MICROFINE GROUTING IN TIGHT FRACTURES

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ABSTRACT

Microfine cements were used to grout tight fractures in basalt at McNary Dam in Umatilla, Oregon. Six boreholes were grouted with different microfine mixes. Hydraulic conductivity testing before and after the grouting provided a quantitative estimate of average fracture apertures and the effect of grouting on rock mass permeability. A downhole video camera survey was conducted in each hole to determine which fractures and joint sets allowed grout penetration. Pressure and the flow rate for grout were monitored during the testing. Total grout takes were calculated for each borehole stage grouted. Grouting pressures varied from less than a quarter to more than five times the estimated overburden pressure. The results of this testing indicate that tight fractures can be grouted with microfine cements. In addition, for tight fractures the relationship of injection pressures to grout take is significantly more non-linear than conventional grouting experience has suggested.

INTRODUCTION

Ongoing research at Waterways Experiment Station has as its objective investigation of the flow behavior of grouts in fractured rock masses. As part of this effort, a field investigation was conducted at the second powerhouse site of McNary Dam, a U.S. Corps of Engineers structure on the Columbia river near Umatilla, Oregon. The in situ study involved several overlapping research efforts that had as their focus grout rheology. The flow of grout in fractures is an issue of concern to designers of structures founded on rock, to engineers involved in underground construction, and to those planning the secure disposal of hazardous and radioactive wastes. Current plans for the disposal of high-level nuclear waste call for its isolation in underground, geologic repositories. Fractures in the rock mass surrounding a repository and its shafts may provide paths for contaminated fluids. In order to reduce their permeability, such discontinuities may have to be grouted.

Sinclair (1) reviewed major factors that determine the groutability of fractured rock masses. The primary factor is the geometry of the discontinuities or voids. The geometry of a discontinuity includes its widths or aperture, orientation, continuity, surface characteristics and filling. The width or aperture of the discontinuity to be grouted is critical. If the discontinuity is not wide enough, the cement particles cannot enter. Littlejohn (2) states that maximum particle sizes for cements range from 0.044 to 0.100 mm. A number of researchers have investigated the minimum fracture width that will allow grout to pass. Kennedy (3) suggests that aperture must be three times the maximum particle size. Morozov and Goncharov (4) state that the ratio should be four to five. Ruiz and Leone (5) establish a minimum fracture width of 0.2 to 0.4 mm. Cambefort (6) suggests widths of 0.1 to 0.5 mm. Burgin (7) proposes widths of 0.15 to 0.20 mm. Houlsby (8) states that 0.5 mm is the minimum fracture wdth while Littlejohn (2) and Bruce and Millmore (9) suggest 0.16 mm as a minimum.

Recent research by Shimoda and Ohmori (10) and others suggests that microfine cements may be able to penetrate fracture widths as tight as 0.02 to 0.05 mm, assuming ratios of fracture aperture to maximum particle size of two to five. Manufacturers of microfine cements claim a maximum particle size of approximately 0.01 to 0.014 mm.

Test Site

The test site is located at the projected location of a second powerhouse for McNary Dam, a U.S. Corps of Engineers structure on the Columbia River near Umatilla, Oregon. The powerhouse site lies in the central portion of the Columbia Plateau. Previous to the testing, the local geology had been extensively investigated through a program of exploratory drilling for construction site characterization.

The bedrock units on which the second powerhouse is to be founded consist of three major units. These are the Umatilla flows of the Saddle Mountain basalt, the Mabton interbed and the Priest Rapids member of the Wanapum formation. Extensive areas of glaciofluvial and modified fluvial gravel terraces are apparent on both sides of the dam. Eolian sands and silt mantle most of the gravel terraces.

Drilling and testing for this research was conducted in the Umatilla Member of the Saddle Mountain Basalt. This unit consists of a breccia top of varying thickness and a massive basalt. The breccia is closely fractured with basalt fragments in a clay matrix. Basalt fragments are surrounded by a weathering halo. The basalt is dark gray to black, fine-grained, vitric, and dense with small plagioclase laths weathered to clay. Fractures in the basalt are primarily healed with dark green chlorite and/or occasionally calcite. Very few vesicles are present in the rock. Approximately 6 meters of silts, sands and gravels cover the bedrock in the vicinity of the test site. Nearly a meter of breccia directly overlie the bedrock. All testing was performed in the massive bedrock.

Preliminary permeability testing during construction site characterization indicated a gross average hydraulic conductivity for the Umatilla Member Basalt of 3.8 X 10^{-5} cm/sec. The water table at the site is consistently approximately 2.74 meters from the surface. All testing and grouting were performed under saturated conditions.

