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Advanced Grouting Program at Penn Forest Dam Results in Reduced Construction Costs and High Quality Product

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Abstract

The new Penn Forest Dam was constructed to replace the old earthfilled embankment dam. The new dam is a roller compacted concrete dam located just upstream from the original dam. The new dam is approximately 180 feet high and 2000 feet long.[3]

The new dam includes a triple-row grout curtain. The first grout line (A-Line) was constructed using conventional grouting techniques, including conventional neat cement grouts, manual monitoring techniques and visual pressure gauge recording and dipstick measuring grout flow and takes. The B-Line and C-Line were constructed using balanced stable suspension grouts (additive enhanced formulations) and computer monitoring and evaluation system.

Compared with the conventional method, the advanced grouting system resulted in a higher quality product and significant cost savings for the owner in construction, inspection and schedule related costs as summarized in Fig. 1. The following paper summarizes and outlines the benefits of using stable suspension grouts and a computer monitoring and evaluation system.

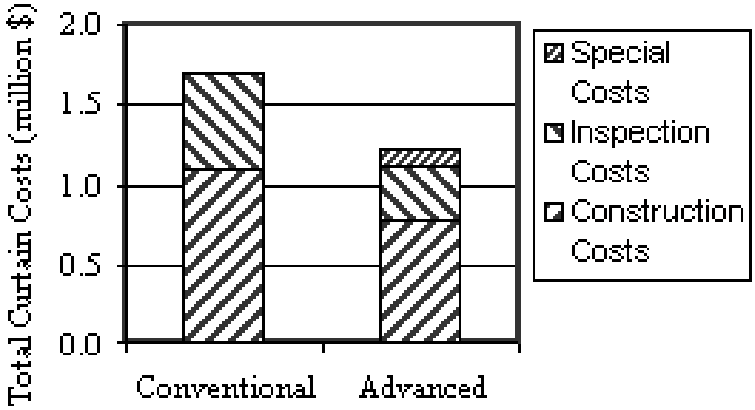

Fig.1 Total Curtain Costs Between the Two Methods

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Grouting Materials and Mixes

The purpose of using additives in cement-based grouts is to improve the stability (bleeding) and rheological properties (viscosity, cohesion and internal friction or bond) of the grout in order to enhance the penetrability and flow characteristics of the grouting material. Fig. 2 shows two laws of rheological behavior: a purely viscous fluid such as water (Newtonian) and a Binghamian fluid, characterized not only by viscosity but also by cohesion.

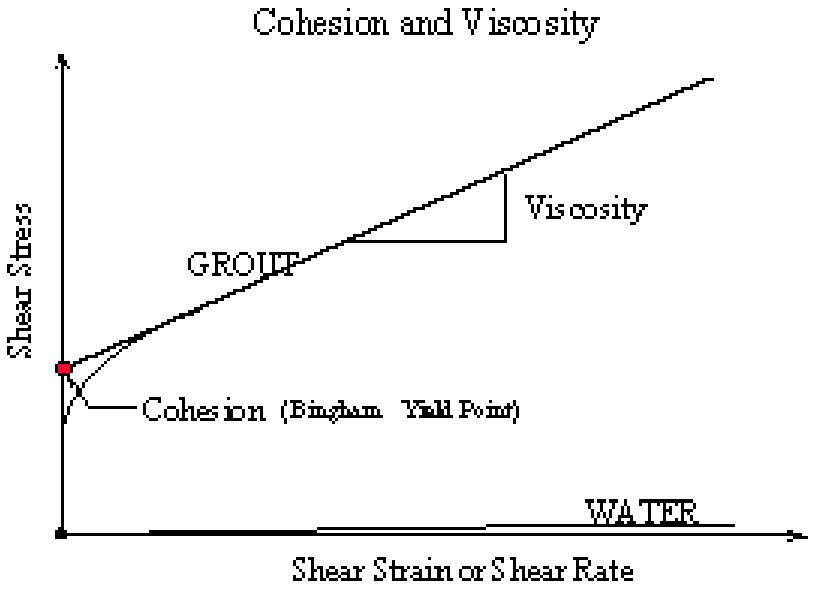

Fig. 2 Typical Rheological Laws of Two Types of Fluids

The additives used for this project include bentonite, flyash, welan gum and superplasticizer. The properties of the enhanced neat cement grouts (B and C Lines) used at the Penn Forest Dam are summarized in comparison with the conventional neat cement grouts (A Line) and are shown in Fig. 3-8.

