Laboratory and Field Testing Parameters to Determine Concrete Crack Geometry and Polyurethane Grout Design

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Abstract

The presenters will highlight research designed to use flow and permeability data to predict crack geometry as applicable to leak-sealing applications. This research is being performed by speaker Dr. Chadi El Mohtar. The laboratory results from pressure and flow testing through varying crack sizes will be examined to ultimately suggest pre-injection exploratory efforts to identify crack geometry and, ultimately, improved methods for polyurethane grout selection. This presentation should prove informative to the specifying community and building owners as a possible new quality assurance standard in chemical grouting.

Speakers

Chadi El Mohtar – University of Texas at Austin, Austin, TX

Dr. El Mohtar is an associate professor in the Department of Civil, Architectural and Environmental Engineering. He holds a master’s degree from Michigan State University and a PhD from Purdue University, both in civil engineering. El Mohtar serves on multiple national and international committees. He was host of the 37th Grouting Fundamentals and Current Practice in Grouting course and is cochair of the upcoming Grouting 2017 conference in Hawaii. He was the recipient of the ASCE Arthur Casagrande Award and the National Science Foundation Faculty Early Career Development Program (CAREER) Award.

Jim Spiegel – SealBoss Corporation, Santa Ana, CA

Jim Spiegel is CEO of his company. He has 11 years’ experience specializing in chemical injection applications. Spiegel has consulted on chemical injection projects in over 20 countries on six continents. He is on technical committees for ICRI and SWRI chemical injection guidelines. Spiegel holds a bachelor of science degree from the University of Pittsburgh in neuroscience with related studies in chemistry.
SYNOPSIS
This paper will highlight and examine research efforts designed to use flow and permeability data to predict concrete crack geometry applicable to leak-sealing applications. This research is being performed by Dr. Chadi El Mohtar, an associate professor at the University of Texas’s Cockrell School of Civil Engineering in Austin. Laboratory results from pressure and flow testing through varying crack sizes will be examined to ultimately suggest pre-injection exploratory efforts to identify crack geometry and, ultimately, improved methods for polyurethane (PU) grout selection. This should prove informative to the specifying community and building owners as a possible new quality assurance (QA) standard in chemical grouting. Finally, three relevant and feasible field adaptations will be identified and discussed.

Learning Objectives
1. Familiarize attendees and readers with testing parameter possibilities to determine crack geometry.
2. Provide future possibilities for field-application of said testing parameters.
3. Lay groundwork for application of crack geometry results to determine grout selection.
4. Educate on geotechnical applications utilizing similar permeability testing procedures.

BACKGROUND
The geotechnical industry has been utilizing Lugeon calculations for decades as a way to quantify permeability in bedrock and other strata. “A Lugeon is a unit devised to quantify the water permeability of bedrock and the hydraulic conductivity resulting from fractures. It is named after Maurice Lugeon, a Swiss geologist who first formulated the method in 1933. More specifically, the Lugeon test is used to measure the amount of water injected into a segment of the bored hole under a steady pressure; the value (Lugeon value) is defined as the loss of water in liters per minute and per meter borehole at an over-pressure of 1 MPa” (https://en.wikipedia.org/wiki/Lugeon).

Although the Lugeon test may serve other purposes, its main object is to determine the Lugeon coefficient, which, by definition, is water absorption measured in liters per meter of test stage per minute at a pressure of 10 kg/cm² (1 MN/m²).

Based on this technique, our efforts are focused on applying Lugeon principles to concrete structures in order to establish quantifiable chemical injection results. By examining pre- and post-water and flushing agent tests, our goal is to provide quantifiable data that will aid in determining concrete crack geometry, quantifying injection results, and assisting in grout selection.

RESULTS
Initial testing has been conducted at the University of Texas’s Cockrell School of Civil Engineering in Austin. Testing procedures were designed to evaluate flow and pressure characteristics of water and flushing agents through various geometries of simulated crack widths. Testing procedures are explained in detail herein. For the purpose of this paper, please refer to the following example for terminology respective to crack geometry:

Example: Plate 0.5 in. x 0.002 in. Crack (depth) x (width)

Initial testing has proven to be conclusive to and supportive of the theory that crack geometries can be explored and predicted, based on flow and pressure evaluations of said cracks. The initial round of testing herein represents baseline findings toward this notion. Further testing in this regard could expand upon water behaviors in various geometric conditions, variations in flushing agent viscosity and subsequent behaviors, more precise and defined permeability-reduction indicators, and more detailed field adaptation protocol for equipment and accessories.