Drilling and Testing

The six boreholes used in this study were nx diameter, cased through the overburden and loose breccia, and cored to depths of 12.2 to 13.7 meters. The core for each hole was logged and analyzed for fracture geometry. Figure 1 is a frequency plot for orientation of fractures in one of the boreholes tested. Average dip values for the holes ranged from 30 to 40 degrees. Figure 2 is a histogram of fracture spacing for the same borehole.

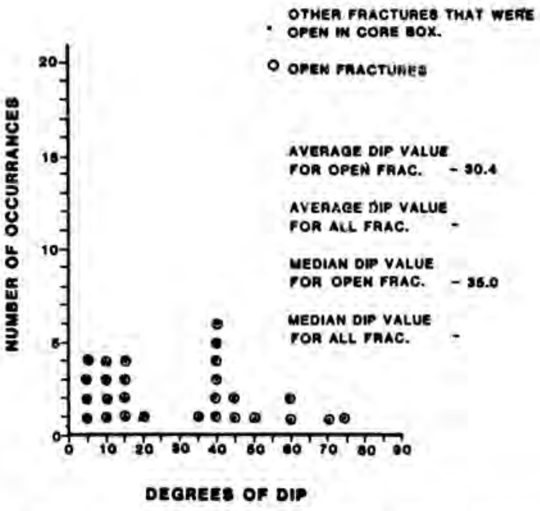

Fig. 1. Frequency Plot for Borehole Fracture Orientation.