Viscosity: Viscosity was measured with a Marsh Cone following the API standard procedure[2]. As indicated in Fig. 3, balanced stable cement grouts can be formulated to provide similar apparent viscosity or Marsh Cone flow time, compared to conventional neat cement grouts. A slightly higher viscosity was obtained with the additives.

Cohesion: Cohesion values were determined in accordance with the procedures outlined by Lombardi[4]. The cohesion of the balanced stable grouts is lower than the neat cement grouts due to the deflocculating effect of the superplasticizer (Fig. 4). The slightly higher viscosity values result in a slightly lower injection rate. However, the lower cohesion value theoretically provides a greater radius of grout penetration with the balanced stable grouts for a given fracture aperture.

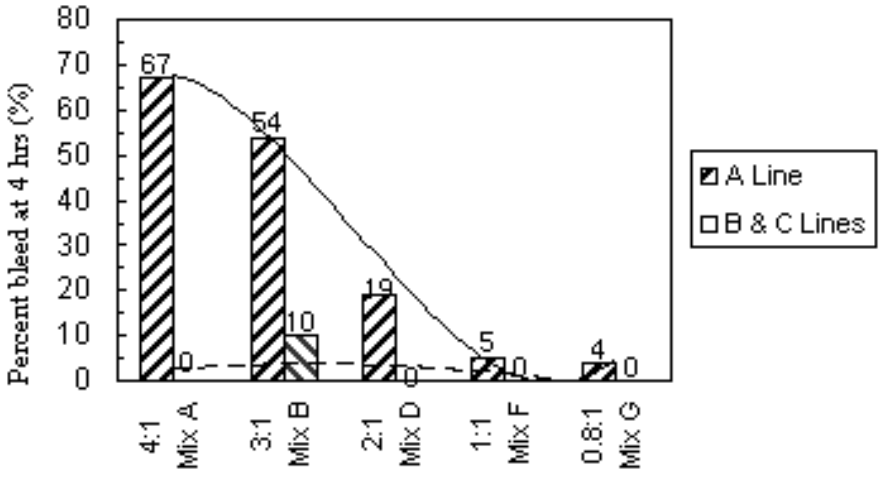

Fig. 3 Average Marsh Funnel Viscosity

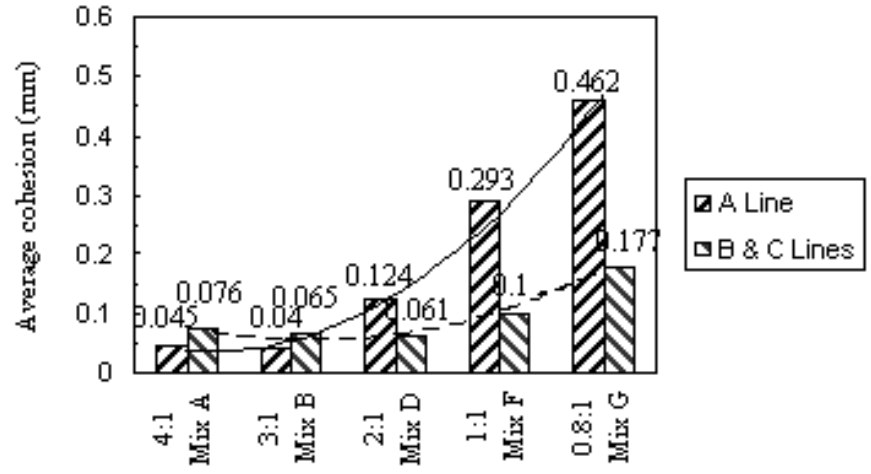

Fig. 4 Average Plate Cohesion

Bleed: Bleed was measured in 1-liter graduated cylinders. The difference in stability or bleed between the two types of grout is very significant as shown in Fig. 5. Bleed water accumulation that occurs in the grout after refusal has been obtained will result in incomplete filling of the fractures. This incomplete filling results in the likelihood of significant secondary permeation after grouting and a subsequent reduction in durability due to the network of flowpaths provided by the bleed channels.

