SAND99-1749C

Chemical Grouting Lost-Circulation Zones with Polyurethane Foam

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JUL 21 1999
OSTI

Key Words: lost circulation, polyurethane, & drilling.

Abstract

Sandia National Laboratories is developing polyurethane foam as a chemical grout for lost circulation zones. In past work polyurethane foam was tried with limited success in laboratory tests and GDO sponsored field tests. Goals were that the foam expanded significantly and harden to a drillable firmness quickly. Since that earlier work there have been improvements in polyurethane chemistry and the causes of the failures of previous tests have been identified. Recent success in applying pure solution grouts (proper classification of polyurethane – Naudts) in boreholes encourages reevaluating its use to control lost circulation. These successes include conformance control in the oil patch (e.g. Ng) and dam remediation projects (Bruce et al.). In civil engineering, polyurethane is becoming the material of choice for sealing boreholes with large voids and high inflows, conditions associated with the worst lost circulation problems. Demonstration of a delivery mechanism is yet to be done in a geothermal borehole.

Solution Grouts

Chemical or solution grouts, in simple terms, are mixtures or solutions that react to produce a gel or foam resulting in a change in viscosity over time. One common category of such materials, colloidal solutions, includes mixtures of sodium silicate. Thus chemical grouting is not foreign to lost circulation control. However, as most realize, sodium silicates alone have not been very successful in stopping major lost circulation in large open fractures. Besides the difficulty in controlling the process or placing the materials, the major problem with sodium silicate is its low viscosity and strength.

A second category of chemical grouts is pure solutions or resins. Resins, which include polyurethanes, are solutions of organic products in a solvent, capable of forming a gel or foam. This category includes single component solutions that are catalyzed by water and two component solutions that are mixed and react with each other. An advantage of this class of materials is the ability of the chemist to engineer the properties, in particular, viscosity and setting time. The material can be engineered to have a low viscosity while being pumped and then gain strength in a short period, minimizing "waiting-on-cement" and the potential for the plug to be washed out.

The role of polyurethane in civil engineering grouting is reviewed and compared to traditional cement grouting in a recent paper by Bruce et al. Quoting from that paper:

> One of the most difficult challenges facing the grouting industry is the reduction or elimination of high volume water inflows into or through major civil engineering structures such as dams, tunnels, and quarries. Often these flows are occurring at high velocities, under high heads, and in locations which render treatment logistically and practically very awkward. . . . Over the years, many existing structures have been treated by remedial grouting operations, but with varying degrees of success. One of the major reasons contributing to this erratic

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> performance has been the inappropriate selection of the grouting materials. . . . Polyurethanes are usually appropriate for remedial grouting given cost, performance and environmental implications.

Thus polyurethane is becoming the material of choice in conditions of voids and high inflows, conditions associated with the worst lost circulation problems.

Past Work

Past successful tests included work in a high pressure (900 psi) and temperature (300°F) chamber at Southwestern Research Institute (SRI) (Tschoepe) and a simulated borehole/loss zone (ambient temperature and pressure) (Polk et al.). These tests were deemed a success because of significant expansion of the foam. Past tests deemed unsuccessful include high-pressure laboratory tests and Geothermal Drilling Organization sponsored field tests (3200 ft in the Geysers, ~1400 psi) (Glowka et al.). Since those tests new chemical formulations have been developed that react better in aqueous environments. Also techniques for controlling the process have improved. Past work targeted high pressure and temperature lost-circulation zones. Deployment of the chemicals was by a two-chamber tool lowered into the well.

The target application has changed. Many of the most troublesome loss zones are in the upper part of geothermal boreholes; thus, there is a need for cost effective techniques that can be used near the surface (first 1000 ft.). At the Long Valley Exploratory Well, more that $400k was spent on cement plugs in the first 700 ft all above the water table. It is estimated that polyurethane squeeze grouting of the entire section could have been done for $150k. Initially, zones will be targeted that can be serviced from the back of a "pick-up truck" using the infrastructure that supports construction and civil engineering projects: the goal, simple & cheap. The depth should be less than 1000 ft and the temperature less than 250°F (polyurethane foams should work at higher temperatures, but further testing is needed). The deployment of the chemicals must be as simple as possible. A challenge, but one that has been addressed in the mining industry.

