DESIGN AND EVALUATION
OF LOST CIRCULATION MATERIALS
FOR SEVERE ENVIRONMENTS

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by

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ABSTRACT*

An independent analysis of lost circulation materials for geothermal applications has been completed using unique laboratory tools developed for the purpose. Test results of commercial materials as well as mathematical models for evaluating their performance are presented. Physical attributes that govern the performance of lost circulation materials are identified and correlated with test results.

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INTRODUCTION

The evolution of lost circulation technology in the petroleum drilling industry has an interesting history [1,2]. Early lost circulation materials (LCMs) were often chosen because they were inexpensive and could be found in sufficient quantity near the drilling site. Later, LCMs were made from salvage materials or waste from other manufacturing processes. This is still true, although processing is now more advanced and some raw materials are manufactured specifically as LCMs. Requirements for LCMs have become more demanding as the economy has forced well drilling to become more efficient and a more severe environment is encountered in deeper, hotter wellbores.

Analysis shows that one of the most serious and costly problems affecting geothermal drilling is lost circulation [3]. Drilling costs have an even greater impact on the economics of developing the geothermal resource than that of oil and gas. Lost circulation zones encountered in geothermal reservoirs are typically more severe than those in oil and gas drilling. Formations are often underpressured, fracture-dominated (the nature of the production zone), and can have temperatures that exceed the capability of the cellulosic LCMs often used in oil and gas drilling.

As part of the U.S. Department of Energy's Geothermal Technology Development Program, Sandia National Laboratories has conducted an extensive testing program to evaluate candidate materials that could aid in solving the severe lost circulation problems encountered in geothermal well drilling [4]. Our work has concentrated on fracture-dominated loss zones, rather than the matrix zones more typical of oil and gas drilling. The results should have applicability to the petroleum industry, however, particularly with the inevitable progression into more fracture-dominated reservoirs.

The purpose of this paper is to present the test methods developed and the results of the LCM tests. Most of the materials tested are commercially available. A goal of the present work was to conduct an independent evaluation and to present all identifiable attributes of each material. Also presented is a theoretical model of the fracture plugging process, which is used to guide evaluation of the material tests.

MECHANICS OF THE FRACTURE PLUGGING PROCESS

Solid-particle plugging of a fracture that intersects a wellbore is a complex process involving the dynamic interaction of multiple solid bodies with each other, with a flowing fluid, and with the solid boundaries of the fracture walls. Although detailed fluid mechanics modeling of the dynamic plugging process itself would be an ambitious undertaking, insight into the process can be attained by examining the dynamics of particle-laden flows with incipient plugging and the mechanics of the static plug after it has formed.

At low solids concentrations, a particle-laden fluid may be considered a continuum, and conventional fluid mechanics models may be used to characterize the flow in the fracture and in the vicinity of its aperture at the wellbore wall. In this case, the motion of a single particle as it travels through the fracture can be estimated by examining the dynamic forces exerted on the particle by the surrounding fluid.

Previous work [5,6] shows that with dilute mixtures in drilling mud, cylindrical particles inherently seek orientations favorable to the development of a plug inside the fracture and unfavorable to the development of a plug at the fracture opening. As the fluid accelerates to enter the fracture, surface stresses tend to orient each particle such that its longest dimension is parallel to the fluid streamlines and thus the fracture direction. As a result, the longest dimension is not available to span the fracture opening, and any plug that does develop must rely on one of the particle's smaller dimensions to provide the necessary bridging. If the smaller dimensions are less than some minimum fraction of the fracture width, the particle will pass inside the fracture without forming a plug. Once inside the fracture, the flow generally decelerates because of an increase in flow area. This generates dynamic pressures that orient the particles normal to the direction of the flow, thus making the longest particle dimension available to form a bridge that leads to a plug.

In the laboratory slot tests reported in this paper, we observed that plugs capable of supporting significant pressure differentials (1000 psi) generally form at the leading edge of the slots, regardless of the slot length used (1/4-inch or 6-inches). The irregular shapes of typical lost circulation material particles probably have an effect

on particle orientation, but factors other than particle orientation also undoubtedly have an effect on plugging characteristics. It is therefore reasonable to assume in field practice that plugs develop both at the fracture openings along the wellbore wall as well as inside the fractures. The desirable internal plugs are likely to be more stable than those that develop on the wellbore wall where the actions of the drill string and the annular fluid flow may inadvertently dislodge the plug.

Regardless of the location of the plug, its effectiveness in preventing fluid loss into the fracture is dependent on its mechanical strength as well as its permeability. In this paper, we refer to the portion of the plug responsible for its mechanical strength as the bridge, while the portion that controls the plug permeability is defined as the filter.

The primary functional requirements for bridge material particles are that they must have appropriate dimensions and mechanical properties to withstand the differential pressure across the plug. It is generally recognized in industry that flow passages are susceptible to plugging if the fluid contains rigid particles larger than about one-third the width of the passage. This implies that bridges involving one, two, and three particles can achieve stability under favorable conditions but that bridges involving more than three particles are inherently unstable. During formation of a stable bridge, the particles must have adequate compressive, tensile, and shear strengths to withstand the bending and longitudinal stresses imparted by the differential pressure loading. At the same time, the particles must have adequate rigidity to prevent strain deformation from changing the particle geometry to one incapable of spanning the fracture.

The primary functional requirement for filter materials is that they must have the capability to form a seal over the bridge to reduce plug permeability. This implies the need for adequate strength to span the gaps in the bridge material and yet sufficient elasticity or plasticity to deform and block a significant portion of the flow area through those gaps. The functional requirements for filter materials are sufficiently different from those of bridging materials that few materials would be expected to perform both functions adequately. As a result, a mixture of rigid, granular particles with more pliant flakes and/or fibers generally provides

the best fracture plugging characteristics in both the lab tests reported here and by others [7].

Mathematical models are developed in Appendix A that quantitatively describe the geometry and mechanical property requirements of bridging materials. These models and the results are summarized in the following subsections and are used to guide evaluation of the lost circulation materials reported in this paper.

Single-Particle Bridging

If the dimension of a particle normal to the fracture direction is larger than the width of the fracture opening, single-particle bridging is possible, as illustrated in Figure 1. This type of bridging can also occur inside fractures at locations where the fracture tapers in width. For the purpose of analysis, the actual particle is idealized as a beam of length L with a rectangular cross-section of height h and depth d . The particle is held against the wellbore wall by the pressure differential p across the fracture opening of width w . It is assumed that the pressure seal between the particle and the wellbore wall is confined to the corners of the opening. This assumption allows the idealized particle to be modeled as the simply supported beam shown in the figure.

The maximum bending stress in the equivalent beam occurs at mid-span and is compressive at the top of the beam and tensile at the bottom of the beam. When these stresses exceed the compressive or tensile strength, respectively, of the bridge material, the material is expected to undergo irreversible strain (i.e. plastic deformation or brittle fracturing), and the bridge is expected to fail. As shown in Appendix A, the maximum allowable pressure differential based on inelastic collapse of a single-particle bridge is

$$(p_{\max})_{II} = \frac{4S}{3} \left(\frac{L}{w}\right)^2 \left(\frac{h}{L}\right)^2, \quad (1)$$

where S is the tensile or compressive strength of the bridge material, whichever is lower. Brittle materials, which characteristically have low tensile strengths, are thus expected to fail at much lower differential pressures than more ductile materials of comparable compressive strength.

Eq. 1 also indicates that for a given L/w , the maximum allowable pressure differential is very sensitive to the particle aspect ratio, L/h . This result clearly demonstrates why long, slender

particles ($L/h \gg 1$) are ineffective in forming bridges.

Some potential bridging materials are relatively strong but are so elastic that bridge collapse due to extrusion of the material into the fracture is possible without exceeding the material's elastic limit (i.e. tensile or compressive strength). In this case, bending deflection of the particle becomes so significant that the curved length of the particle is no longer capable of spanning the fracture width, as illustrated in Figure 2. Although the material survives such a collapse without permanent deformation, the plug nevertheless fails.

To analyze the elastic plug failure, the equivalent beam loading shown in Figure 2 is assumed. Because of the large beam curvatures considered, the nonlinear form of the beam deflection equation must be used to determine if the extruded shape of the particle is capable of spanning the fracture width. The non-dimensional deflection equation is developed in Appendix A. It was numerically integrated, and the results are shown in Figure 3 as a function of the friction coefficient between the particle and the fracture wall. The group of parameters,

$$\left(\frac{pw^3}{Eh^3} \right)_{\max},$$

is defined as P_1 , the dimensionless elastic failure pressure for single-particle bridges. The maximum allowable pressure differential based on elastic collapse of a single-particle bridge is then

$$(p_{\max})_{1E} = E \left(\frac{h}{L} \right)^3 \left(\frac{L}{w} \right)^3 P_1, \quad (2)$$

where P_1 is taken from Figure 3.

The results indicate that for a given friction coefficient, the maximum allowable pressure differential increases sharply with increasing particle lengths slightly larger than the fracture width. Beyond a certain ratio of L/w , however, any further increase in particle length does not yield improvements in pressure capability. In this region, the particle is so highly deflected that further increases in pressure cause the bridge to become inherently unstable, regardless of the particle length.