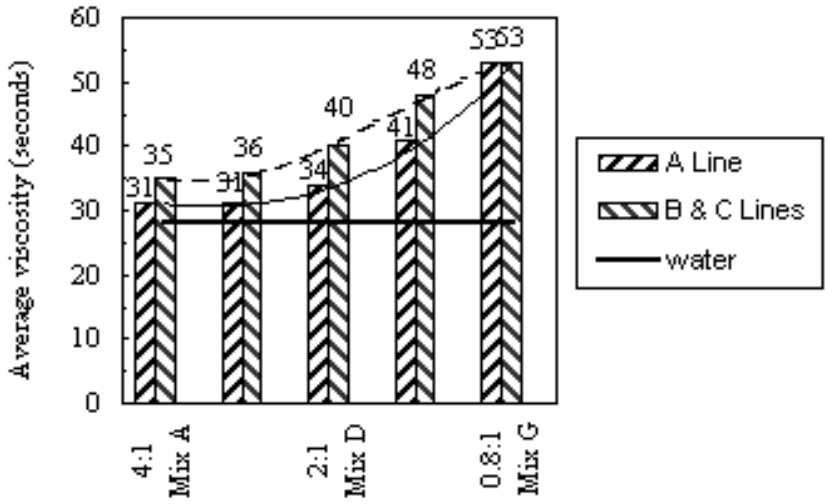

Fig. 2 Typical Rheological Laws of Two Types of Fluids

Pressure filtration: Pressure filtration is the occurrence of mix water within the fluid grout separating from the cement, particularly during the pressure grouting operation. The coefficient of pressure filtration is determined based on the API filter press test procedure[1]. The pressure filtration characteristics of the balanced, stable mixes are clearly superior to the conventional neat cement grouts, as indicated in Fig. 6. It was observed that the neat water cement grouts blow air after only 2 to 3 minutes, which indicates that most of the water has been squeezed out. Two negative impacts are clearly indicated by the high-pressure filtration value and bleeding, as shown in Figs. 9-10. Firstly, the rheology of the neat cement grouts is not stable during the pressure injection process and results in self- thickening (sedimentation). The balanced stable grouts sustain a longer pumping distance with no sedimentation or dry packing occurring. The second negative impact is that significant amounts of water are being injected into the formation being attributed to "grout take".