The chemical reactions to produce polyurethane progress through several stages that can be affected by temperature, pressure, and moisture. An advantage of two component materials is the chemist has greater control over the properties of the product. Those experienced in applying polyurethane grouts in civil engineering describe the need for the two components to remain in a mixing chamber long enough for the reaction to "reach a point of irreversibility" before being exposed to water or mud. At SRI the foam was reacted in a bag within the test chamber. For the simulated borehole/loss-zone test, the effective mixing chamber was longer in length than for the Geysers field tests and the quantity of foam may have been sufficient to sweep the water away. For those tests the two components reacted and expanded properly, whereas, for the unsuccessful tests, the mixing chamber was probably inadequate and the reactions were poor.

Current Work

A successful polyurethane lost-circulation plug should be able to withstand 1000 psi across the plug while leaking at an acceptably low level (<< 1 BBL/day per 100 psi for 10' long zone in 12-1/4" diameter hole was assumed for this work). 1000 psi is needed to withstand the pressures of tripping and cementing. Foam used in the construction industry typically is a

product with a density of about 1.75 lb/ft^3 and compressive strength of about ~10 psi. Clearly, such material cannot merely occupy space in an open channel and stop 1000 psi. Polyurethane raw material has a density close to that of water (~64 lb/ft^3). Thus, normal construction-industry foam has expanded about a factor of 36. As the foam is confined and the density approaches the raw material the product becomes a solid. Such solid polyurethane can be quite strong (compressive strengths in excess of 1000 psi. — enough for almost any shallow loss zone). Even low-density foam can resist high pressures if adequately backed-up -- a 2" thick piece of 1.75 lb/ft^3 will not extrude through a 3/8" hole when 80 psi is applied and has an acceptably low leakage.

As a test of construction-industry polyurethane's ability to form adequate plugs, a series of tests have been performed on plugs formed by injecting polyurethane into 1 ft long 2" diameter tubes filled with pea gravel. When adequate foam was used, the injection process resulted in foam with a density of about 4 lb/ft^3 (Figure 1). The chemical reactions created 35 to 50 psi of pore pressure. When inadequate quantities of foam was injected, the result was granules of foam dispersed in the mud. While the granules were sufficient to turn the mud white, when pressure was applied, the granules were swept away in a matter of seconds, too fast to quantify the flow rate. Injecting more, but not quite adequate, foam results in a porous material, much like that used for thermal insulation in the construction industry. Such plugs, while very open celled, will resist flow allowing a mud cake to form that is sufficient to meet the leakage goal (<< 1 BBL/day per 100 psi for 10' long zone in 12-1/4" diameter hole). When adequate foam is injected, a hard almost closed cell plug is formed. Such plugs have been tested at 450 psi. The measured leakage was equivalent, for a ten-foot-long lost circulation zone in 12-1/4" hole, to less than 0.05BBL/day per 100 psi, significantly less than the goal. This leakage rate is less than one millionth of the leakage before the foam was injected into the pea gravel.

To demonstrate how to deploy polyurethane foam for lost-circulation control a series of bench scale tests have been performed. From these tests a number of important requirements for a successful job have been determined. First, the grout must be squeezed into the loss zone. Just pouring it into the hole, and having it adhering to the borehole wall, is not adequate. This requires some means of packing the hole off and forcing the polyurethane to flow into the loss zone. To meet the goal of simple and cheap, hydraulic pipeline flusher bags may be used as a way of packing off the hole. This temporary packer helps contain the injected foam. These bags have been tested (with a slight outlet restriction) and found to work, inflating and packing-off, with polyurethane foam discharging at a rate of ~ 1 ft^3/sec. (Figure 2). A hydraulic pipeline flusher bag is a product available in many hardware stores for less that $320 dollars (<12" diameter) that is connected to a water hose and inserted into a sewer line to blow out a blockage.

