Use of AMD Sludge for Low-Cost Mine Grout

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Summary

Disposal of metal precipitates (sludge) from the treatment of acid mine drainage (AMD) normally involves construction of a surface pond for settlement and decant of clear water. Accumulation of the sludges (typically less than 3% solids) requires cleanout and disposal. Placement of sludges in above drainage underground mines (the type which produce the most AMD) is risky since the sludge has the potential to exit the mine through some weakness in roof or barrier. This paper evaluates the potential of turning AMD sludge into a flowable grout which would develop enough strength to prevent subsidence and flow well enough to minimize the number of injection holes.

The objective of this research was to design a method for the disposing the sludge from a Acid Mine Drainage (AMD) treatment pond in underground mines. A case study developed in a typical West Virginia setting required disposal of approximately 1,000,000 yd^3 of sludge from a treatment pond and a mine void volume of about 400,000 yd^3. An AMD sludge from a typical Kittanning seam Lime treatment plant was used.

The study found that kiln dust/sludge mixtures will form an acceptable grout. However, later study indicated that a mixture of sludge, class F fly ash and kiln dust in a ratio of about 1:1:1 will form a grout that can be easily injected into the mine and will form a reasonably strong, solid material. Addition of fly ash substantially reduces the kiln dust requirement and provides a stronger grout.

The strength of the grout was tested with unconfined compression tests of grout samples approximately 28 days after pouring. The flowability of the grout was established by measuring the physical and rheological properties of the grout and using those parameters in analytical and numerical models to calculate the spread in particular room and pillar mines.

Requirements

In its untreated state, the AMD sludge at the site is not stable and will not achieve rigidity after any reasonable amount of curing time. Stability and curing time can be improved by chemically binding the excess water in the sludge with a pozzolanic material and forming a grout. In order to dispose of the AMD sludge in this manner, the grout produced with the sludge must satisfy some basic requirements. For purposes of economy, the grout must be a mixture of the sludge and an inexpensive industrial byproduct. The amount of sludge that can be disposed in the mine is directly proportional to the sludge content of the grout, therefore the grout should contain as much sludge as possible. After the grout is injected into the mine, it must be able to flow an indefinite distance under the influence of gravity and remain reasonably stable and homogeneous. In order to stabilize the AMD sludge, the grout must also achieve rigidity after 28 days of curing. Because the grout will not be required to mitigate mine subsidence at the site, rigidity is defined as having an ultimate strength that will prevent grout movement after the injection operation is complete. Therefore the minimum allowable strength was determined to be 200 lbs/in^2.

Stability

The stability of the grouts produced with cement kiln dust appeared to be a function solely of the water content. Because the grout is produced by mixing the cement kiln dust directly with the AMD treatment pond sludge without any additional water, the final water content depends entirely upon the water content of the sludge. Because the sludge is created by natural processes operating in the treatment pond, the sludge water content is a function of the location inside the pond where the sludge is collected and the amount of runoff present in the pond. Due to the variability present in the sludge, this research was forced to specify that the treatment pond sludge have a specific weight of 64 ± 1 lbs/ft^3 which roughly corresponds to a solids content of 8%.

Flowability

The ability of the grout to flow was measured by performing spread tests. This test is performed by filling an open ended, 3.0 in diameter, 6.0 in high, cylinder with grout. When the cylinder is quickly lifted off the surface, the grout forms a circular mound, and the average diameter of the mound is recorded. The most important parameter in the flowability of the grout is the yield stress. The yield stress of the grout is calculated with the following equation derived from the radial spread formula presented by ASTM, STP1331 (Gray, Reddy, Black and Ziemkiewicz, 1997).

$$\tau_y = \frac{225\gamma V^2}{128\pi^2 r_{max}^5} = \frac{225\gamma V^2}{4\pi^2 D^5} \qquad (1)$$

Where:	V	=	Volume of the open-ended cylinder used for the spread test.
		=	0.024544 ft^3
	r_{max}	=	Radius of the circular mound of grout.
	D	=	Diameter of the circular mound of grout.
	t_y	=	Yield stress of the grout.
	g	=	Specific weight of the grout.

The specific weight of the grout is normally directly measured, but can also be calculated from the grout recipe and the solids density of the grout's ingredients. Table 1 contains a summary of the results of the spread tests with the cement kiln dust grouts. While, the yield stress appears to decrease as the cement kiln dust content increases, more data is required before a general rule could be established.

Table 1. Cement Kiln Dust Grout Spread Test Data.