The results of Figure 3, together with Eq. 2, again illustrate the important role of particle shape in determining a material's bridge forming

capabilities. With an exponent of 3 on the inverse of the particle aspect ratio, the maximum allowable pressure differential for long, slender particles is seen to be exceedingly low.

Greater friction between the particle and the fracture wall improves the pressure capability of the single-particle bridge. The range of η shown in the figure covers the range for most available materials.

In addition to particle size, shape, and friction factor, the relative values of the material's elastic modulus and compressive/tensile strength determines whether plug failure occurs by elastic or inelastic deformation as well as the pressure level at which failure occurs. The minimum value of $p_{\max}$ as predicted by Eq. 1 or Eq. 2 is the value that applies in any given case. Since inelastic failure governs the bridge in cases where $(p_{\max})_{II} < (p_{\max})_{IE}$, Eqs. 1 and 2 can be used to derive the inelastic failure criterion:

$$\frac{S}{E} < \frac{3}{4} \left(\frac{L}{w} \right) \left(\frac{h}{L} \right) p_1 \quad (3)$$

In cases where Eq. 3 holds for the material of interest, Eq. 1 applies. In cases where S/E exceeds the calculated value on the right, the bridge fails by elastic collapse, and Eq. 2 applies.

Multiple-Particle Bridging at Fracture Openings

If all particle dimensions are smaller than the fracture width, bridges are possible only when two or three particles interact at the right moment in time to form a stable arch from one fracture wall to the other. Multiple-particle bridges on the surface of the wellbore wall as well as inside the fractures are possible.

We restrict our analysis to two-particle bridges and first consider a plug at the entrance to the fracture along the wellbore wall, as shown in Figure 4. It is initially assumed for simplicity that both particles are identical in shape, size, and mechanical properties.

As two particles near a fracture entrance first contact each other and the fracture wall, the contact forces increase from zero at the moment of contact to some maximum value once stability of the bridge has been achieved. During formation of the bridge, the particle orientation angle, α , decreases from its initial value, α_i , to its final equilibrium value, α_e . This particle rotation can occur only with an

accompanying reduction in length, which in turn requires that a longitudinal force be imparted on each particle. At some point in the particle rotation, if conditions are right, these longitudinal forces will balance the pressure and wall contact forces, yielding a stable bridge. This balance of forces is examined in Appendix A, where an equation relating the equilibrium angle to the other variables is derived:

$$\frac{pL}{Eh} = 2 \tan \alpha_e \left(2 \frac{L}{w} \cos \alpha_e - 1 \right) \quad (4)$$

The group of parameters,

$$\frac{pL}{Eh} \quad , \quad (5)$$

is the dimensionless differential pressure, P_2 , across a stable two-particle bridge at equilibrium. Eq. 4 is valid only for equilibrium angles of 45° or less. Larger angles require the force $(F_{wx})_e$ in Figure 4 to be negative, which is physically impossible.

Eq. 4 is plotted in Figure 5 for a range of particle sizes greater than one-half the fracture width. To understand the trends in this figure, consider the effects of increasing pressure on the equilibrium angle of a stable bridge for which $L/w=0.7$. When the bridge first reaches equilibrium, the pressure drop across the bridge may be only a fraction of its final value. As filter material accumulates behind the bridge to form a seal the pressure drop increases, resulting in a corresponding decrease in equilibrium angle. The bridge will remain stable during the plug pressurization process as long as a finite increase in pressure differential results in a finite reduction in equilibrium angle, i.e. as long as $|\partial \alpha_e / \partial p|$ is finite. At the point where the $L/w=0.7$ curve becomes vertical, however, $|\partial \alpha_e / \partial p|$ is infinite. This is the point of instability, where the bridge is on the verge of collapse. Any increase in pressure causes an unbounded decrease in equilibrium angle; as the angle goes negative, the bridge falls apart. Below the maximum pressure point, the curves pass through an unstable region where increasing pressure results in increasing equilibrium angle, a physically impossible condition in actual practice. Similar behavior is experienced by particles smaller than $L/w = 0.7$, although the maximum pressure that smaller particles can support is markedly lower.

Curves for particles larger than $L/w = 0.7$ display an interesting feature. Stability of the larger particles is not achieved unless the pressure differential is above some minimum value. This implies that the gradual plug pressurization scenario

described above for smaller particles is not applicable here. Instead, the particles require the development of a significant pressure differential before the bridge stabilizes and filter material accumulates to form a seal. Such large pressure differentials in the absence of a seal can develop only with large dynamic fluid pressures acting upon the particles, as occurs in highly transient or other accelerating flows. Consequently, the probability is relatively low that particles larger than $L/w > 0.7$ will develop two-particle bridges, compared with the plugging probability for smaller particles. Furthermore, any bridge that does develop with large particles is likely to become unstable and collapse if the pressure differential imposed across the plug is subsequently reduced below the levels defined by the upper dashed line in Figure 5.

The maximum pressure differential at which a two-particle bridge is elastically stable is obtained by setting $\partial p / \partial \alpha$ to zero, using Eq. 4, solving for the equilibrium angle at failure, and substituting this angle back into Eq. 4. The result is the dimensionless elastic failure pressure,

$$P_3 = 2 \tan \alpha_{f3} \left(2 \frac{L}{w} \cos \alpha_{f3} - 1 \right), \quad (6)$$

where

$$P_3 = \left(\frac{pL}{Eh} \right)_{\max} \quad (7)$$

and

$$\alpha_{f3} = \cos^{-1} \left(\frac{w}{2L} \right)^{1/3}. \quad (8)$$

The maximum allowable differential pressure based on elastic failure of a two-particle bridge is thus

$$(p_{\max})_{2E} = E \left(\frac{h}{L} \right) P_3, \quad (9)$$

where P_3 is given by Eq. 6.

The minimum pressure differential at which a two-particle bridge can form is obtained by setting α_e in Eq. 4 to its maximum valid value of 45° (see Appendix A):

$$(p_{\min})_{2E} = E \left(\frac{h}{L} \right) P_4, \quad (10)$$

where

$$P_4 = 2 \left(1.414 \frac{L}{w} - 1 \right). \quad (11)$$

Eqs. 6 and 11 are plotted in Figure 6. The stable plug range is the area between the minimum and maximum pressure curves. Note that as the particle/fracture size ratio increases, the stable plug range shrinks to zero. Plugs composed of smaller particles are thus more resilient to rapid changes in the pressure differential, although their maximum pressure capability may not be as high.

If the elastic limit of the material is relatively low compared with its elastic modulus, it is possible for inelastic failure of the bridge to occur. This occurs if the combined longitudinal and bending stresses in the particles exceed the compressive or tensile strength of the material. In dimensionless terms, inelastic collapse of a two particle bridge occurs if

$$P_5 = \frac{|\sigma_c|}{E} > \frac{S}{E}, \quad (12)$$

where P_5 is the dimensionless stress,

$$P_5 = \left| \left[\frac{h}{L} \tan \alpha_e \left(2 \frac{L}{w} \cos \alpha_e - 1 \right) \right] \left[\frac{L}{h} \frac{w}{L} \frac{1}{\sin \alpha_e} + \frac{3}{2} \left(\frac{L}{h} \frac{w}{L} \frac{1}{(\cos \alpha_e + v \cos \alpha_e - \frac{vw}{2L})} \right)^2 \right] \right| \quad (13)$$

and α_e is the equilibrium orientation angle for a given differential pressure across the plug. The positive sign applies to the high-pressure side of the particle, while the negative sign applies to the low-pressure side. This equation with the positive sign is presented in Figure 7 for several values of l/w , l/h , and v (Poisson's ratio). The data are plotted in a manner that shows the ranges of α_e for which the plug is elastically stable.

To use Figure 7, the equilibrium angle corresponding to the dimensionless pressure differential and particle size of interest is taken from Figure 5. This angle is used to determine P_5 and thus the particle stress from Figure 7. Alternatively, the pressure differential at which inelastic bridge failure occurs can be determined by setting P_5 to S/E for a material of interest and finding the value of α_e at failure from Figure 7. This angle is then used in Figure 5 to find P_2 for calculation of the maximum allowable pressure differential based on inelastic failure of a two-particle bridge:

$$(p_{\max})_{2I} = E \left(\frac{h}{L} \right) P_2, \quad (14)$$

where P_2 is evaluated at P_5 . This pressure differential must be compared with the maximum allowable pressure differential based on elastic failure, Eq. 9, to determine which failure mechanism controls the plug. The smaller of the two values of $p_{\max}$ applies in any case.