The bench scale tests have also shown that successful plugging of lost-circulation zones depends upon the quantity and rate of injection. The quantity and rate of injection must be sufficient for the polyurethane to sweep out the mud and/or formation water so that the polyurethane becomes the continuous phase (Figure 3). If insufficient polyurethane is used, only granules of polyurethane dispersed in the mud are formed. These are easily washed away. If polyurethane is injected at too low a rate it can be washed away by cross flow before it sets. A successful job requires a solid consolidated plug.

As the ambient temperature increases, rigid polyurethane foam, like that used in the construction industry, first softens, then melts, and eventually decomposes. The specific temperatures, at which these occur, depend upon a number of factors, in particular the formulation of the components used to produce the foam. Pressure and confinement may also be factors. Foam samples were heated in an oven to observe the effect of temperature on their appearance and weight. Figure 4 shows a plot of weight vs. temperature for a typical sample. At ~350°F the foam started turning tan and by 450°F, it was becoming quite dark. It should be noted that these tests were done on foam formed at ambient temperature and pressure. Foams formed at elevated pressure and temperature are physically different and may be affected by temperature differently. Furthermore, the foam tested was not formulated for temperature resistance.

The cost of sealing a lost circulation zone with a polyurethane plug depends upon a number of factors including raw material cost, borehole diameter, penetration of the plug into the loss zone, loss zone void fraction, and foam density. Foam density depends upon the chemistry used to create the polyurethane, the hydrostatic pressure and permeability of the loss zone, and the quantity of raw material used. Foam density can vary from ~2 lb./ft^3 for foam formed at atmospheric pressure to ~64 lb./ft^3 , solid polyurethane. Figure 5 shows the material cost per foot for a polyurethane plug penetrating 2" into a 30% void fraction loss zone as a function of foam density for various borehole diameters assuming $2.65/lb. raw material.

Polyurethane foams can be made using a wide range of raw materials. The raw materials are reactive and can be toxic. Thus, it is difficult to give blanket statements regarding the environmental issues of using polyurethane. In general, however, the raw materials decompose, when exposed to moisture, into non-toxic materials that can be disposed of as non-hazardous material. Polyurethane can be used to seal potable water tanks. Polyurethane is used in home products (seats, pillows, etc.) and construction. Thus, if handled properly polyurethane should not pose a problem to workers or the environment.

Conclusions

Polyurethane grouting is being regularly applied to create grout curtains and seal boreholes in dam remediation projects. This work has been documented in civil engineering literature (Bruce et al., Naudts, and Smoak et al.). Several drilling and grouting companies have experience with pumping polyurethane down boreholes and at lest one grouting contractor has used polyurethane to control lost circulation. Tests at Sandia are focusing on how to progress polyurethane grouting to engineering practice. This progression is ready for field-testing.

Sandia is seeking opportunities to test the application of polyurethane to lost circulation zones in geothermal drilling projects. Prime targets would be close to or above the water table, near the surface (≤1000 ft.). A list of consultants, grouting contractors, drilling companies, and chemical suppliers with experience in solution grouting boreholes is available on request.

Sandia is multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

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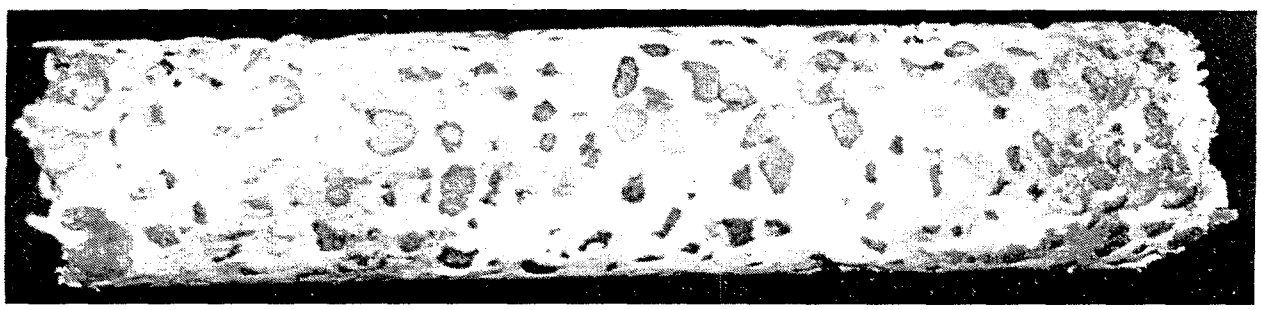