Content (lbs/yd^3)	Spread (in)	Specific Weight (lbs/ft^3)	Yield Stress (lbs/ft^2)
280	7.1	69.6	3.3

290	8.0	69.8	1.8
742	9.3	78.8	1.0

Ultimate Strength

The ultimate strength of the grout was measured by pouring cylindrical molds with an inside diameter of 3 inches and an inside height of 6 inches. After pouring, the top of the molds were covered with thin plastic sheets held with rubber bands and the grout was allowed to harden in the molds for approximately two weeks. When the two weeks, the grout achieved some degree of solidity and the molds were removed with compressed air. After the molds were removed, the grout cylinders were allowed to harden for two more weeks in open air. After the final hardening period was completed, the strength was measured by determine the compressive force required to destroy the unconfined grout cylinder. The ultimate unconfined compressive strength of the grout was calculated by dividing the load required to destroy the unconfined cylinder by the cross section area of the grout cylinder.

A summary of the unconfined compression tests performed on the cement kiln dust grouts is shown in Table 2. The data from the tests with the cement kiln dust grout indicate that the primary variable controlling the final strength is the material content.

Table 2. Observed Strength of Cement Kiln Dust grouts.

Content (lbs/yd^3)	30 Day Unconfined Compressive Strength (lbs/in^2)
280	170
290	150
545	230
742	290

A statistical model of the relationship between cement kiln Dust content and 30 day unconfined compressive strength can be derived by fitting a regression model to the data listed in Table 2. The following linear model had a maximum error of 12 lbs/in^2 when compared to the observed data. Therefore, approximately 430 lbs/yd^3 of cement kiln dust will be required to achieve an unconfined compressive strength of 200 lbs/in^2. Given the properties of the AMD treatment pond sludge, the specific weight of the grout will be 72.6 lbs/ft^3 and the yield stress will be between 1.0 lbs/ft^2 and 1.8 lbs/ft^2.

$$F = 79.30 + 0.2815\,C \quad (2)$$

Where:	F	=	Estimated unconfined compressive strength of grout (lbs/in^2).
	C	=	Cement kiln dust content (lbs/yd^3).

Spread

As was stated above, the most important rheological parameter controlling the ability of the grout to spread after being injected in the mine is the yield stress. If the underground mine consists of a level, open room without any pillars to divert the flowing grout, then equation (1) can be rearranged and used to calculate the ultimate spread of the injected grout. Figure 1 is a plot of the radial distance covered by the injected grout versus the yield stress of the grout. Since experience has shown that it is possible to inject 700 yd^3 of grout into an underground mine in a day, Figure 1 uses an injected grout volume of 700 yd^3 and a specific weight of 72.6 lbs/ft^3. In order to cover most physically realistic grouts, the yield stress is varied between 0.1 lbs/ft^2 and 10 lbs/ft^2.