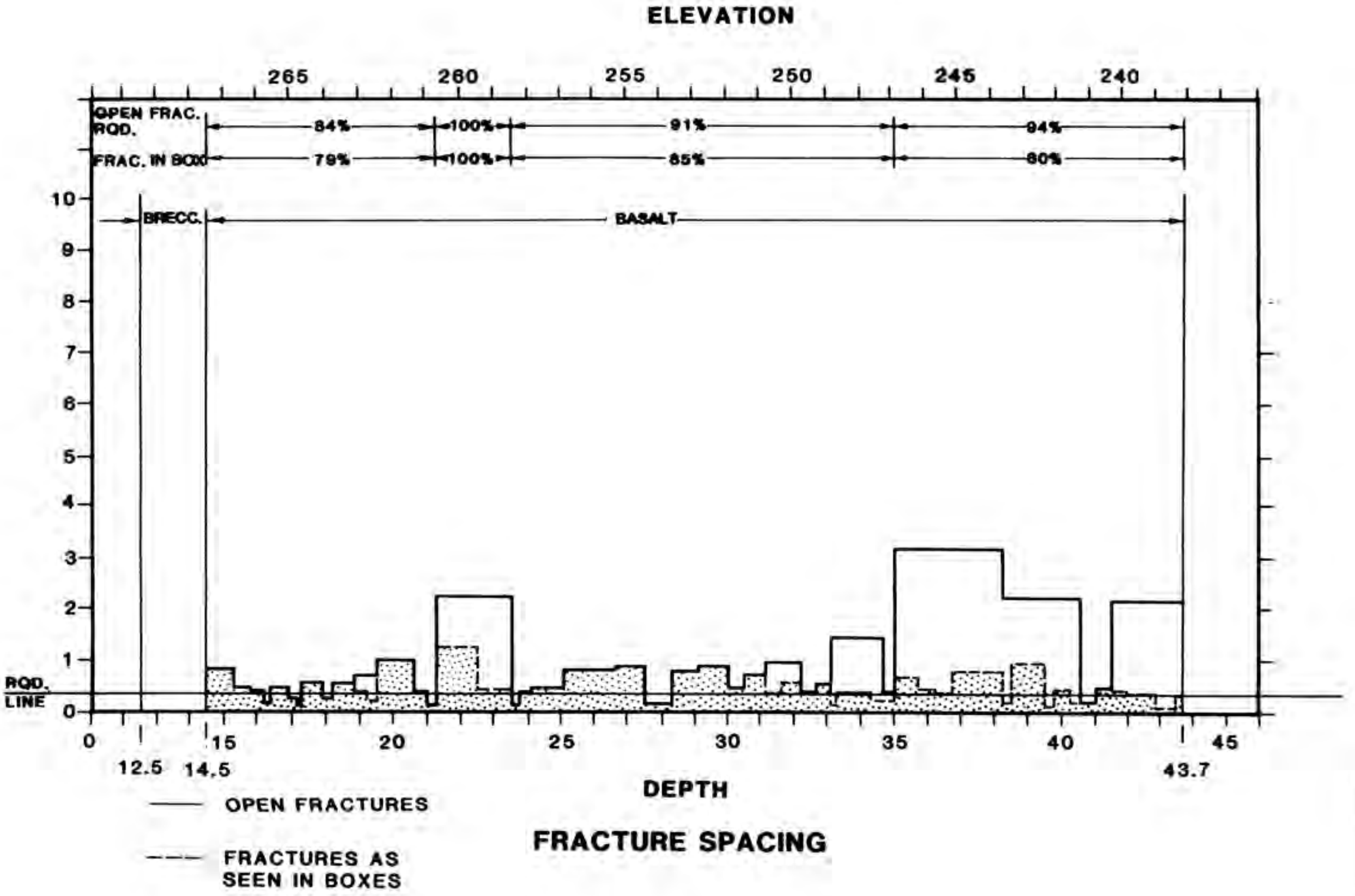

Fig 2. Borehole Fracture Spacing.

Permeability testing of the boreholes was performed with a straddle-packer injection system and a multi-transducer downhole tool. The tool is described in detail in Bennett and Anderson (11). Flow was measured using a differential pressure flowmeter designed and built at Waterways Experiment Station. The flow meter uses a system of sized orifices mounted in-line and can be calibrated and used for fluids of various viscosities. The flowmeter was used for water and grout injection. Uphole instrumentation included a 12-channel data logger and a 3 pen strip chart recorder.

Table I summarizes the results of hydraulic conductivity testing at the field sites. Boreholes were numbered 413 through 418 consecutively. A total of 39 meters of borehole was tested for hydraulic conductivity and estimated effective fracture aperture. Test lengths were uniformly .88 meters. Each interval was tested with a minimum of three pressures. Pressures ranged from less than half to more than five times the estimated overburden pressure. At no time during the testing was any fracture jacking or fracture deformation indicated in the flow-pressure real-time record. Each test was continued until pressure and flow had stabilized.

It should be noted that effective fracture aperture calculations are made assuming that all fractures mapped from the core record are capable of conducting fluid. The apertures calculated for each interval are average values over the number of fractures noted. Effective fracture apertures were estimated by assuming that the cubic law is valid over the pressure and flow domain used in this testing.

Grouting

Grouting at McNary Dam was performed with a microfine cement manufactured in Japan and distributed in the United States by Geotechnical Corporation, Ridgewood NJ. Microfine grout is a finely ground cementatious mix with approximately fifty percent slag by weight. Average particle size is approximately 4 microns. Extensive testing of the grout in the laboratory at Waterways Experiment Station has shown that in stable mix proportions, the microfine cement exhibits high strength, extremely low permeability and a set time of 4 to 6 hours.

The grout was prepared for injection in a large-capacity, high speed colloidal mixer. Two different mix ratios were used. The five-to-one water-to-cement ratio was prepared (per batch) with 200 liters of water, 40 kilograms of microfine cement and 0.4 liters of a Naphthlene Sulfonate dispersant in liquid form. The two-to-one water-to-cement ratio mix used 200 liters of water, 100 kilograms of microfine cement and 1 liter of dispersant.

Marsh funnel viscosity measurements were made before each injection. A surprising aspect of the grout preparation was that the flow characteristics of both types of mixes were approximately the same. Viscosities for both ratios were very close to water. This observation was later repeatedly confirmed in laboratory testing both at Waterways Experiment Station and by the Bureau of Reclamation in a similar investigation.

TABLE I

Results of Hydraulic Conductivity Testing

HYDRAULIC CHARACTERISTICS	BOREHOLE					
	DH 413	DH 414	DH 415	DH 416	DH 417	DH 418
Length of hole tested	20.3 ft	17.4 ft	20.9 ft	28.6 ft	17.4 ft.	23.2 ft
Number of fractures	42	61	71	76	49	75
Average Fracture Spacing	.5 ft	.3 ft	.3 ft	.4 ft	.4 ft	.3 ft
Fracture Density	2.1	3.5	3.4	2.7	2.8	3.2
Thickness of Breccia Zone	8 ft	6 ft	2 ft	1 ft	5 ft	2 ft
Flow Rates Measured (gpm)	.003-.07	.004-3.3	.002-19.9	.002-2.0	.001-.02	.002-.02
Test Section Pressures (psi)	1-250	12-212	90-286	45-256	48-325	9-250
Estimated Fracture Aperture (average)	10-30	10-40	8-65	9-28	8-10	9-12
Range of Calculated Hydraulic Conductivities (cm/s)	$1.9x10^{-7}$ $1.0x10^{-6}$	$2.4x10^{-7}$ $2.3x10^{-4}$	$7.9x10^{-8}$ $3.9x10^{-4}$	$1.1x10^{-7}$ $4.1x10^{-5}$	$5.2x10^{-7}$ $1.0x10^{-6}$	$1.2x10^{-7}$ $1.0x10^{-6}$
Estimated Lugeon	.01-.3	.02-14	.01-85	.01-9	.005-.1	.01-.1