Multiple-Particle Bridging Inside Fractures

Multiple-particle bridging may occur inside a fracture if the fracture undergoes a step or gradual reduction in width or if sufficient friction develops between the particles and the fracture wall to stabilize the bridge. The assumed geometry for a friction-type plug is shown in Figure 8. The governing equations for this type plug are identical to those for plugs at the fracture entrance, with the additional constraint that

$$(F_{wy})_e \leq \eta (F_{wx})_e, \quad (15)$$

where η is the friction coefficient between the particle and the fracture wall. This constraint would also apply to two-particle bridges at the fracture openings in cases where particle rugosity is not sufficient to effectively hold the particles onto the corner of the fracture opening. The analysis of Appendix A shows that the result of Eq. 15 is

$$\eta_{\min} = \left[\frac{1}{2 \sin \alpha_e \cos \alpha_e} - \tan \alpha_e \right]^{-1}, \quad (16)$$

where $\eta_{\min}$ is the minimum allowable friction coefficient for a given equilibrium angle and thus differential pressure.

Eq. 16 is plotted in Figure 9. By setting the available friction coefficient for the case of interest to $\eta_{\min}$, the equilibrium angle at the point of bridge failure due to wall slippage can be determined. The corresponding value of P_2 in Figure 5 then allows calculation of the maximum allowable pressure differential based on bridge failure due to wall slippage:

$$(p_{\max})_{2S} = E\left(\frac{h}{L}\right)P_2, \quad (17)$$

where P_2 is evaluated at the η of interest. This pressure differential is then compared with the maximum allowable pressure differentials due to elastic failure (Eq. 9) and inelastic failure (Eq. 14) to determine the controlling plug failure mechanism for a given set of conditions. As before, the minimum value of $p_{\max}$ applies in any case.

An examination of the curves in Figures 9 and 5 indicates that for friction coefficients less than 1, which is common for most materials, only very small particles, $L/w \leq 0.6$, are able to form stable friction bridges inside fractures. Consequently, it may be concluded that any such plugs that do form are relatively weak compared with plugs that form at fracture openings and tapered sections.

Significant fracture rugosity on a scale smaller than the particle length may result in an effective friction coefficient greater than 1. In this case, particles larger than $L/w = 0.6$ are able to form stable plugs. As a result, the probability of forming strong friction plugs inside the fracture is increased.

Implications of the Bridging Models

The mathematical models for both the single- and two-particle bridges indicate that the particle size and shape play important roles in determining the maximum allowable pressure differential across the plug. This result has implications with respect to particle size distribution and concentration in the drilling fluid.

A wide distribution of particle sizes makes available a large combination of particle sizes for bridging a wide range of fracture width. The bridging models show that stable bridges can develop only with particles of certain dimensions. As a result, particles outside an effective range for the fracture of interest do nothing to contribute to a stable bridge, although they may act as filter material. Consequently, a moderate particle size distribution tailored for a narrow range of fracture widths should provide the best plugging capabilities. Of course, it is not always possible to estimate fracture dimensions, but future lost circulation diagnostic techniques may help in this regard.

Further work is also needed to determine theoretically optimal particle distributions. The existence of an optimal distribution is suggested by the finding that the probability of forming a stable two-particle bridge declines with increased particle size, but the strength of a bridge that does form increases. This conclusion agrees with experience obtained in the laboratory slot-plugging tests reported in this paper, where optimal particle distributions have been empirically determined.

Particle concentration affects the probability of forming a bridge because higher concentrations lead to smaller spacings between the particles in the drilling fluid. As the probability of forming a plug increases, the volume of drilling fluid that passes through the fracture before a plug forms decreases. It is thus concluded that increased concentrations should reduce filtrate loss, at least to the point where the probability of bridging is no longer the controlling factor. Since only one, two, or three particles may be involved in any given bridge, a reasonable conclusion is that particle concentration does not significantly affect the pressure capability of any given plug, but it does improve the probability of forming bridges, including those with inherently higher pressure capabilities.

Further implications of the bridging models are discussed in conjunction with the slot-plugging test results presented below.

TEST METHODS AND CONDITIONS

Three test systems were developed for testing potential lost circulation materials, as shown in Figures 10-12:

- 1) a modified version of the bridging materials tester defined in the API recommended practice RP 13I [8] (Figure 10);
- 2) a large-scale facility designed to provide a more realistic test of an LCM's plugging ability (Figure 11); and
- 3) a bench tester designed to measure material properties at ambient and elevated temperatures (Figure 12).

These systems and the testing procedures are described in this section.

Modified API Tester

The bridging materials tester defined in API RP 13I was first adopted as a standard after an industry survey in 1962 [7]. Since that time no significant changes have been made in the hardware. In the API test procedure a pressurized LCM-laden drilling fluid is imposed against a slotted steel disk that simulates a loss-zone fracture. Variables in the test include the slot size in the disk and the concentration of the LCM in a standard water-based bentonite mud with an apparent viscosity of 25 ± 2 cP. A prescribed mud/slurry volume 0.925 gallon (3500 ml) is loaded in a test cell and forced by a nitrogen gas-driven piston through the slot. A pressure differential of 100 psi (690 kPa) is applied and, if a plug forms, the

pressure is increased at a 10 psi/s (69 kPa/s) rate until the plug fails or 1000 psi (7000 kPa) is reached. If no plug forms, the test ends when the 0.793 gallon (3000 ml) useable slurry volume has passed through the slot. The accumulated filtrate and pressure are recorded as a measure of the LCM's performance.

Hundreds of tests have been conducted at Sandia using this tester and modifications of it. The most serious shortcoming of the tester has proven to be the lack of repeatability of test results. This appears to be for several reasons. The small quantity of the mud/LCM sample tested gives a low probability that the same distribution of LCM particle sizes will be found in any test. The fact that the test is static (no mixing during the test) and the random orientation of the particles that form the plug contribute to the problem. The method used to estimate the amount of filtrate that has accumulated in the receiver is crude. Finally, the test procedure and data recording is subject to operator interpretation and performance.

In an effort to improve the usefulness of the tester, several modifications have been made (Figure 10):

- 1) a set of six-inch-deep slots is used in place of the 1/4-inch-thick disks;
- 2) rough surface plates simulating fractures with three different rugosities or smooth surfaces can be used in the six-inch slots;
- 3) a closed filtrate receiver similar to the test cell is used to catch and measure the amount of fluid passing through the simulated loss zone; and
- 4) the test system has been instrumented and coupled to a computer to provide a menu-driven test procedure and real-time data acquisition and data summary.

Another important improvement in test methods has proven to be the sieving and accurate controlling of the LCM particle size distribution that goes into each test batch. In the development of this process it was natural to find the most effective and efficient particle size distribution.

The nature of the plug formation in our laboratory tests is that a few large particles must be available at the slot to bridge it so that a plug will start to form. Smaller sizes and shapes will then follow to form a liquid-tight plug. If too few large particles are available repeatability of the test suffers. Laboratory experiments showed that by shifting the distribution to a higher percentage of larger particle sizes, as shown in Figure 13, better

repeatability, reduced data scatter and lower filtrate loss resulted. This distribution (called SAN-2 for Sandia design no. 2) is now used as baseline for all material tests. It is reasonable that the same logic can be applied to field application of LCMs. That is, the small percentages or tails of the distribution curves outside the effective range for a given fracture size reduce the efficiency of the product. A comparison of results for tests conducted with the SAN-2 distribution and a commercial product in the original and the modified API tester is shown in Table I. These data demonstrate the reduced filtrate and standard deviation of the tests conducted with each evolution of the test system.

Lost Circulation Test Facility

The large-scale Lost Circulation Test Facility (LCTF) employs essentially the same test procedures as the modified API tester, but there are some fundamental differences in the facility hardware and the conditions imposed on the LCM. A schematic of the LCTF is shown in Figure 11.

In the LCTF dynamic test a much larger volume of slurry (272 times that in the API tester) is circulated through a full-scale vertical annulus that simulates the flow geometry of the wellbore. A test section near the center of this flow section is designed such that a simulated loss zone can be attached at the annular surface normal to the flow. This "loss zone" can consist of a permeable matrix material or interchangeable slots as used in the API test system.

The results for a typical LCTF test are shown in Figures 14 and 15. After first establishing a standard annular flow velocity of 1.3 ft/s (0.4 m/s), a valve is opened to apply a 200 psi pressure differential across the slot. If a plug develops, the pressure is maintained for 10 seconds. The pressure is then increased in increments to a maximum value of 1000 psi. A continuous record of filtrate versus time and pressure differential versus time is made during the test. These parameters are used to determine when plugs develop in the slot in order to evaluate the effectiveness of the LCM.

The 60 gallon (0.23 m³) useable filtrate volume is 75 times that of the API tester. The effect of this difference and possibly the circulating mud system is to improve the plugging probability of the LCM in some cases. Other advantages of the LCTF are:

- 1) More realistic flow conditions are created, which results in more repeatable test results.
- 2) LCMs can be tested at elevated temperatures up to 400°F (240°C), whereas the API test is run at ambient temperature after temperature aging the mud slurry in a roller oven. The roller oven test (discussed later) has proven to be ineffective as a measure of high-temperature performance.
- 3) Test control as well as data acquisition is handled by a computer, which also contributes to more repeatable results.