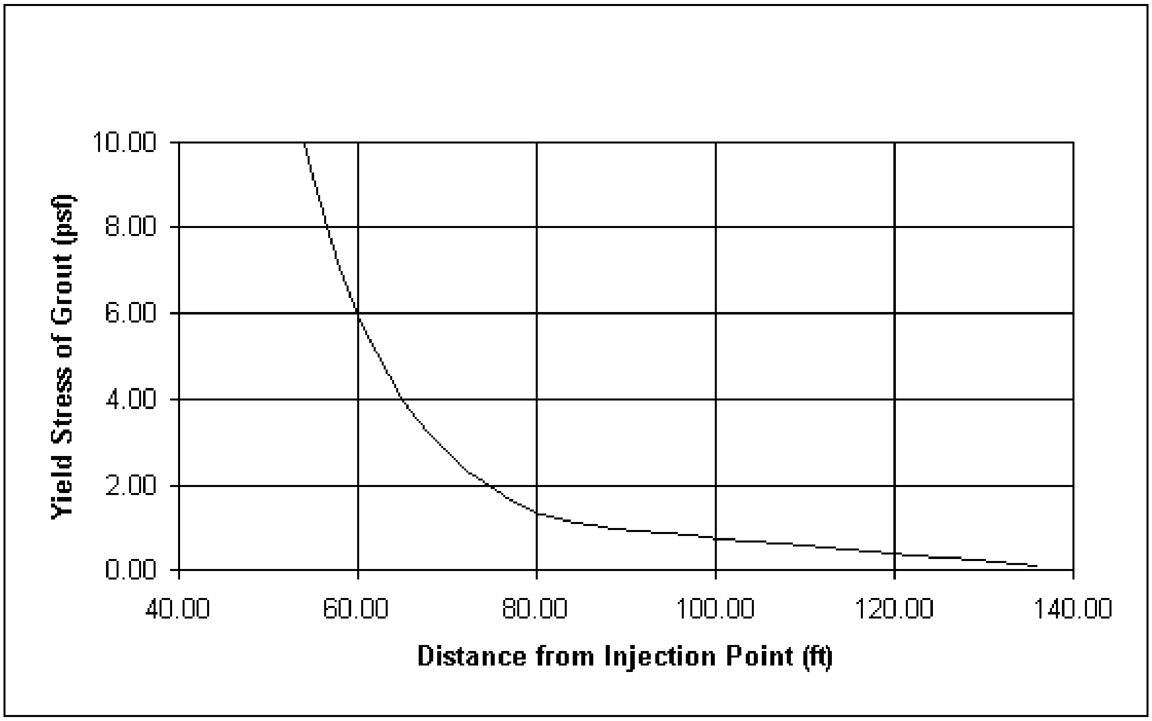

Figure 1. Maximum Spread of Injected Grout.

While the formula used to create Figure 1 indicates that the grout with a yield stress of 0.1 lbs/ft^2 will spread 135.8 ft, the yield stress does not specify the time required by the grout to spread the predicted maximum distance. Since the grout is assumed by this research to be a Bingham fluid, this information is provided by the plastic viscosity (Steffe, 1996). Unfortunately, the solution of the transient grout spread problem will require a more sophisticated method of analysis.

Groutnet

Groutnet is a two dimensional, vertically averaged, finite difference, hydrodynamic computer model designed to simulate the slow flow of injected Newtonian and Bingham fluid grouts in underground room and pillar mines. Groutnet was written in Fortran 90 and originally intended to run on personal computers with the Windows 95/NT operating system (Stiles, 1999). Groutnet was applied to the transient maximum spread problem by simulating the spread of grout in a level, open mine from a group of injection cells in the center of the computational domain. The size of model cells in the row and column direction was 10.0 ft, and the program was allowed to select a time step between 10 s and 1 s. The model contained 25 active rows and columns with 1 injection cell. Multiple injection cells can be used to avoid the numerical difficulties associated with the rapid increase in depth in the injection cell, but the use of more than one injection cell for this problem would have distorted the spread of the injected grout in an undesirable fashion. A reasonable grout injection rate of 0.75 ft^3/s (100 yd^3/hr) was selected for all of the models discussed in this paper. The yield stress of the grout was 1.0 lbs/ft^2, and the specific weight was 72.6 lbs/ft^3. Figure 2 is a plot of the radial spread of the grout versus injection time for three grouts with a plastic viscosity of 0.1, 1.0 and 10.0 lbs-s/ ft^2. As expected, the rate at which the grout spread in the mine was inversely proportional to the plastic viscosity of the grout. Because Groutnet is a finite difference model, the spatial domain is divided into model cells and the difference in the calculated radial spread of the three models is only observable at a few points in time.