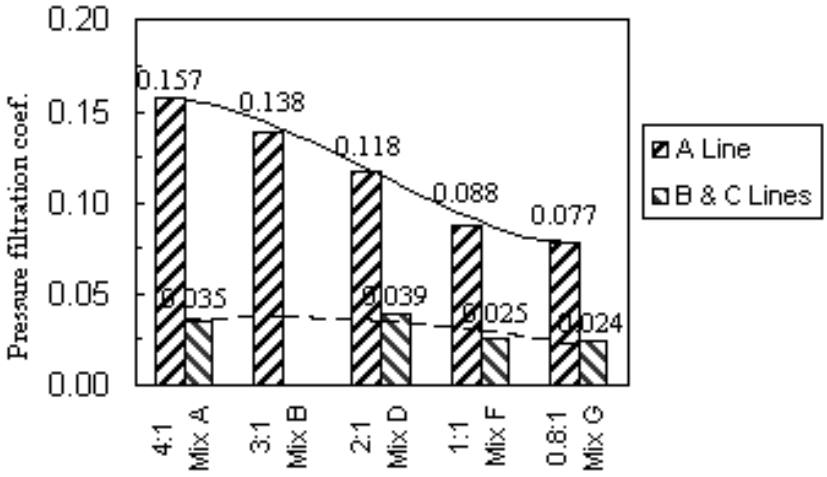

Fig. 6 Pressure Filtration Coefficient

Thixotropic set time: This test was performed in accordance with the procedures described by Weaver[6]. The results of thixotropic set time testing are indicated on Fig. 7. As expected, the additives in the balanced stable grouts slow the hydration process and thus result in a slower set time. These results also suggest that the neat cement grouts older than 2 hours should be discarded as significant chemical bond or internal friction are beginning to form. The balanced stable grouts provide a longer working time and reduce possible costs by discarding grouting materials.

Compressive strength: Fig. 8 shows the comparison of compressive strengths, indicating the balanced stable grout having a lower overall compressive strength than the neat cement grouts, but are greater than 500 psi (Mix B is about 200 psi). Grouts with a compressive strength in excess of 200 psi are generally sufficient to perform their water seepage control function and provide adequate durability.