Disadvantages of the LCTF are:

- 1) Tests of brittle LCMs have shown that performance degradation occurs after the slurry is circulated for a short time. This limits the usefulness of a slurry batch to approximately 4 tests. This degradation may be more realistic relative to field applications than is the static API test.
- 2) Due to the large slurry batch size (approximately 6 barrels) the system is not suitable for frequent changes in batches, as is needed to screen material compositions and particle size distributions. The API tester is therefore used for screening materials, with promising candidates subsequently tested in the LCTF under more realistic conditions.
- 3) It is difficult to control flow conditions in such a large system when the mud/slurry properties change with temperature.

Particle Material Properties Tester

It was evident from slot test results that the physical properties of LCMs affected their performance. Also the plugging models developed in this paper demonstrate that several LCM mechanical properties are important in the bridging process. To determine the utility of using such properties to guide the evaluation of LCMs and to provide a more effective means of evaluating high temperature performance, the Particle Material Properties Tester (PMPT) was developed. A schematic of this system is shown in Figure 12.

The PMPT is a simple compression tester designed to measure the material stress/strain relationship as a function of temperature. The tester can provide a measure of the compressive strength and elastic and resilience moduli of LCM particles and show how they are affected at elevated temperatures. The critical part of this test method is the LCM particle sample preparation. In order to provide repeatable test results, a relatively large number of particles (≈ 20)

must be used, each hand picked for uniform shape and size. Each particle is measured so that the surface area subjected to the applied force and the material height are known. The time to prepare for a test then is not trivial; however, once the sample is prepared the test is completed in a few minutes.

The elastic modulus and unconfined compressive strength of a material are measured by placing the particles on the bottom platen of the PMPT and forcing the platens together with a hydraulic ram while measuring platen displacement and compressive force. The resulting stress-strain relationship yields the desired properties. The resilience modulus is a measure of toughness and is the area under the stress-strain curve, which represents the energy stored in the particles at the compressive strength. It would be convenient to use handbook values for these properties but they are not available for all materials and would not be a measure of manufactured products.

The softening temperature of a material is measured by placing the particles under compression in the linear portion of the stress-strain curve and heating the platens slowly to increase the temperature of the particles. At the softening temperature, the particle strain at a constant force increases markedly and continues with further temperature increases until complete failure occurs. This test provides an indication of the useful temperature range of the LCM in a field application.

LOST CIRCULATION MATERIAL TESTS

The importance of compressive strength, elastic modulus, and particle shape on a material's plugging ability have been previously discussed. Other factors to be considered are particle stability, temperature dependence, wettability, specific gravity, and abrasiveness. Particle stability has a direct impact on mud properties and can affect plugging performance. If a material decomposes because of fluid interaction, temperature, or crumbling, the mud properties can change dramatically. Although some field applications may take advantage of certain reactions, they often have a deleterious effect in laboratory tests. For example, cellulosic materials, which were among the materials screened, will decompose at high temperature and can increase the mud viscosity to the consistency of peanut butter. The temperatures encountered in most oil and gas drilling seldom restrict the use of most commercial LCMs. However, geothermal well temperatures can exceed the limits of virtually all

materials in general use. Specific gravity is an indicator of how efficiently an LCM can be suspended in the drilling fluid. A specific gravity above approximately 1.5 is a real problem for the API static test because the LCM tends to settle to the bottom of the cell, negating the test validity. A specific gravity lower than that of the drilling fluid is one factor that can make an LCM hard to mix, the other factor being wetability. The LCMs that are discussed in this paper are generally weak in one or more of the attributes that are important in fracture plugging.

Table II shows the materials and material combinations that have been tested in each test system. Improvements in the test techniques and systems have evolved during the course of the tests. Materials were selected for testing if they appeared to have a high-temperature capability. Previous tests of conventional (mostly cellulosic) LCMs showed that all were degraded by temperature aging in the roller oven [9]. Only ground thermoset rubber did not degrade and has since been tested extensively in this test series. At temperatures below approximately 150°F (90°C) it has excellent LCM qualities. The fact that it does not degrade, decompose, or otherwise contaminate the mud system made it an ideal choice as a baseline granular material for composite material studies and other tests used to analyse our test system design changes. The method used to evaluate an LCM was to first investigate its plugging characteristics as a function of concentration, size distribution, etc., using the modified API tester. Promising candidates were then tested in the large scale LCTF at elevated temperatures. The PMPT, which was recently developed, has been used to measure material properties at ambient temperatures and at elevated temperatures beyond the capability of the LCTF.

Material Properties Test Results

Table III lists the material properties measured in this study. In addition to the mechanical properties determined with the PMPT, the specific gravity, bulk density, void fraction, and % swelling were also measured and are listed.

The results for a typical softening temperature test with thermoset rubber are shown in Figure 16. Plotted here is the ratio of the compressive force divided by the displacement of the particles from their original uncompressed height. This type of plot was found to be relatively insensitive to minor fluctuations in applied force over the course of a

test and yet very sensitive to actual changes in the particles' elastic modulus with temperature. For thermoset rubber, the elastic modulus gradually declines over a range from 110 to 192°F. These two temperatures are listed in Table III as the softening temperature range for this material.

The results for the other materials indicate that coal, expanded aggregate, gilsonite, and perlite are all relatively brittle materials. Both the coal and the gilsonite demonstrated softening at elevated temperatures. The coal tended to disintegrate, while the gilsonite, an asphaltic, melted. Expanded aggregate showed no deleterious effects of temperature up to 500°F.

The mixed nut and black walnut shells not only performed better than expected at elevated temperatures, they were also "tough as a nut." Very high compressive strengths, elastic moduli, and resilience moduli were measured. Degradation at elevated temperatures is characterized by a charring and gradual weakening of the particles.

The results of the material tests may be used together with the bridging models developed here to predict the performance of materials under a given set of conditions. This is done in the following subsection, where the theoretical predictions are compared with experimental slot-plugging results.

Slot-Plugging Test Results

When using the API tester and the LCTF, five and four test runs, respectively, are made for each set of test conditions. This technique provides the data quality required to show the effects of the controlled test variables. All slot tests reported here (API and LCTF) utilized the 6-inch-deep slot design.

A plugging performance plot has been developed so that different LCMs or different LCM grades can be compared. This is a plot of concentration versus a pluggable slot-to-particle size ratio. This dimensionless ratio is a comparison of the slot sizes tested to the maximum particle size of the LCM, which is defined as the "95% size" of the LCM particle distribution. That is, 95% of the particles (by weight) are smaller than that size. For the SAN-2 particle size distribution shown in Figure 13, the "95% size" is 0.085 inches (2.16 mm).

A typical plugging performance curve is shown in Figure 17 for thermoset rubber particles in the

modified API tester. All five tests for a given particle size and concentration are plotted here, 75 tests in all. If a plug formed and held 1000 psi (7000 kPa) differential pressure in a given test, the plug is considered successful, and the data point "x" is plotted. If the plug failed in the test, the data point "0" is plotted. Thus, three regions on this plot can be identified: the region where the plugs always held at 1000 psi (7000 kPa); the region where the plugs always failed; and the region where the plug stability at 1000 psi (7000 kPa) was variable.

As can be seen, this method of data presentation is a worst case analysis since not all field applications require such a high pressure capability; but, it is a useful tool for material comparisons. Another material attribute that is clearly shown by this type of curve is the effect of increasing concentration. For granular materials alone, concentrations above 10 lbs/bbl are progressively less effective, and very little can be gained with concentrations above 20 lbs/bbl. Another conclusion can also be drawn here. If a field application using a reasonable concentration of a particular grade of material is unsuccessful, then that material is not suited to the application. Assuming there is no other problem, e.g. temperature, a different size or grade of material should be tried rather than more of the same, as is often done.

The following subsections discuss the performance of individual LCMs and the combinations of materials tested.

Thermoset Rubber

Thermoset rubber in the form of ground automobile battery casings was tested in both the modified API tester and the LCTF. The results shown in Figure 17 confirm that the performance of this LCM as a bridging material is a function of the slot or fracture size. At slot/particle size ratios less than 1, single-particle bridges composed of the largest particles are possible. As the slot size increases beyond the particle size (0.075 inches), the plugging ability suffers because the plugs must rely on two- and three-particle bridges composed of smaller particles in the distribution. Successful multiple-particle plugs that hold 1000 psi (7000 kPa) or more occur at concentrations as low as 5 lb/bbl, but the probability of success is much lower than the virtual certainty associated with single-particle plugs of this material. The primary effect of concentration at a

given particle size is to increase the probability of achieving 1000 psi (7000 kPa) plugs.

The performance of thermoset rubber as a filter material is displayed in Figure 18. Here the filtrate loss as a function of particle concentration is shown. Increased concentration makes a higher volume of small particles available to seal the bridges formed by larger particles, and the filtrate drops to very low relative levels.

Tests conducted with a mix of these thermoset rubber granular particles and a commercial blend of thermoset plastic flakes (Super Wes-Bridge) demonstrated dramatically improved performance, with a greatly increased probability of developing 1000 psi (7000 kPa) plugs as well as reduced filtrate loss. Apparently the flakes interact with the granular particles to help stabilize and promote multiple-particle bridging. Moreover, the flakes are extremely pliant ($L/h \gg 1$) and are therefore easily extruded into the gaps between the granular particles to form an effective filter.