Table II summarizes the results of grout injection for each borehole. Grouting procedure involved trimming each borehole stage with grout before packer emplacement and pressure injection. Volumes injected are therefore volumes emplaced in the fractured rock. The flow meter was calibrated for each mix and flow rate monitored during the entire time grout was under pressure. A minimum of two, and frequently, three different grouting pressures, were used. At no time was there evidence of fracture jacking or fracture deformation.

TABLE II

Results of Grout Injection

GROUTED CHARACTERISTICS	BOREHOLE DH 413	DH 414	DH 415
Length of Grouted Hole	**26.1 ft**	**25.5 ft**	**26.0 ft**
Number of Zones Grouted	**1**	**2**	**1**
Grouting Pressures	**100-150**	**50-100**	**50-100**
Grout Type Used	**MC 500**	**MC 500**	**MC 500**
Marsh Funnel Viscosity	**27.6**	**26.9**	**27.6**
Water/Cement Ratio	**5:1**	**2:1**	**5:1**
Grout Take	**1.5 gal**	**6.7 gal**	**1.5 gal**
Length of Time Grouted	**19.5 min**	**21.5 min**	**16 min**
Grouting Rates (gpm)	**.06-.07**	**.13-.63**	**.05-.17**

GROUTED CHARACTERISTICS	BOREHOLE DH 416	DH 417	DH 148
Length of Grouted Hole	**23.7 ft**	**24.0 ft**	**28.9 ft**
Number of Zones Grouted	**1**	**1**	**2**
Grouting Pressures	**50-150**	**50-150**	**50-150**
Grout Type Used	**MC 500**	**MC 500**	**MC 500**
Marsh Funnel Viscosity	**27.6**	**27.2**	**27.6**
Water/Cement Ratio	**2:1**	**5:1**	**5:1**
Grout Take	**3.0 gal**	**6.3 gal**	**3.0 gal**
Length of Time Grouted	**21.5 min**	**38 min**	**29 min**
Grouting Rates (gpm)	**.1-.2**	**.15-.28**	**.1-.13**

An important part of any grouting job is an estimate of the extent of penetration by the grout into the fractured rock mass. This is usually inferred from the grout take for each hole grouted. For grouting in tight fracture environments, conventional comparisons may be misleading. With flow rates low enough to suggest rejection under most commercial grout applications, tight fractures may be taking grout to significant distances from the borehole wall. Figure 3 illustrates this possibility with an idealized, uniform aperture, horizontal and planar fracture set intersecting a borehole.

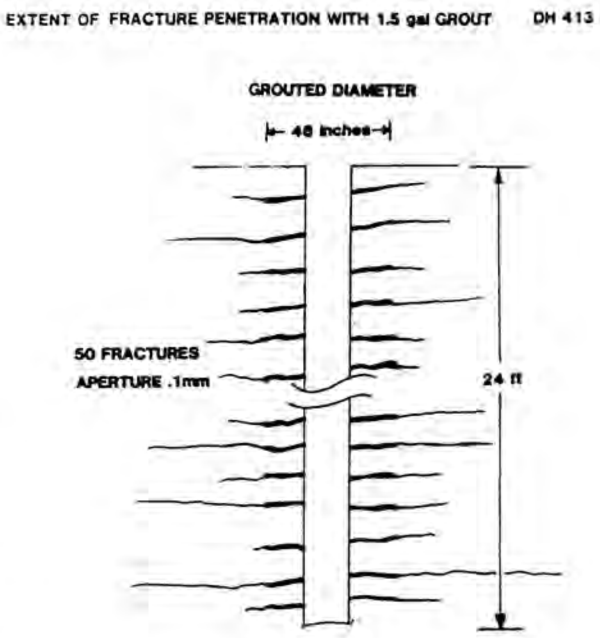

Fig 3. Grout Penetration into Rock

A downhole video camera was used to review the results of the grouting. One month was allowed for curing and then the six boreholes were carefully reamed to remove all grout from the holes and borehole walls. The video record shows that most of the fractures took some grout but that a number of fractures were empty over part of their visible trace.

A post-grouting permeability test was conducted in selected intervals of the reamed holes. A minimum of three test sections were investigated in each hole. In all cases, the hydraulic conductivity was too low to measure with the equipment available at the site. In most cases, no flow could be detected at any of the test section pressures previously used.

