joints or fractures will be mapped during the fracture and joint study.

Grout injection boreholes will usually be oriented perpendicular to the dominant structural trend to intersect the maximum number of joints or fractures. The exception to this rule is when bedrock permeability is anisotropic in a direction which does not coincide with fracture orientation. In general, if fracture spacings are irregular in a given direction, bedrock will exhibit trending heterogeneity with regard to permeability. If fracture spacings are different in one direction than another, permeability will be anisotropic (Freeze and Cherry, 1979). In areas where fracture density is low it may be necessary to analyze the permeability of discrete fractures or fracture systems and orient grout injection boreholes accordingly.

Hydrogeologic Studies and Permeability Testing

The hydraulic conductivity of the bedrock is an important factor in designing grouting programs. Grout selection to a large degree depends on the size and effective permeability of fractures in the bedrock. Hydraulic conductivity can be determined by pumping or slug tests performed in monitoring wells, or from constant head injection tests in boreholes using a packer assembly to test discreet intervals. Packer injection tests are by far the most common permeability tests used to determine hydraulic conductivity for grouting programs. Under optimum conditions, packer permeability tests should be performed prior to, and during, the installation of the grout curtain.

Monitor wells should be located downgradient from the site to delineate the lateral extent of the AMD plume and provide information about depth to ground water and hydraulic gradient. The vertical extent of contamination should also be determined using nested wells. Hydraulic conductivities for bedrock can be calculated from rising head tests or from pumping tests performed in monitoring wells. Under some conditions, monitoring wells may indicate zones of higher hydraulic conductivity. This information may be used to determine locations of pilot holes, the distance between grout injection boreholes, the type of grout to be used, and the depth to which the grout curtain should be installed.

Geophysical methods can also be used to help plan a grouting program. Geophysical surveys can identify fracture systems and zones of higher hydraulic conductivity that could provide flow pathways for AMD. Techniques which may be useful include IP-resistivity dipole-dipole surveys, VLF-magnetics, loop-loop conductivity surveys, and VLF-resistivity surveys. These techniques, with the exception of the magnetic survey, measure conductivity or resistivity. In general, AMD will be more conductive than uncontaminated ground water and the limits of the contaminated plume may be detectable using geophysical methods.

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Pilot Boreholes

After evaluating data from the above sources, a pilot borehole program should be initiated to obtain additional information for the grouting program. The objective of this program is to develop additional information about bedrock below the interceptor system. Information obtained from pilot holes includes the frequency and type of joints or fractures, the lithologic characteristics and soundness of bedrock, the Rock Quality Designation (RQD), the thickness of the alluvial cover, the permeability or hydraulic conductivity of bedrock, and tests the reliability of geophysical techniques used to identify flow paths. The location and orientation of pilot boreholes will be determined from the results of the fracture, hydrogeologic, and geophysical studies. Usually, pilot boreholes will be located 40 to 50 feet from each other and oriented to encounter the maximum number of fractures as determined from the joint and fracture study. Pilot boreholes should be drilled using a core rig, and when possible, the core should be oriented. Packer permeability tests should be conducted in each of the pilot boreholes. A single wireline packer assembly and a down stage testing method can be used to quickly evaluate the hydraulic conductivity for bedrock intervals as the borehole is advanced. Information obtained from pilot boreholes will be used to determine the spacing of grout injection holes, type of grout to be used, amount of grout necessary to form the curtain, sequence of grouting, and potential problems that might occur during grout injection.

Evaluation and Selection of Grout Mixtures

The evaluation of potential grout compositions or mixtures is an important part of planning a grouting program designed to control the flow of AMD. The three most common types of grout used are cement, clay, and chemical grouts. It is recommended that grout types be thoroughly researched and tested before being selected for use in a program to control AMD. Information about the chemical composition and suitability of specific grouts for a project can be obtained from the manufacturer or grouting contractor. Factors which need to be considered when selecting grout composition include the rheological characteristics of the grout, its resistance to chemical attack, and its strength after setting.

The rheological, or flow properties required will be determined by fracture size and effective hydraulic conductivity of the bedrock. In general, bedrock with open joints and fractures can accommodate clay grouts or coarser grouts such as portland cement, while tighter fractures require finely-ground grouts or chemical grouts. Selection of a grout which will be able to penetrate far enough into the bedrock to insure a good seal is critical to the success of the program.

The chemical resistance of grout to corrosion by chemically active solutions is important for applications in AMD environments. At present, there are few references in published literature about the suitability of different grouting mixtures for this application. Therefore, bench scale testing could be required to determine the suitability of a particular grout. Acid mine drainage typically has low pH and high sulfate concentrations which can be corrosive to some cement-based grouts, but, sulfate resistant cement grouts are available which are suitable for use in acid mine drainage situations. Clay-based grouts and chemical grouts can also be used to control the flow of AMD, but, laboratory testing is recommended before committing to an expensive grouting program.

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Design of the Grout Curtain

The placement and spacing grout injection boreholes is critical to the success of a grouting program. In most instances, construction of a grout curtain will require primary and secondary injection boreholes and some applications may require tertiary and quaternary sequences. Primary holes for a grout curtain are usually drilled on 20 to 40 foot centers. Secondary holes are placed approximately half way between primary holes in areas of higher permeability, or between primary holes that accept large quantities of grout. Tertiary holes are drilled between secondary and primary holes where appropriate. The grout curtain may be designed with all the primary holes in essentially a straight line with the same bearing and the same inclination. This is the least complicated approach, but, many situations prevent this type of design. Physical constraints or site layout may require that some holes be drilled at different orientations or inclinations. The transition from one grout hole orientation to another should be taken into account when designing the grout curtain. Under normal circumstances, primary holes will be slightly deeper than secondary holes. Total depth of primary holes will be determined by several factors including the depth of contamination by AMD, natural permeability barriers in the subsurface, or depth of well-developed fracture systems. Forty foot spacing between primary holes is typical in areas where hydraulic conductivity is relatively high and fracture connection is expected. A spacing of 20 feet between primary holes is recommended in areas where fractures are tighter and grout may not be able to penetrate great distances (Houlsby, 1990).

Summary

Pressure grouting can be used to control the flow of acid mine drainage in fractured bedrock. A review of geologic information, a compilation of fracture patterns in bedrock, and hydrogeologic studies to determine permeability are important in designing a grouting program. It is recommended that a pilot borehole program be initiated to develop additional specific information for the project. The AMD should be analyzed to determine its chemical and physical properties. Grout types should be evaluated to ascertain their suitability for use with AMD, which typically has a low pH and high sulfate concentration. The grout's rheological properties, resistance to chemical attack, and strength after setting, need to be considered in relation to the fracture size and hydraulic conductivity of the bedrock. Primary grout injection boreholes are usually drilled on 20 to 40-foot centers and are often inclined to intersect the greatest number of fractures. Secondary holes are placed approximately half way between primary holes in areas of greater permeability, or where grout takes in primary holes have been particularly large.

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