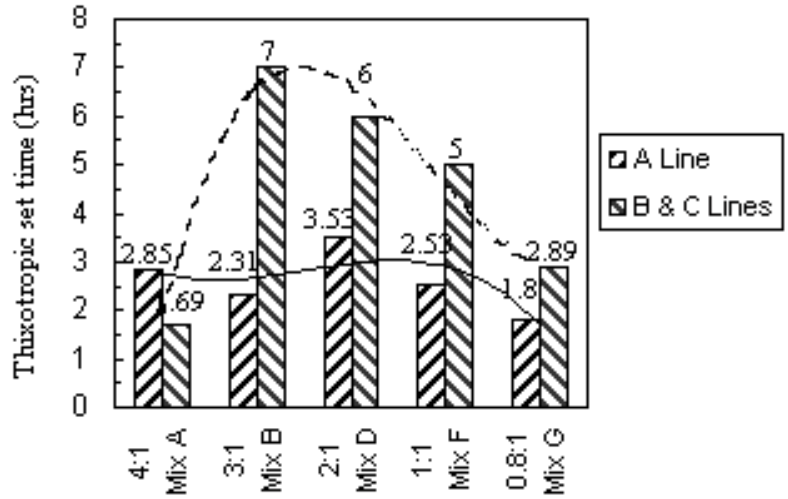

Fig. 7 Thixotropic Set Time

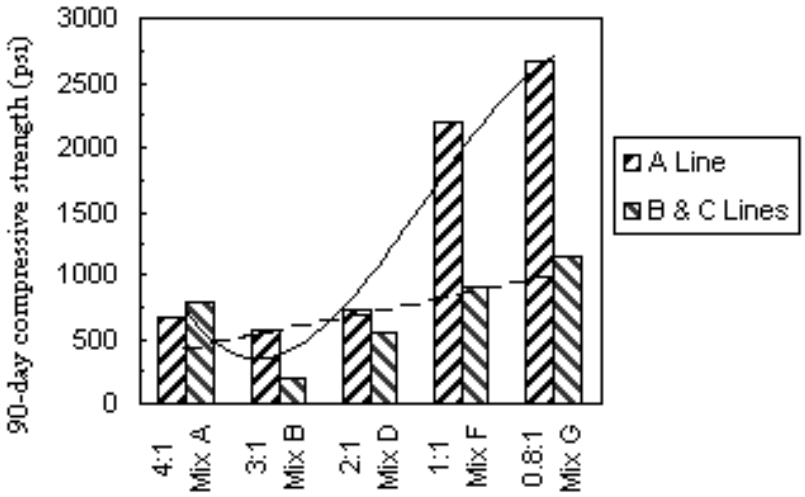

Fig. 8 90-Day Uniaxial Compressive Strength

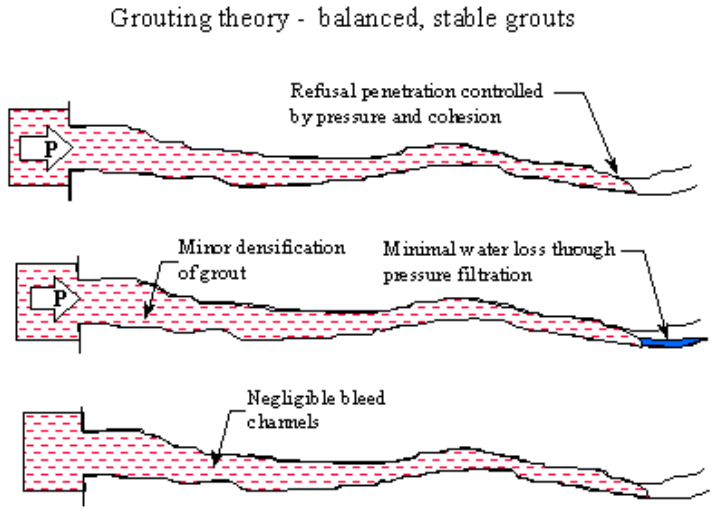

Fig. 9 Grouting Theory – Balanced, Stable Cement Grouts

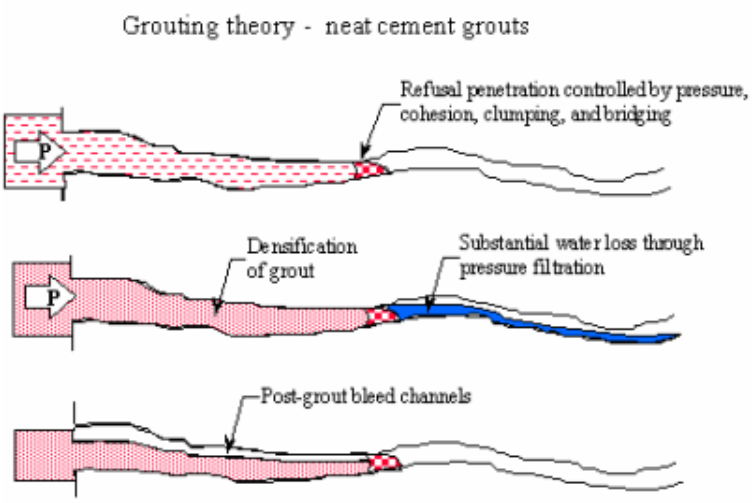

Fig. 10 Grouting Theory – Neat Cement Grouts

Computer Automatic Monitoring and Evaluation System

A-Line was grouted using conventional monitoring and control technology. Grouting monitoring, recording and analysis were primarily performed with mechanical instruments and manual methods. The execution of the grouting work was performed to a high standard consistent with the means, method and equipment used for this level of control technology.

The B-Line and C-Line grout curtains were constructed using advanced monitoring and control system. This system consisted of pressure and magnetic flow transducers, data acquisition hardware and windows based computer monitoring, analysis and assessment software called Computer Aided Grouting Evaluation System (CAGES)[2].

CAGES is real-time data acquisition, monitoring, analysis and evaluation software. CAGES performs three major functions:

- Monitoring the evolution of the grouting operation by displaying the trend of grout flow, grouting pressure and apparent Lugeon value (apparent permeability) in a real-time and graphical form.
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- Evaluating the suitability of initial grout mix and grout takes of the formation to be grouted in real-time.
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- Displaying other grouting data such as grouting time, radius of grout spread, and effective grouting pressure.

CAGES has the capability to select the type of grouting (rock or soil grouting), number of holes/stages to be injected, grout formulations and displaying and recording frequency. Each hole or stage has its own user-defined parameters such as file name, stage length, grout column, water table, gauge height, and hole angle.