To take best advantage of this synergistic effect of granules and flakes, a series of tests was conducted to determine the optimal blend of the two material shapes. The results indicate that a 4:1 weight ratio of granular to flake particles with a 1:2 size ratio, respectively, provides the minimum filtrate loss over a wide range in these parameters tested. The resulting LCM particle distribution for combined shapes is designated the SAN-1 distribution.

Tests were conducted in the LCTF and the modified API tester with the SAN-1 distribution. The results are shown in Figure 19. Under the dynamic flow conditions of the LCTF, a slightly larger slot size is pluggable with this elastic material combination than in the more static API test. Note that reliable plugging at 1000 psi (7000 kPa) was obtained in the LCTF with slots that are well over twice the size of the granular particles. Three-particle bridging is apparently a high-probability event with the higher concentrations of this granule/flake mixture.

The effects of slot size on the maximum allowable pressure differential for this combination bridging material are shown in Figure 20. The results for the API tests of thermoset rubber particles only (Fig. 17) are also shown here. It is apparent that the granule/flake mixture promotes higher strength bridges capable of spanning wider fractures.

Predictions of the bridging models for this case are shown in Figure 20 as the closed symbols. These were calculated by assuming that the largest 5% of the particles in a distribution control the plug strength. The dimensions of the controlling particles are then such that the middle dimension is equal to the "95% size" used to characterize the LCM grades tested. By assuming that these particles arrive at the fracture in a random orientation, a range in calculated plugging characteristics is expected. For example, if a particle arrives with its smallest dimension spanning the fracture, the maximum allowable pressure differential for the bridge will be different from that calculated when the particle arrives with its longest dimension forming the bridge. Thus the random orientation assumption produces a range in calculated pressures for a given slot size. The details of the calculations are presented in Table IV.

The theoretical results agree remarkably well with the experimental data. The random orientation assumption causes the theoretical results to mimic the apparent scatter in the laboratory data. As concluded in an earlier study [9], most of the variability in controlled slot-plugging tests is due to the inherent variability of the plugging process itself, not to inadequate laboratory procedures.

The predictions of the bridging models are most accurate for slot sizes less than twice the particle size. This is expected, because the models consider only one- and two-particle bridges. The higher pressure capability of the combination LCM in the larger slots is due to three-particle bridging. This material was the only material tested that demonstrated significantly strong three-particle bridges.

An inherent shortcoming of thermoset rubber is its tendency to soften at temperatures as low as 100-200°F (38-93°C). Tests conducted in the modified API tester at room temperature after the material aged for 4 hours at 400°F (204°C) in a roller oven did not reveal any degradation in plugging performance, since the particles are not significantly stressed during the thermal aging and thus recover to perform well at low temperatures. The behavior of the material under stress is quite different, as the results reported in Figure 16 showed. Tests run in the LCTF with granular thermoset rubber particles confirmed the effects of stress, as shown in Figure 21. There is an excellent correlation between the deleterious effects of temperature on particle strain in the heated compression tests and on plugging pressure in the slot

tests. Tests conducted at various concentrations indicate that the degraded performance at elevated temperatures is not improved with higher concentrations of material; i.e. increased concentrations of a degraded material do not compensate for reduced particle strength. This supports the hypothesis that concentration plays little or no role in determining plug strength beyond an improvement in the probability of forming a plug.

A series of tests was designed to determine the synergistic effects of mixing thermoset rubber (an excellent LCM except for its high-temperature properties) with an LCM known to perform well at high temperatures (expanded aggregate). This test approach using commercially available materials, although probably unique in laboratory tests, yields valuable information on the benefits of using complimentary materials. This approach can be compared to using several particle sizes and shapes for better performance.

The results of the test series are shown in Figure 22. Shown here is the maximum allowable pressure differential vs. temperature with a mix of thermoset rubber granules and expanded aggregate in a 2:1 ratio at 15 lb/bbl. The dashed curve taken from Figure 21 represents the baseline results for thermoset rubber only. A comparison of the data indicates that reduced performance may occur with the mixture at room temperatures, but the performance is significantly improved at elevated temperatures. Apparently the rigid expanded aggregate particles effectively support the softened rubber particles at the higher temperatures and make possible bridges that would otherwise be elastically unstable. The concentration and particle size distribution of the expanded aggregate used in these tests were typical of drill cuttings found in the wellbore during drilling (5 lb/bbl and medium-course size class). This points out the possible importance of drill cuttings in modifying the performance of lost circulation materials.

The final slot test results involving thermoset rubber are shown in Figure 23. In these tests, combinations of fibrous filter materials with granular thermoset rubber particles were evaluated in the modified API tester. Small concentrations of fiberglass, magma fiber, and Stratawool all reduce filtrate loss from that measured with the thermoset rubber particles alone. (Note that the logarithmic scale of the plot tends to mask the significance of the effects, which are quite large.) At

concentrations of 5 lb/bbl, however, the fibers cause increased filtrate loss. This is a problem commonly encountered with the static API tester. At high additive concentrations the fibrous or flake material congregates in the tester throat filtering out the particles necessary to bridge the slot, resulting in higher filtrate loss. However, this may also be an indication that excessive fiber content can interfere with plug formation in actual application.

Expanded Aggregate

Expanded aggregate was also tested by itself in both the modified API tester and the LCTF. This heat-expanded (3000°F/1649°C) rock, which could be a slate, shale, or clay according to the patent, has no observable temperature sensitivities over the range tested (75-500°F/24-260°C). It has proven to be effective at low concentrations. The results are shown in Figure 24.

The data indicate that multiple-particle bridging with this material is not successful in forming 1000 psi (7000 kPa) plugs. As a result, to get a reliable plug in the API tests, the concentration of the LCM must be high enough that a sufficient number of larger particles accumulate to form single-particle bridges.

In the LCTF, the maximum pluggable slot size was reduced from that measured with the API tester. The cause of this reduction in performance was thought to be breakage of the brittle particles under the dynamic flowing conditions of the LCTF. After the particles passed through the mud pump and piping system, their dimensions were smaller than the original particles. A further gradual reduction in plugging performance was noted when the same mud/LCM batch was circulated over a period of time.

The calculations presented in Table IV for this material are difficult to plot but show excellent agreement with the experimental results. All six possible orientations of the particles yield a predicted maximum sealing pressure in excess of 1000 psi (7000 kPa) with a 0.06-inch slot. Only two of the possible particle orientations are capable of 1000+ psi (7000+ kPa) bridges in the 0.08-inch and 0.10-inch slots according to the model. A larger concentration of particles is thus necessary to plug the larger slots.

The specific gravity of the expanded aggregate (2.2-2.6) made it difficult to keep the material in suspension for testing in spite of the manufacturer's

claim that the porous lattice structure allows fluid to penetrate the particle, making it easy to suspend. The yield and gel strengths of the base mud were raised to 18 lbs/100 ft² (8.62 Pa) and 30 lbs/100 ft² (14.4 Pa) in order to keep the LCM mixed in the static API test. One factor contributing to this problem may have been the poor quality control of the early sample we received. Also the abrasive nature of this material had a very deleterious effect on the LCTF.

Ground Coal

Ground coal was tested in both the modified API tester and the LCTF. The plugging performance curves from the API tester are shown in Figure 25. Note that only single-particle bridges (slot/particle size < 1) are possible with this extremely brittle material. The effects of aging the coal at 400°F (204°C) for four hours prior to testing were found to be relatively small.

In the LCTF, the ground coal was able to plug only the 0.04-inch slot reliably at 1000 psi (7000 kPa) differential. With larger slots, plugs formed at lower pressures, but subsequently ruptured before the maximum 1000 psi (7000 kPa) was reached. The maximum sealing pressure is plotted as a function of slot width in Figure 26. Also plotted are the predictions of the bridging models, as calculated in Table IV. Once again, excellent agreement is attained between the experimental results and the predictions of the relatively simple bridging model.

The effect of circulation on this material is significant breakage of the particles. This was evident in an increased mud viscosity and discoloration and the need for frequent mud changes during the test series. The predictions plotted in Figure 26 include calculations made with an assumed 30% reduction in particle dimensions. These results more accurately predict the LCTF test results than those calculated with the original particle dimensions.

The effects of temperature on ground coal performance were evaluated in an LCTF test series conducted at temperatures up to 330°F (166°C). The results indicate about a 30% reduction in maximum pressure differential at the higher temperatures. This is in accordance with the softening temperature test results shown in Table III. As with the thermoset rubber, increased concentrations of the ground coal did not compensate for reduced particle strength at elevated temperatures.

With respect to other desirable LCM properties, ground coal was found to have an acceptable specific gravity, and no problems were encountered in mixing or suspending the LCM in drilling mud. The deleterious effects of the broken coal on mud properties, as previously mentioned, however, could cause undesirable pumping and chip removal effects in the field.