Grout Flow and Pressure

One interesting aspect of the investigation at the McNary Dam field site was the relationship of grout flow rates to pressure and time. A preliminary analysis of the data shows that grout take will decrease relatively over time even as the pressure is increased. Figure 4 is a plot of normalized flow over pressure against time for grouting in one of the boreholes. Grouting was continued over a range of pressures with no significant increase in grout take recorded. Figure 5 is a plot from another hole that shows a very similar trend. In this case, flow is plotted against time for three different pressures. These results suggest that for tight fracture environments, high pressures may not achieve an enhanced flow rate unless the fractures are jacked or deformed.

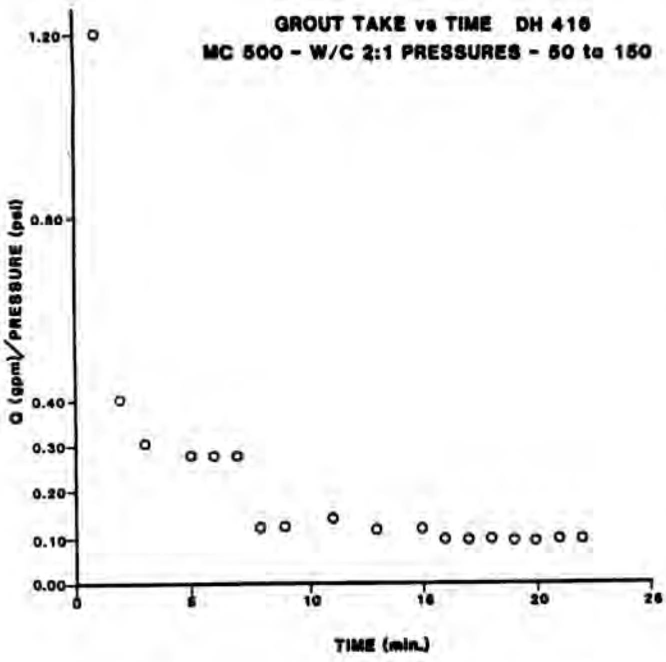

Fig. 4. Normalized Grout Flow Over Time.

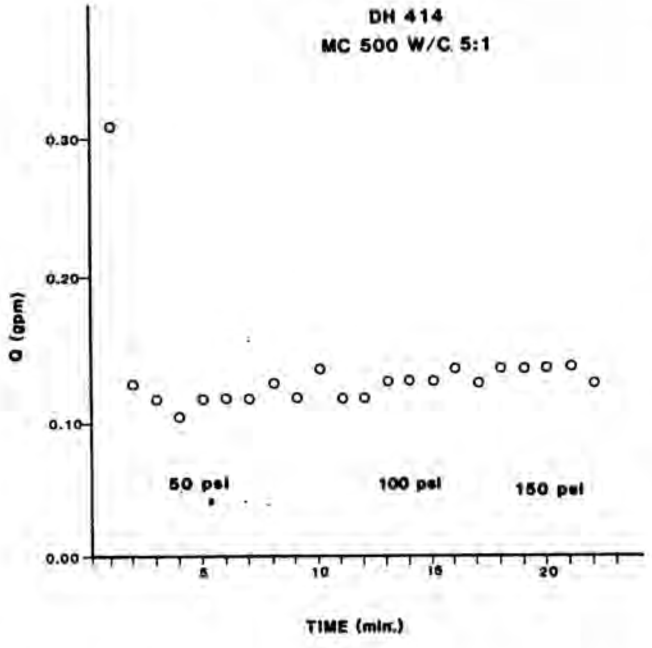

Fig. 5 Grout Flow for Three Injection Pressures.

CONCLUSIONS

Experience at the McNary Dam field site suggests that fractures with very tight effective apertures can be grouted with microfine cement grouts. Though it is difficult to distinguish fractures allowing fluid flow from those that do not, the grouting record and post-grouting borehole examination suggest that fractures with apertures of less than 100 microns and perhaps as small as 40 microns can be sealed with practical grouting pressures that do not deform the fractures. The results of the grouting demonstrate a significant decrease in an already low hydraulic conductivity rock mass. The volume of grout take per stage grouted can be used for an approximate estimate of grout penetration. Even low volume takes may provide significant rock mass penetration in a tight fracture environment. Finally, the flow and pressure records at McNary suggest that high grouting pressures may not achieve any increase in grout take in tight fracture environments. For applications such as foundations or geologic repositories, where minimizing fracture deformation is required, this may be an important consideration and an area of future research.

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