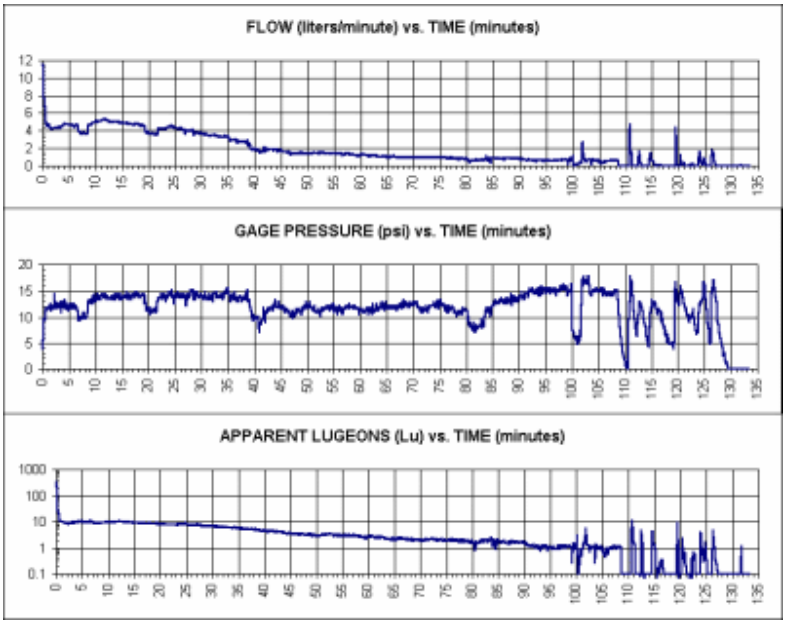

Fig. 11 Typical graphical presentation for a stage with a water Lugeon value of 20

CAGES can also perform water tests using water instead of cement grout. The permeability (Lugeon value) of a particular hole or stage is continuously displayed both graphically and digitally. The duration of the water test can be significantly reduced when the Lugeon value becomes constant.

Particularly, all grouting parameters and grouting data are stored in the computers hard-drive. These data can be used for retrospective analysis. Upon grouting a hole or stage, the grout flow, gauge pressure and apparent Lugeon value can be printed out immediately as shown in Fig. 11.

The most crucial part is the determination of initial mix formulation. The selection of the initial mix formulation is based on the water test. The suitability of the initial formulation is assessed at the initial stage of grouting operation by the Amenability coefficient[5], which is a measure of the suitability of a given suspension grout for permeating fissures and apertures accessible to water in the grouting zone. A low amenability coefficient indicates that grout is not permeating the apertures that are accessible to water. Based on the trends of flow and apparent Lugeon value, the grouting operator can initiate subsequent changes in grout mix.

By visually displaying grouting data, the engineer can track the trend of the apparent Lugeon, flow and radius of grout spread and the accumulated grout takes in real-time. This information allows the engineer to assess how well a particular grout suits the formation and to make quick, sound decisions when changes are needed in the grout formulation during the rock or soil grouting operation.

There are several major advantages of the advanced monitoring and evaluation system over the conventional method, namely

- Providing real-time information on flow rate, pressure, apparent Lugeon value and theoretical grout spread,

- Visually displaying the trends of grout flow, apparent Lugeon value and grout takes,
- Sudden changes in apparent Lugeon values are timely identified and dealt with. Higher pressures can safely be used as long as no sudden increase in apparent Lugeon value takes place,
- Allowing engineers pay more attention on decision-making than manual recording and hand-calculation,
- Providing detailed, accurate, permanent records showing complete history of
- grouting operation,
- Allowing multiple holes or stages grouting,
- Reducing the amount of inspection time required,
- Eliminates non-effective (run-away) grouting operations,
- Select amenable formulations avoiding the use of expensive microfine cement when regular cement based grouts are equivalently amenable,
- Providing scientific data regarding suitability of grout-mixes for a given formation.

Summary

The introduction of advanced stable grouting materials and implementation of electronic monitoring and computer aided analysis for the Penn Forest Dam have shown an improved grouting quality at a reduced overall cost. The construction industry and Engineering community can now construct and design qualitative engineered grout curtains for dams with a high degree of confidence.

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