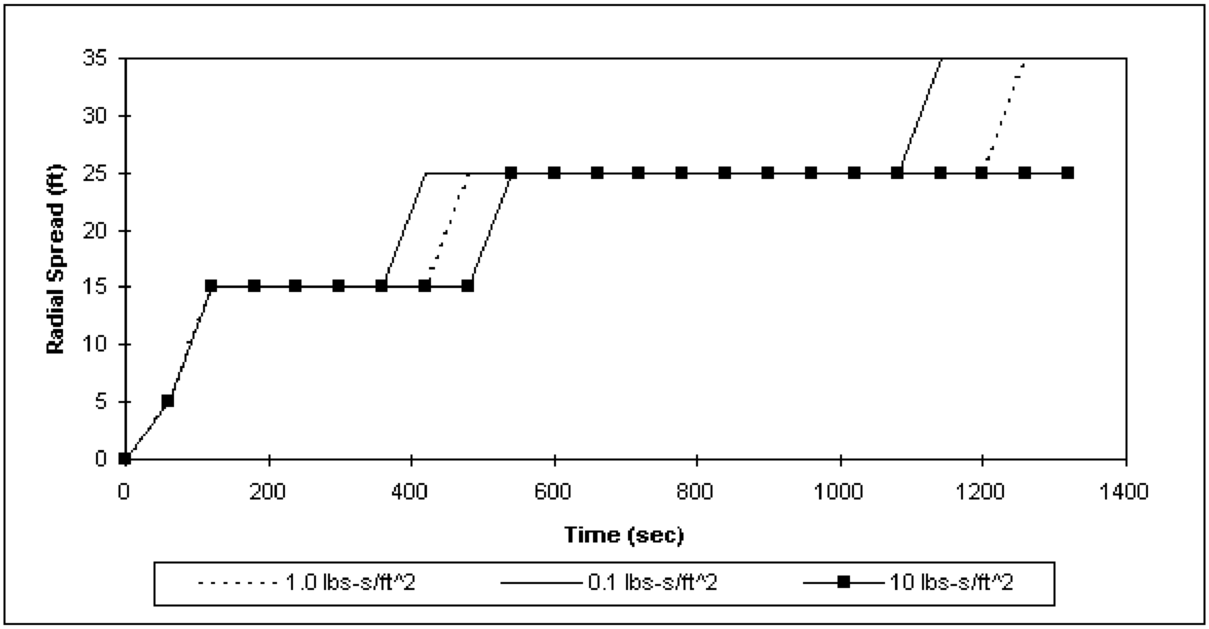

Figure 2. Simulated Radial Spread of Grout in an Open Mine.

Effect of Mine Pillars

Mine pillars, which are present in any open, underground mine, serve to increase the spread of the grout in the mine by directing the flow of the injected grout into specific directions. Figure 3 is a plot of the radial spread of a grout versus injection time in a mine without pillars and in a mine with pillars. The finite difference grid for the simulation without mine pillars is the same as the models shown in the above section. The finite difference grid of the simulation with mine pillars consists of a checkerboard of inactive cells in the computational domain and is shown in Figure 4. In Figure 4, the black squares denote inactive cells, and the gray square denotes the grout injection model cell. The number and size of the active rows, columns and injection cells are unchanged in these models. The yield stress of the grout was 1.0 lbs/ft^2, the specific weight was 72.6 lbs/ft^3, the injection rate was 0.75 ft^3/s and the plastic viscosity was 10.0 lbs-s/ft^2.

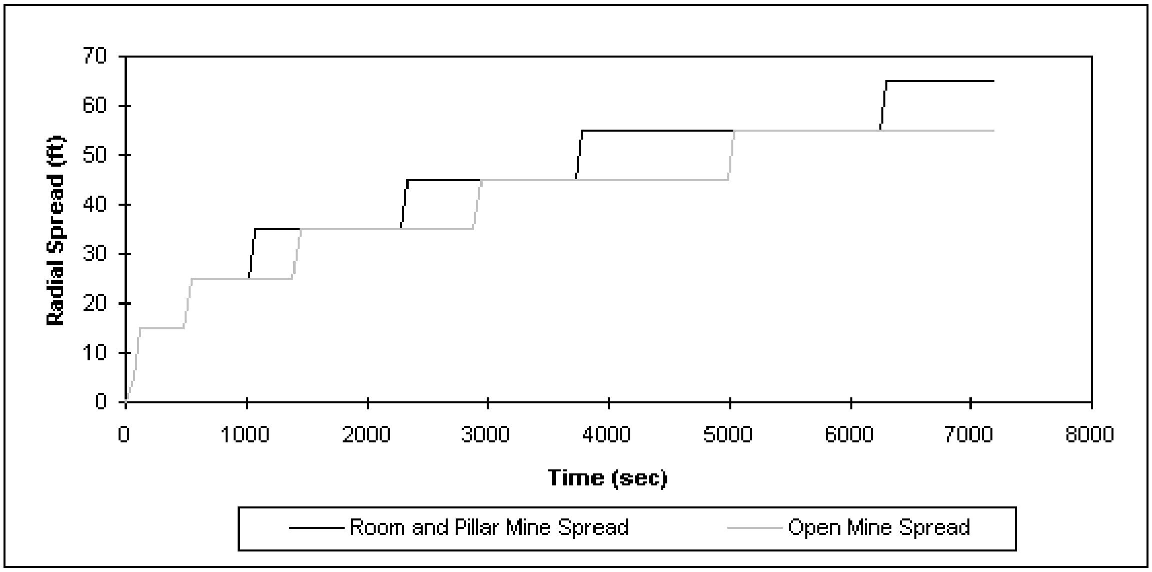

Figure 3. Simulated Radial Spread of Grout in Open and Room and Pillar Mines.