Other LCMs

Other LCMs underwent preliminary tests but were dropped from consideration for various reasons. A promising plastic flake (possibly a cellulose derivative) tested well at room temperature but turned to a paste when subjected to the high-temperature roller oven. Attempts were made to test a commercial mica flake LCM in the API tester, but the specific gravity was so high the material settled to the bottom of the test cell. Mica should have good high temperature stability, so an attempt will be made to find a more suitable/higher quality product for testing in the future. An engineered wood fiber was tested in the API tester and performed well at room temperature but permanently degraded in the 400°F roller-oven test.

DISCUSSION

Although the laboratory tests reported here were conducted with LCM particles of a given size range for each material, the results should have applicability to other particle sizes of the same material as long as the particle shape (i.e., aspect ratio), material properties, and size relative to the fracture are similar. This conclusion is a result of the bridging models, which indicate that the maximum sealing pressure of a bridge plug is a function of the shape of the particle relative to the fracture and its material properties, but not its absolute dimensions. A plot such as Figure 27, which compares the performance of the materials on the basis of the ratio of slot to particle size, should therefore have general applicability for those materials. The materials shown in this figure are those that were tested in the API tester.

Figure 27 shows how well each material would be expected to perform if the fracture size and LCM particle size are known. It should again be noted that an increased concentration of material beyond a certain limit does not increase the fracture size that the material can plug, although it may reduce filtrate loss by causing the plug to form quicker. Concentrations of granular materials alone above 20

lb/bbl in most cases imply waste of the LCM and may, in fact, increase filtrate loss. With combinations of granules and flakes or fibers, concentrations up to 35 lb/bbl may be beneficial. The fraction of the LCM composed of the flake/fiber material should also be controlled to achieve the beneficial sealing effect without possible interference with bridge formation.

The ability of a material to plug a large fracture seems to correlate well with the ratio of the compressive strength of the material to its elastic modulus, S/E . The values for coal (0.11), expanded aggregate (0.13), and thermoset rubber (0.32) increase in apparent agreement with the pluggable slot size in Figure 27. This also agrees with the bridging models, which include the ratio S/E as a variable.

Using the S/E ratio as a guide to suitability of materials as LCMs, Table III shows that both the mixed nut shells ($S/E=0.29$) and black walnut shells (0.48), should be excellent LCMs. Their relative temperature stability suggests that these materials may have utility in more severe environments than most common cellulosic materials can tolerate. The nut shells were not examined until late in the testing program and have not yet been tested in our slot testing facilities.

The theoretical bridging models developed in this paper have provided insight into the plugging process and are shown to predict laboratory slot-plugging results quite accurately. The simplicity of the models and their non-dimensional form permit them to be used to evaluate the approximate bridging characteristics of potential LCMs. The excellent correlation of these models with test results adds credibility to the ultimate goal of designing an expert system for the application of LCM in the drilling industry.

The PMPT developed in this program is a simple apparatus that provides the necessary mechanical properties needed in the mathematical models. This tester complements the capability of the slot testers, providing effective high-temperature evaluation as well as measurements of other LCM attributes that govern performance.

Further work is necessary to confirm the validity of the results reported here in field applications. Further investigation of the bridging model implications on particle size distributions and the development of a three-particle bridging model are also needed.

Our research and field experience has revealed that product quality control is an area that requires much improvement. If a high probability of success is expected in the application of this technology, then the LCM delivered to the wellsite must be as advertised. In our work we sieve random samples from each product received and invariably find a size distribution and sometimes product properties significantly different from the product specification. Field experience reported to us cites examples of applications that have resulted in plugged or burned bits because of an LCM where a different batch of the product had been successfully used before. This product variation is especially evident in blended materials where substitutions appear to be made depending on availability.

SUMMARY OF CONCLUSIONS

- 1) A modified version of the API bridging materials tester was developed to improve the data quality of slot tests, making it a more effective tool for screening potential lost circulation materials.
- 2) A large-scale lost circulation facility (LCTF) has been developed that more accurately simulates dynamic flowing conditions prevalent in fracture plugging applications. Significant differences in plugging performance are noted between the LCTF and the API tester with some materials.
- 3) A simple test system to complement the slot tests has been developed that measures the material properties important in bridge plugging mechanics. The particle material properties tester (PMPT) has proven valuable in measuring the elastic modulus, compressive strength, and softening temperature of LCM particles. The softening temperature has been found to correlate well with the effects of temperature on slot-plugging performance.
- 4) Effective theoretical models of the one- and two-particle bridging process have been developed that predict the maximum sealing pressure differential sustainable by a plug. Variables in the models include the shape and size of the particle relative to the fracture width as well as the mechanical properties of the bridging material. The models have been shown to provide accurate predictions of laboratory slot-plugging test results.
- 5) Plugging performance plots have been developed that allow the comparison of LCMs of different particle sizes and different types in fractures of

known width. These plots can also serve to determine the potential for plugging bit nozzles in field LCM applications. Plugging performance plots have been developed for several commercial LCMs that have potential in severe fracture-dominated, underpressured loss zones.

6) Concentrations of granular LCM particles as high as 20 lb/bbl can reduce filtrate loss and improve the probability of forming a high-pressure plug; however, higher concentrations are not beneficial and may be detrimental. Concentrations of composite materials as high as 35 lb/bbl may be beneficial, but the proportion of granules and fibers/flakes must be carefully controlled.

7) An optimal granule:flake LCM mixture of 4:1 weight ratio and 1:2 size ratio, respectively, was developed for thermoset rubber. This combination was found to be superior to all other LCMs tested at low temperature but displayed reduced performance at temperatures above 200°F.

8) Particle size distribution is an important factor in the bridge plugging process, as predicted by the bridging models and confirmed with laboratory experience. Tight control of the size distribution is necessary to successfully and economically use an LCM treatment. Quality control is also important in the LCM manufacturing process to ensure LCM with consistent mechanical properties.

9) Brittle materials tend to degrade in size during exposure to dynamic flowing conditions. This can contribute to unwanted changes in drilling fluid properties and plugging characteristics. If the material arrives at the fracture face intact, it can form effective plugs under high differential pressures in relatively small fractures if the compressive strength is adequate.

10) Random orientation of particles at the plug location is a plausible explanation for apparent variability in laboratory slot-plugging performance, although particle size distribution also has an effect.

11) The possibility that drill cuttings may modify the plugging characteristics for a given LCM treatment should always be considered. If applied while drilling, the LCM used should complement the effects of rigid rock particles present in the drilling fluid.

NOMENCLATURE

d	particle depth, in (cm)
E	elastic modulus, psi (kPa)
F_L	longitudinal force on particle, lb (N)
F_P	contact force between particles, lb (N)
F_w	particle/wall contact force, lb (N)
h	particle height, in (cm)
I	particle moment of inertia, in ⁴ (cm ⁴)
L	particle length, in (cm)
M	bending moment, in-lbf (N-cm)
p	pressure differential across plug, psi (kPa)
$(p_{max})_{1E}$	maximum allowable pressure differential for a single-particle bridge based on elastic failure, psi (kPa)
$(p_{max})_{1I}$	maximum allowable pressure differential for a single-particle bridge based on inelastic failure, psi (kPa)
$(p_{max})_{2E}$	maximum allowable pressure differential for a two-particle bridge based on elastic failure, psi (kPa)
$(p_{max})_{2I}$	maximum allowable pressure differential for a two-particle bridge based on inelastic failure, psi (kPa)
P_1	dimensionless elastic failure pressure for a single particle bridge
P_2	dimensionless differential pressure across a stable two-particle bridge
P_3	dimensionless elastic failure pressure for a two-particle bridge
P_4	dimensionless minimum pressure differential for a two-particle bridge
P_5	dimensionless particle stress in a two-particle bridge
S	particle compressive or tensile strength, psi (Mpa)
w	fracture width, in (cm)
α	particle orientation angle, deg (rad)
α_e	particle equilibrium angle in a stable two-particle bridge, deg (rad)
α_{f3}	elastic failure angle of a two-particle bridge, deg (rad)
ϵ	longitudinal particle strain
θ	single-particle bridge deflection angle
θ^0	deflection angle at ends of particle
η	particle/fracture wall friction coeff.
η_{min}	minimum required η for two-particle bridge stability in a friction plug
ν	Poisson's ratio
ρ	particle radius of curvature, in (cm)
σ_b	particle bending stress, psi (Mpa)

σ_c	combined stress in two-particle bridge, psi (MPa)
σ_L	longitudinal particle stress, psi (MPa)

Subscripts

e	at equilibrium
E	elastic
I	inelastic
1	single-particle bridge
2	two-particle bridge

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APPENDIX A

Single-Particle Bridging

The maximum bending stress in the equivalent beam of Figure 1 occurs at mid-span and is

$$\begin{aligned}\sigma_b &= \frac{Mh}{2I} \\ \sigma_b &= \frac{3}{4} p \left(\frac{w}{L}\right)^2 \left(\frac{L}{h}\right)^2\end{aligned}\quad (A1)$$

Inelastic failure occurs when $\sigma_b = S$. Inserting this relation into Eq. A1 and solving for p gives the result shown in Eq. 1.