PROCEDURE
A. Rheometer
First we find the viscosity of water at room temperature (70°F) using the Rheometer. Since water is a Newtonian fluid, the Rheometer will show a straight-line plot of the viscosity vs. the shear rate or an average value of 1.4125x10⁻⁷ lb.sec/in². For the flushing oil, which is also a Newtonian fluid, the average value was equal to 8.1925x10⁻⁶ lb.sec/in², which is around 60 times the viscosity of water.

B. Sensor
For water, the desired pressures were small (0-10 psi). Therefore, we used the 10-psi pressure membrane for the sensor. Because the flushing oil has a higher viscosity than water, we should use a 100-psi membrane. The screws of the membrane are tightened using a hand torque wrench. Hand-tightening was used to prevent extra compression on the membrane, which
The sensor should be calibrated (see Figure 1) when the membrane is changed. This is done by connecting the sensor to the software Easy Sense 2100, which reads the pressure at very small intervals (in our experiment, it's used to take a reading each 100 ms).

The scale factor is set to one, and the offset factor is set to zero. We connect the sensor to an air gauge pressure system and start taking several single-shot values at each pressure. Pressures ranging from 0 to 10 psi for water and 0 to 100 psi for flushing oil are recorded. Then we plot the recorded values as a function of the pressures supplied by the gauge pressure system. Using linear regression of a straight line, we will be able to find the scale factor (slope) and the offset factor (y-intercept).

The straight-line equation for water turned out to be:

\[ y = 35.074x + 1.315 \]

The straight-line equation for flushing oil was:

\[ y = 723.93x + 12.702 \]

The graph in Figure 2 illustrates the best-fit model for the 100 psi membrane calibration.

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C. Plates

In our project, the purpose is to be able to find the depth and width of a crack in rocks or concrete using induced flow of Newtonian and non-Newtonian fluids. To start with the basic case, we assumed two parallel frictionless plates having a rectangular channel, which represents the crack. Two steel plates are used and stiffened by bolts and nuts. A small amount of grease is used around the channel to prevent leakage pathways between the plates (see Figure 3). The plates were designed in the machine shop with a precision of 0.001 inch. Therefore, we assumed the error range to be 0.0005 inch.

The governing formula relating the pressure, flow, viscosity, and dimensions of the plate is the cubic law (Witherspoon, Wang, Iwai, and Gale):

\[ Q = -\frac{L_y}{12\mu} \frac{d^3}{dx} \frac{dp}{dx} \]

The cubic law will allow us to verify the pressure read by the sensor and to predict the sources of errors.

D. System

The system consists of an accurate flow supply pump (see Figure 4), which is connected to a computer running a software called Load Frame – Sigma. The software will allow us to apply precise flows. It’s done by sending a signal to the GeoJac system to start applying a force on the piston to achieve a desired flow. A pipeline connected from the pump to the plates will carry the flow, and a branch just before the plate will be connected to the sensor to measure the pressure and record it in an Excel file.

Applied speeds varied from 0.0015625 to 0.8 inches per minute, and a minimum of three trials per flow were conducted. Since we are using Newtonian fluids, the pressure function of time plot should always stabilize on a certain pressure. The stabilizing process varied from seconds (largest plate using water) to an hour (smallest plate using flushing oil) per flow.

To convert the speed to flow, we multiplied the inner diameter of the pump cylinder by the speed. The multiplication factor was equal to 0.14144.

The system has two valves (see Figure 5)—one that supplies the pump with the fluid, and the other that allows the flow through the plates. They should never both be closed while applying a flow; otherwise, the system will be defective. To run the test, we should close the supply valve and open the sensor’s valve; while in order to fill the system with the fluid, we should open the supply valve and close the sensor’s valve.
E. Errors

Several errors were encountered during the experiment. The most common problem was leakage of the pipes and the slipping of the pump O-rings. Sometimes, connections between the pipes were changed and O-rings were replaced. In flushing oil, the drop of pressure was very slow, so a proposed solution by Dr. El Mohtar was to use step-up flows without going back to base pressure each time. This was a helpful solution that saved time.

RESULTS SUMMARY

The table in Figure 6 shows the average pressure read by the sensor at the stabilization phase at each trial per flow on each plate for water. Up to six trials were reached to ensure at least three similar pressures and achieve consistency.

To better illustrate, Figure 7 is a sample trial for the 1.0 x 0.05 in. As you can see, the test for water has a fast stabilization rate.