Figure 1: Consolidated gravel plug; leakage less than 0.2 BBL/day per 500 psi for 10' long gravel zone in 12" diameter hole.

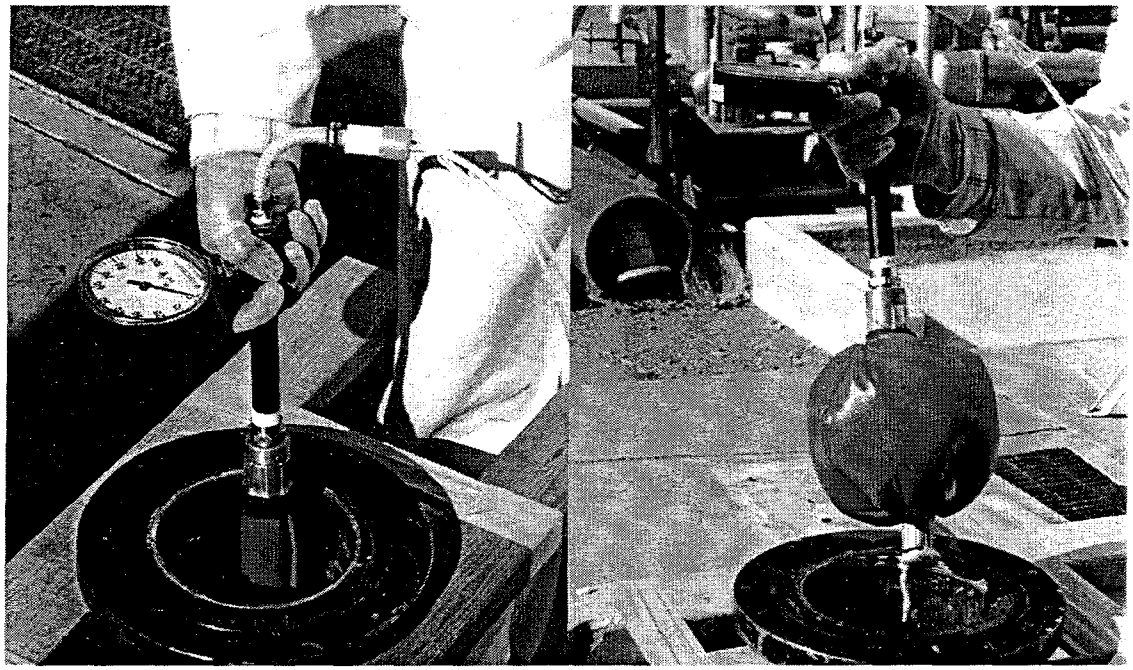

Figure 2: Hydraulic pipeline flusher bags, before and after inflation by polyurethane.