For the beam of Figure 2, the wall contact force is found by balancing forces in the y -direction:

$$F_w = \frac{p w d}{2 (\cos \theta_o + \eta \sin \theta_o)} \quad (A2)$$

The moment in the beam at any point x is

$$\begin{aligned}M = F_w [x \cos \theta_o + y \sin \theta_o + \eta(x \sin \theta_o - y \cos \theta_o)] \\ - \frac{pd}{2} (x^2 - y^2)\end{aligned}\quad (A3)$$

The radius of curvature of the deflected beam at any point x is

$$\rho = \frac{EI}{M} \quad (A4)$$

Inserting Eqs. A2, A3, and the relation $I = h^3 d / 12$ into Eq. A4 gives the result,

$$\begin{aligned}\frac{\rho}{w} &= \frac{1}{6} [P_1]^{-1} \\ \left[\frac{x}{w} + \frac{y}{w} \frac{\sin \theta_o - \eta \cos \theta_o}{\cos \theta_o + \eta \sin \theta_o} - \left(\frac{x}{w}\right)^2 - \left(\frac{y}{w}\right)^2 \right]^{-1},\end{aligned}\quad (A5)$$

where

$$P_1 = \frac{p}{E} \left(\frac{w}{h}\right)^3 \quad (A6)$$

The distance s along the deflected beam at any point is

$$s = \int_0^s ds = \int_{\theta_o}^{\theta} \rho d\theta \quad (A7)$$

The corresponding values of x and y are

$$x = \int_0^x dx = \int_0^s \cos \theta ds \quad (A8)$$

$$y = \int_0^y dy = \int_0^s \sin \theta ds \quad (A9)$$

Eqs. A5-A9 are a set of non-linear integral equations that must be solved to determine the beam length required to span the fracture. The boundary conditions on the beam deflection are:

$$y = 0 \text{ at } x = 0 ,$$

$$\theta = \theta_0 \text{ at } x = 0 ,$$

and

$$\theta = 0 \text{ at } x = w/2.$$

These equations were solved numerically over a range of the parameters P_1 and η using the following procedure:

1. Specify η .
2. Specify some value of the beam angle $\theta_0 > 0$.
3. Make an initial estimate of P_1 .
4. $\Delta s/w = 10^{-4}$; $s/w = 0$; $x/w = 0$; $y/w = 0$; $\theta = \theta_0$.
5. Calculate ρ/w using Eq. A5.
6. $s/w = s/w + \Delta s/w$; $x/w = x/w + \cos \theta \Delta s/w$;
 $y/w = y/w + \sin \theta \Delta s/w$; $\theta = \theta - (\Delta s/w)/(\rho/w)$.
7. If $x/w < 0.5$, go to 5.
8. Check θ at $x/w = 0.5$:
 - if $\theta > 0$, reduce estimate of P_1 ; go to 4.
 - if $\theta < 0$, increase P_1 estimate; go to 4.
9. If $\theta = 0$, length of beam required to span fracture is $2s/w$; go to 2 for next θ_0 value.

Values of L/w are plotted in Figure 3 for several levels of friction coefficient. As the dimensionless pressure P_1 increases from zero, the beam begins to deflect, and the calculated value of s/w at $x/w = 0.5$ is the one-half the minimum beam length, L , required to span the fracture (i.e., $L/w = 2 s/w|_{x/w=0.5}$). At some point for each value of the friction coefficient, the curvature of the beam becomes so great that it becomes unstable, and the calculated value of s/w at $x/w = 1$ becomes unbounded with further increases in pressure. Each curve of P_1 vs. s/w actually takes on a negative slope beyond this point; but this represents an unstable region where decreasing pressure results in increasing s/w . As a result, the pressure capability of the particle based on elastic failure is not improved by increasing the length of the particle. For values of L/w greater than the value corresponding to the maximum stable pressure, the curves of Figure 3 are therefore drawn flat.

Two-Particle Bridging

A sum of the equilibrium moments acting about the z-axis on the equivalent beam in Figure 4 yields the result:

$$(F_p)_e = \frac{p L_e d_e}{2 \sin \alpha_e} \quad (A10)$$

A sum of the equilibrium forces acting in the x-direction produces the relation:

$$(F_{wx})_e = p L_e d_e \left(\frac{1}{2 \sin \alpha_e} - \sin \alpha_e \right) \quad (A11)$$

Since $(F_{wx})_e$ as shown in Figure 4 must not be negative, Eq. A11 yields

$$\alpha_e \leq 45^\circ \quad (A12)$$

Thus a stable two-particle bridge cannot form unless the length and elastic characteristics of the particles are such that the final equilibrium angle is less than 45° .

If a stable bridge does form, the longitudinal deflection of each particle from its original length, L , to its equilibrium length, L_e , in the stable bridge position is

$$\epsilon = \frac{\sigma_c}{E} \quad (F_L)_e L$$

$$L - L_e = \frac{h d E}{h d E} \quad (A13)$$

where

$$(F_L)_e = (F_p)_e \cos \alpha_e$$

$$(F_L)_e = \frac{p L_e d_e}{2 \tan \alpha_e} \quad (A14)$$

Geometry considerations give

$$L_e = L \frac{\cos \alpha_1}{\cos \alpha_e} \quad (A15)$$

where

$$\alpha_1 = \cos^{-1} \left(\frac{w}{2L} \right) \quad (A16)$$

Inserting Eqs. A14-A16 into A13 and making the assumption that $d_e = d$ due to lateral confinement of the particle from neighboring bridges, yields Eq. 4.

The longitudinal stress in each particle at equilibrium is

$$\sigma_L = \frac{(F_L)_e}{h d} \quad (A17)$$

while the bending stress at particle midpoint is

$$\sigma_b = \frac{3}{4} p \left(\frac{L_e}{h_e} \right)^2 . \quad (A18)$$

The particle height is assumed to vary with the longitudinal strain according to Poisson's ratio, ν :

$$\frac{h_e - h}{h} = \nu \frac{L - L_e}{L} . \quad (A19)$$

The combined stress is maximum at particle midpoint according to the relation:

$$\sigma_c = \sigma_L \pm \sigma_b , \quad (A20)$$

where the positive sign applies to the high-pressure side of the particle and the negative sign applies to the low-pressure side. Substituting Eqs. A18-A20 into Eq. 12 produces Eq. 13.

TABLE I
TEST SYSTEM COMPARISON

	Particle Size Distribution		
	Commercial Blend		SAN-2 Distribution
	Original API Tester	Modified API Tester	Modified API Tester
Maximum Pressure	1000	1000	1000
Filtrate (cc) at Max. Pressure (10 sec)	1625	1446	521
Standard Deviation	556	398	153
Filtrate (cc) at Max. Pressure (10 min)	1775	1836	644
Standard Deviation	842	424	301

Data from 50 test runs using thermoset rubber.

TABLE II

LOST CIRCULATION MATERIALS TESTED

Material	Type	Size/Distribution	— TEST SYSTEM*—			Commercial Source
			API	LCTF	PMPT	
Thermoset Rubber	Granular	4 grades	x	x	x	Poly Cyle Ind.
Coal	Granular	medium grade	x	x	x	McCabe Woody Co.
Gilsonite	Granular	medium grade			x	American Gilsonite
Expanded Aggregate	Granular	fine grade	x	x	x	International Drilling Products
Mixed Nut Shells	Granular	sized			x	Magcobar
Black Walnut	Granular	sized			x	Generic
Alder wood	Fiber	<.75 inch	x			Weyerhaeuser Co.
Perlite	Granular	10 mesh		x		unknown
Mica	Flake	medium grade	x			NL Baroid
Plastic	Flake	medium grade	x			Conoco
Composite w/ Thermoset Rubber (Granular)						
Expanded Aggregate	Granular	fine grade		x		International Drilling Products
Mineral Wool	Fiber	random/short	x			Lost Circulation Specialists
Fiber Glass	Fiber	1/2 inch	x			Owens Corning
Graphite	Fiber	1/2 inch	x			Generic
Thermoset Plastic	Flake	random	x	x		Poly Cycle Ind.