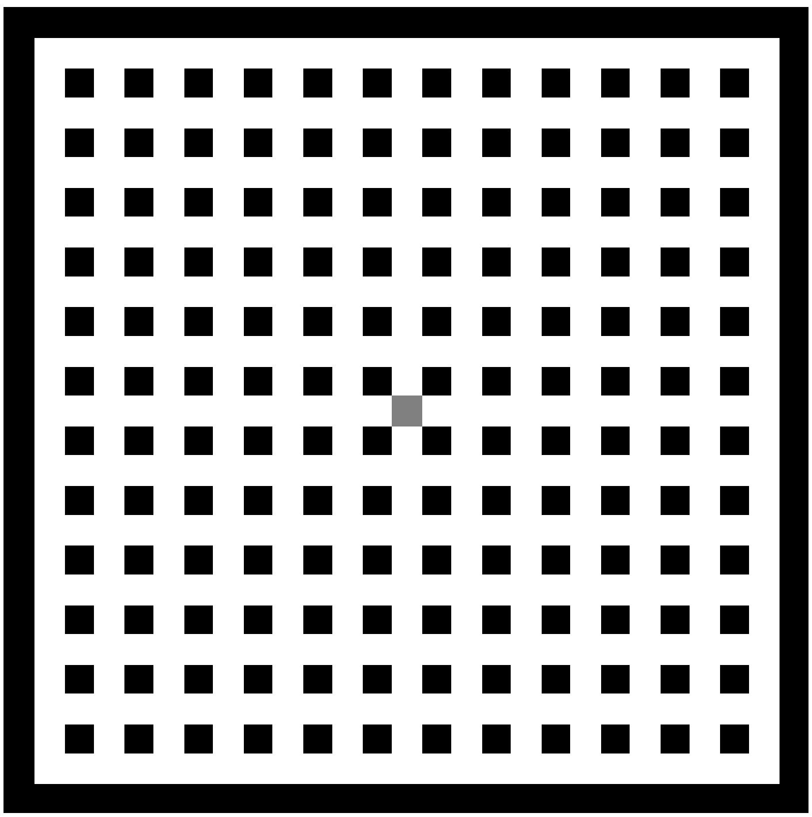

Figure 4. Computational Domain of Room and Pillar Mine Simulations.

Effect of the Slope of the Mine Floor

Because coal seams are rarely horizontal, the floors of room and pillar mines normally possess a slope in one or both coordinate directions. Fortunately, the slope increases the spread of the grout; unfortunately, the slope can make it more difficult to fill all parts of the mine with grout. Figures 5 and 6 are plots showing the spread of an injected grout in a room and pillar mine with a 1% slope in the positive X direction. All of the other model parameters are identical to the room and pillar mine injection simulation presented above. As expected, the spread in the X direction is greatly enhanced by the 1% grade, and the spread in the Y direction is correspondingly reduced.

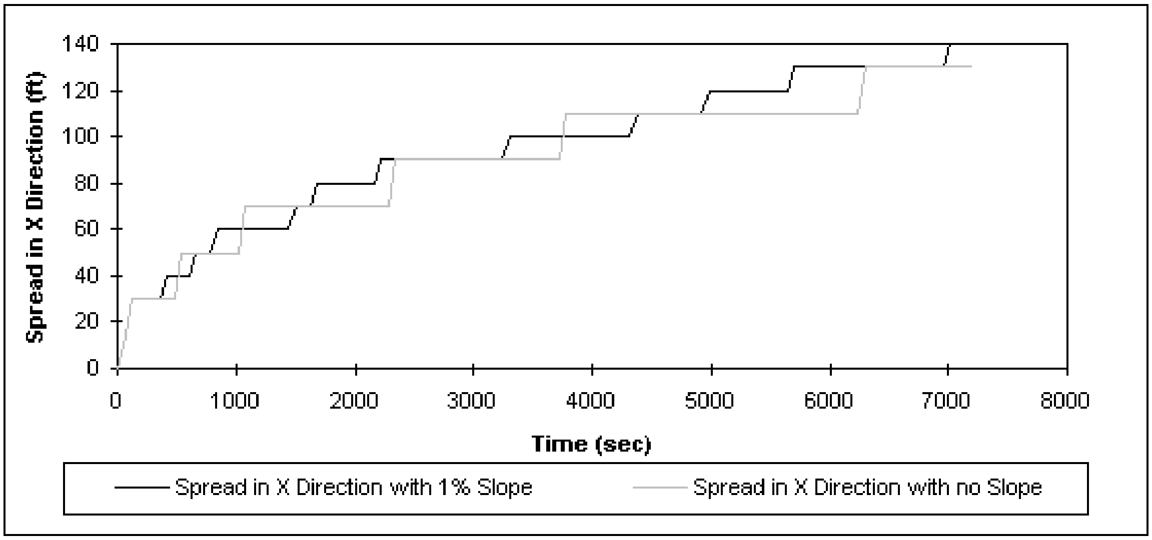

Figure 5. Simulated Spread of Grout in the X direction in a Room and Pillar Mine with and without a 1% Sloping Floor.