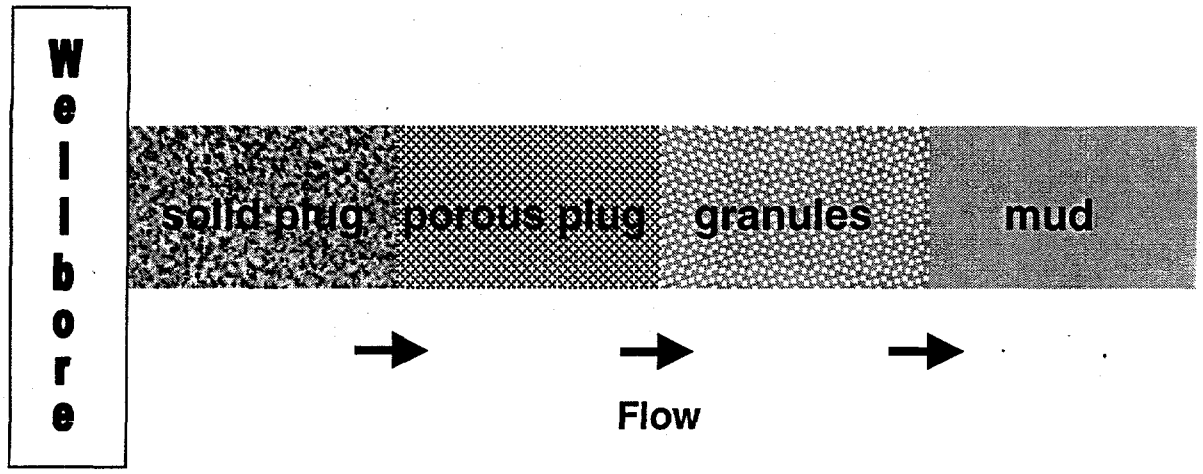

Figure 3: As the polyurethane sweeps out the mud there is a transition from polyurethane granules dispersed in the mud, to porous polyurethane, and finally a hard solid plug of polyurethane.