To verify the experimental work with a theoretical base, the table in Figure 8 and the graph sample in Figure 9 were done.

The error accommodates for the actual thickness range of the plate channel. As shown in the graph in Figure 9, the flow supplied and that calculated by the cubic law are inside of the error range. This means the error is being minimized during the experiment, and the conducted data are accurate.

The table in Figure 10 has the pressure trials record for the flushing oil.

Due to the viscosity of the flushing oil, the pressure stabilization process took more time (see Figure 11).
The graph in Figure 11 illustrates the ideal time needed for the pressure to stabilize and the step-up pressure method suggested by Dr. El Mohtar.

A sample calculation (Figure 12) and results validation (Figure 13) graph for the flushing oil are shown.

CONCLUSION

The results of this base testing have confirmed that Newtonian fluids, such as water, will stabilize relatively quickly when injected into defined cracks at various flow rates. Because of this property, water can provide reasonably conclusive indications of crack geometry based on stabilization pressures compared to baseline stabilization pressures of the same crack pre-treatment.
By varying the viscosity of the material being injected (flushing oil), pressures are affected accordingly. This is when shear stresses within the material play a more impactful role on the stabilization pressures. In each test—water and flushing oil—there is a 1- x 0.002-in. trial (.002 in² surface area) to compare to the 0.5- x 0.0043-in. trial (.002 in² surface area) as a way to reflect the impacts of depth and width to the pressure readings. In both cases, a decrease in width produced a much higher pressure reading for the same respective surface area of crack. The pressure readings were 6.33 and 4.57 times higher for the 1- x 0.002-in. trial for flushing oil and water, respectively.

The pre-injection test could prove to be a parameter for grout selection based on baseline pressures through the crack. For example: In large cracks, a water test would prove to be inconclusive with zero pressure reading. However, a thicker flushing/cleaning agent could provide a much more conclusive pre-injection crack geometry, as shear stresses in the thicker product would produce a relevant pressure reading. This could also be the basis of another round of testing to determine maximum pre-injection pressures of a certain thickness of material. These maximum pre-injection pressures could provide a QA measure to avoid using excessively thick injection grouts in cracks that will not allow adequate travel.

Further, poured concrete cracks that propagate the entire depth of the substrate, which would be assumed if water infiltration were present, would have a constant depth, being the thickness of the concrete substrate. In this scenario, it would then be conceivable that pre-treatment assessment of water pressure values at a controlled flow rate could act as a very accurate indicator of the decrease in width achieved through chemical grout injection. This relative decrease in crack width would be deduced by examining the post-treatment assessment of water pressure values at the same location and at the same controlled flow rate.

In this round of testing, Dr. El Mohtar’s lab has produced an exponential relationship between the relative decrease in crack width and resulting order of magnitude increase in stabilization pressures at a constant crack depth. In the water trials, at .3535 in³/min flow, the crack width was tested at 0.0065, 0.0043, and 0.002 in., with stabilization pressures found to be 0.08psi, 0.38psi (4.75x), and 5.76psi (72x). In the flushing oil trials, at 0.0883 in³/min flow, the crack width was tested at 0.0065, 0.0043, and 0.002 in., with stabilization pressures found to be 2.17psi, 4.10psi (1.89x), and 50 psi (23.04x). These results can be attributed to the relative increase in viscosity compared to water and resulting shear stresses on the material, even at a much lower flow rate.

These test results suggest that it is possible to administer field-testing procedures in cracked concrete substrates in order to predict crack geometry and/or at least crack permeability as a function of flow and pressure. It is then conceivable that the same test could be administered, post chemical grout leak-sealing injection, in order to quantify the relative decrease in crack width, permeability, and/or flow characteristics. Final field applications are yet to be determined, but could include:

1. Flow gauge sensors in exploratory port locations to quantify pre- and post-injection flow characteristics. The order of magnitude increase in water test at the testing port is reflective of the decrease in the overall crack width, which is a direct measure of permeability reduction of the substrate.

2. Calculation of pressures required for viscosity-specific product selection. If further testing and interest dictate, parameters can be put in place for the creation and subsequent flow testing of varying viscosity crack-flushing agents. Extreme initial pressure results of certain viscosity materials would represent difficulty in substrate penetration and overall effectiveness. This technique can be adapted to product selection as well.

3. Quantification of water permeability in cracked concrete substrates. Ultimately, the concrete repair industry could be given a quantitative approach to indicating success in chemical leak-sealing injection applications. A more systematic and quality-controlled technique and protocol are achievable.