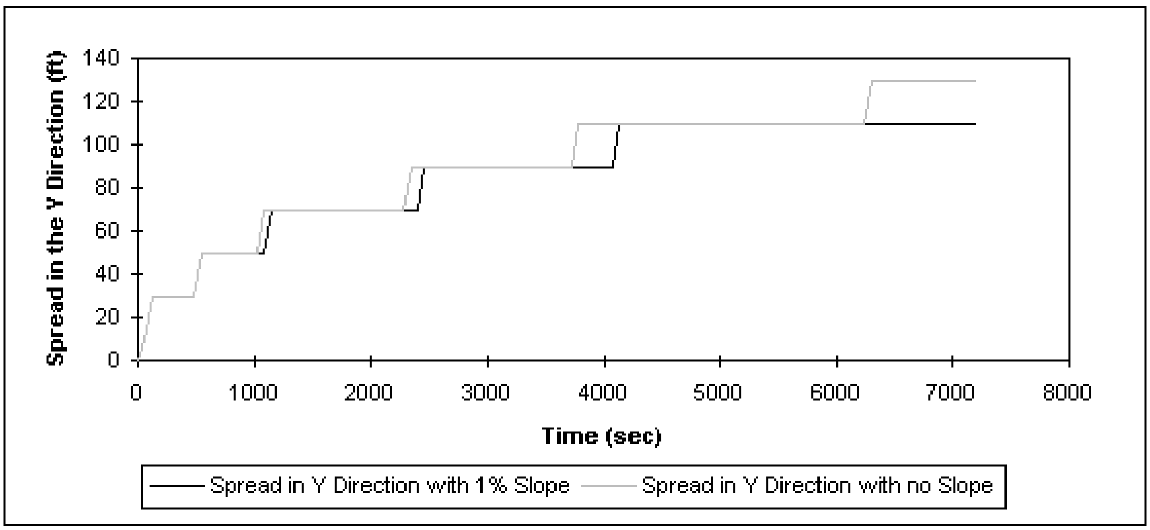

Figure 6. Simulated Spread of Grout in the Y direction in a Room and Pillar Mine with and without a 1% Sloping Floor.

Conclusion

The hardening and rheological tests of the grout demonstrate that an effective grout can be economically mixed with cement kiln dust and the AMD treatment pond sludge available on the site. With a cement kiln dust content of 430 lbs/yd^3, the resulting stable grout will have an unconfined compressive strength of approximately 200 lbs/in^2. The specific weight of this grout will be 72.6 lbs/ft^3, and the yield stress will be between 1.0 lbs/ft^2 and 1.8 lbs/ft^2. The plastic viscosity of this grout is unknown.

The ability of an injected stable grout to spread across the floor of the mine is primarily dependent upon the yield stress. Grouts will a greater yield stress are more likely to form a large mound near the injection borehole that restricts further injection. Other factors influencing the spread of the injected grout include the plastic viscosity of the grout, the arrangement of mine pillars near the injection borehole and the slope of the mine floor. The plastic viscosity of the grout affects the speed in which the injected grout spreads away from the injection borehole.

Grouts will a small yield stress but a large plastic viscosity will require a large amount of time to flow away from the injection borehole thereby limiting the maximum possible injection rate.

The location of pillars in the mine and the slope of the mine floor affect the spread of grout in the mine by directing the grout flow into specific directions. Because these factors depend upon the geometry of the mine, the selection of appropriate injection boreholes is an important part of the planning process. The computer program Groutnet is designed to assist in the selection of injection boreholes by simulating the underground flow of injected grout.

Future research in sludge solidification should be devoted towards:

- Directly testing the strength of the designed grout.
- Determine the effects of hardening under a variety of geochemical conditions.
- Establishing a more precise test of the grout's yield stress.
- Developing a practical test of the grout's plastic viscosity.
- Employing Groutnet to simulate the spread of the grout from various proposed injection sites.

References

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