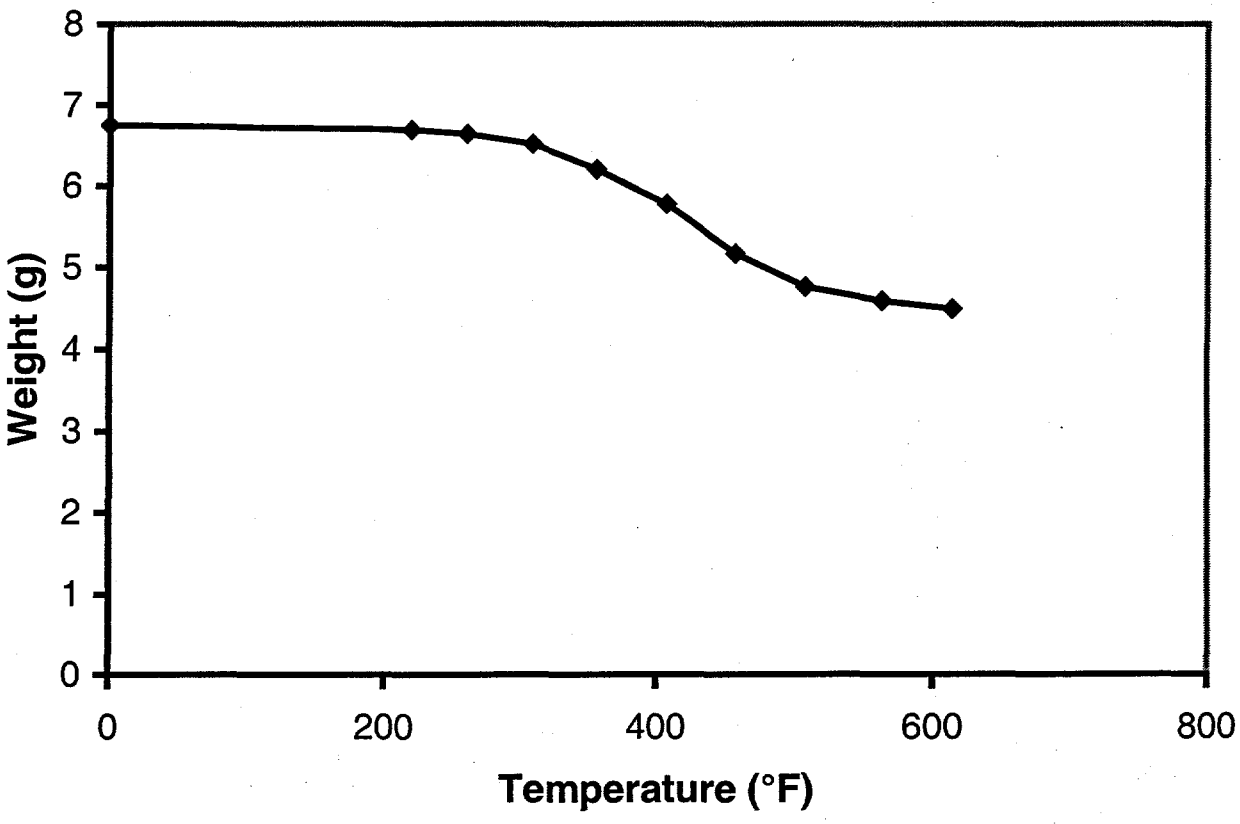

Figure 4: Weight of foam as a function of temperature (sample was soaked at each temperature for 2 hours).

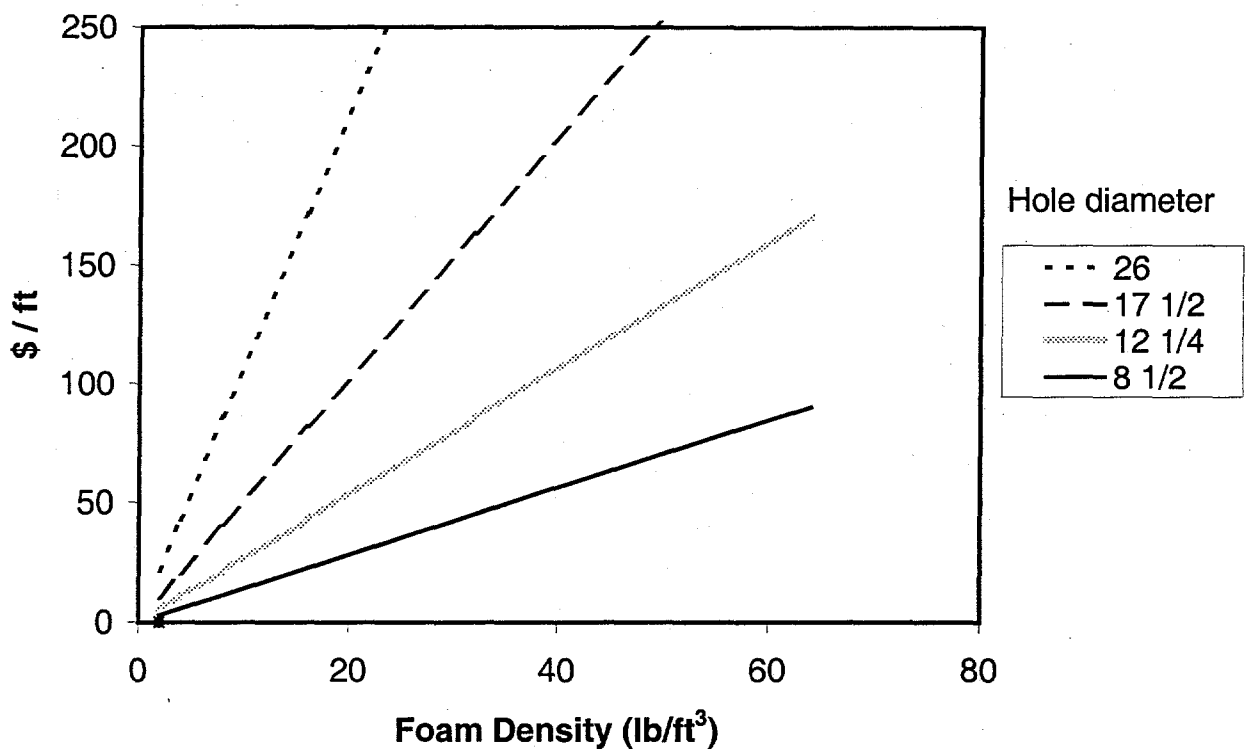

Figure 5: Material cost per foot for a polyurethane plug penetrating 2" into a 30% void fraction loss zone as a function of foam density for various borehole diameters for $2.65/lb. raw material.