* API - Modified API tester

LCTF - Lost Circulation Test Facility

PMPT - Particle Material Properties Tester

TABLE III

RELATIVE MATERIAL PROPERTIES

Material	Type	Specific Gravity (adv./meas.)	Compressive Strength, S (psi)	Elastic Modulus, E (psi)	S/E	Softening Temperature Range (F)	Resilience Modulus (lb/in**2)	Bulk Density (lb/ft**3)	Void Fraction (%)	% SWELLING 24 HOUR water soak
Thermoset rubber	granular	1.10/1.48	2030	6,330	0.32	110-192	333	65.48	31	0
Coal	granular	1.30/2.30	210	1,880	0.11	250-330	12	82.17	43	0
Expanded Aggregate	granular	2.20/2.60	860	6,410	0.13	>500	60	100.20	39	0
Gilsonite	granular	1.06/0.75	340	1,740	0.20	345-375	34	33.23	29	0
Mixed Nut Shells	granular	/1.20	8230	28,500	0.29	380-480	1443	40.80	45	5
Black Walnut Shells	granular	/1.10	9870	20,500	0.48	360-500	2271	34.00	48	11
Perlite	granular	/0.54	190	830	0.22		20	14.89	56	0

TABLE IV

BRIDGING MODELS PREDICTIONS FOR SEVERAL MATERIALS

TYPHOSEY RUBBER: E=2020 psi E=4390 psi S/E=0.32										Particle Dimensions: 0.088 0.075 0.053							
L (in)	h (in)	d (in)	v (in)	L h	L v	Bridge Type	P ₁ (Fig.3)	P ₂ (Eq.6)	P ₄ (Eq.11)	$\sigma_{\text{max}}^{\text{EP}} \frac{S}{E}$ (Fig.7)	P ₂ θ ₀ (Fig.5)	(P _{max}) _{1E} (Eq.2)	(P _{max}) _{1I} (Eq.1)	(P _{max}) _{2E} (Eq.9)	(P _{min}) _{2E} (Eq.10)	(P _{max}) _{2I} (Eq.14)	REMARKS
.088	.075	.053	0.08	1.17	1.10	1	1.16	-	-	-	-	6050	2379	-	-	-	2
.088	.075	.053	0.10	1.17	0.88	2	-	.62	.49	-	-	-	-	3354	2651	-	1.3
.088	.075	.053	0.12	1.17	0.73	2	-	.30	.07	37°	.22	-	-	1623	379	1190	1.2
.088	.075	.053	0.14	1.17	0.55	2	-	.04	0	-	-	-	-	216	0	-	3
.088	.075	.053	0.18	1.17	0.49	3	-	-	-	-	-	-	-	-	-	-	4
.088	.075	.053	0.20	1.17	0.44	3	-	-	-	-	-	-	-	-	-	-	4
.088	.053	.075	0.08	1.66	1.10	1	1.16	-	-	-	-	2135	1188	-	-	-	2
.088	.053	.075	0.10	1.66	0.88	2	-	.62	.49	-	-	-	-	2364	1869	-	1.3
.088	.053	.075	0.12	1.66	0.73	2	-	.30	.07	37°	.22	-	-	1144	267	839	1.2
.088	.053	.075	0.14	1.66	0.55	2	-	.04	0	-	-	-	-	153	0	-	3
.088	.053	.075	0.18	1.66	0.49	3	-	-	-	-	-	-	-	-	-	-	4
.088	.053	.075	0.20	1.66	0.44	3	-	-	-	-	-	-	-	-	-	-	4
.075	.088	.053	0.08	0.85	0.94	2	-	.76	.66	-	-	-	-	5660	4915	-	1.3
.075	.088	.053	0.10	0.85	0.75	2	-	.35	.12	40°	.25	-	-	2606	894	1862	1.2
.075	.088	.053	0.12	0.85	0.63	2	-	.13	0	-	-	-	-	968	0	-	3
.075	.088	.053	0.14	0.85	0.47	3	-	-	-	-	-	-	-	-	-	-	4
.075	.088	.053	0.18	0.85	0.42	3	-	-	-	-	-	-	-	-	-	-	4
.075	.088	.053	0.20	0.85	0.38	3	-	-	-	-	-	-	-	-	-	-	4
.075	.053	.088	0.08	1.42	0.94	2	-	.76	.66	-	-	-	-	3388	2942	-	1.3
.075	.053	.088	0.10	1.42	0.75	2	-	.35	.12	40°	.25	-	-	1560	535	1214	1.2
.075	.053	.088	0.12	1.42	0.63	2	-	.13	0	-	-	-	-	580	0	-	3
.075	.053	.088	0.14	1.42	0.47	3	-	-	-	-	-	-	-	-	-	-	4
.075	.053	.088	0.18	1.42	0.42	3	-	-	-	-	-	-	-	-	-	-	4
.075	.053	.088	0.20	1.42	0.38	3	-	-	-	-	-	-	-	-	-	-	4
.053	.088	.075	0.08	0.60	0.66	2	-	.18	0	-	-	-	-	1899	0	-	3
.053	.088	.075	0.10	0.60	0.53	2	-	.016	0	-	-	-	-	169	0	-	3
.053	.088	.075	0.12	0.60	0.44	3	-	-	-	-	-	-	-	-	-	-	4
.053	.075	.088	0.08	0.71	0.66	2	-	.18	0	-	-	-	-	1605	0	-	3
.053	.075	.088	0.10	0.71	0.53	2	-	.016	0	-	-	-	-	143	0	-	3
.053	.075	.088	0.12	0.71	0.44	3	-	-	-	-	-	-	-	-	-	-	4
EXPANDED AGGREGATE: E=860 psi E=4410 psi S/E=0.13										Particle Dimensions: 0.110 0.081 0.067							
L (in)	h (in)	d (in)	v (in)	L h	L v	Bridge Type	P ₁ (Fig.3)	P ₂ (Eq.6)	P ₄ (Eq.11)	$\sigma_{\text{max}}^{\text{EP}} \frac{S}{E}$ (Fig.7)	P ₂ θ ₀ (Fig.5)	(P _{max}) _{1E} (Eq.2)	(P _{max}) _{1I} (Eq.1)	(P _{max}) _{2E} (Eq.9)	(P _{min}) _{2E} (Eq.10)	(P _{max}) _{2I} (Eq.14)	REMARKS
.110	.081	.067	0.06	1.36	1.83	1	1.26	-	-	-	-	19900	2090	-	-	-	2
.110	.081	.067	0.08	1.36	1.38	1	1.26	-	-	-	-	8320	1170	-	-	-	2
.110	.081	.067	0.10	1.36	1.10	1	1.26	-	-	-	-	3950	752	-	-	-	2
.110	.067	.081	0.06	1.64	1.83	1	1.26	-	-	-	-	11300	1440	-	-	-	2
.110	.067	.081	0.08	1.64	1.38	1	1.26	-	-	-	-	4750	805	-	-	-	2
.110	.067	.081	0.10	1.64	1.10	1	1.26	-	-	-	-	2240	515	-	-	-	2
.081	.110	.067	0.06	0.74	1.85	1	1.26	-	-	-	-	49500	3840	-	-	-	2
.081	.110	.067	0.08	0.74	1.01	1	0.43	-	-	-	-	7240	2180	-	-	-	2
.081	.110	.067	0.10	0.74	0.81	2	-	.47	.29	-	-	-	-	4070	2510	-	1.3
.081	.067	.110	0.06	1.21	1.85	1	1.26	-	-	-	-	11300	1440	-	-	-	2
.081	.067	.110	0.08	1.21	1.01	1	0.43	-	-	-	-	1580	790	-	-	-	2
.081	.067	.110	0.10	1.21	0.81	2	-	.47	.29	-	-	-	-	2510	1550	-	1.3
.067	.110	.081	0.06	0.61	1.12	1	1.21	-	-	-	-	47500	3840	-	-	-	2
.067	.110	.081	0.08	0.61	0.84	2	-	.53	.37	-	-	-	-	5570	3890	-	1.3
.067	.110	.081	0.10	0.61	0.67	2	-	.20	0	-	-	-	-	2100	0	-	3
.067	.081	.110	0.06	0.83	1.12	1	1.21	-	-	-	-	19100	2090	-	-	-	2
.067	.081	.110	0.08	0.83	0.84	2	-	.53	.37	-	-	-	-	4090	2840	-	1.3
.067	.081	.110	0.10	0.83	0.67	2	-	.20	0	-	-	-	-	1540	0	-	3
CRUSHED COAL: E=210 psi E=1880 psi S/E=0.11										Particle Dimensions: 0.174 0.119 0.111							
L (in)	h (in)	d (in)	v (in)	L h	L v	Bridge Type	P ₁ (Fig.3)	P ₂ (Eq.6)	P ₄ (Eq.11)	$\sigma_{\text{max}}^{\text{EP}} \frac{S}{E}$ (Fig.7)	P ₂ θ ₀ (Fig.5)	(P _{max}) _{1E} (Eq.2)	(P _{max}) _{1I} (Eq.1)	(P _{max}) _{2E} (Eq.9)	(P _{min}) _{2E} (Eq.10)	(P _{max}) _{2I} (Eq.14)	REMARKS
.111	.119	.174	0.04	0.93	2.78	1	1.26	-	-	-	-	64000	2520	-	-	-	2
.111	.119	.174	0.06	0.93	1.85	2	1.26	-	-	-	-	19000	1120	-	-	-	2
.111	.119	.174	0.08	0.93	1.39	1	1.26	-	-	-	-	7990	630	-	-	-	2
.111	.174	.119	0.04	0.64	2.78	1	1.26	-	-	-	-	195000	5300	-	-	-	2
.111	.174	.119	0.06	0.64	1.85	1	1.26	-	-	-	-	57800	2350	-	-	-	2
.111	.174	.119	0.08	0.64	1.39	1	1.26	-	-	-	-	24500	1330	-	-	-	2
.119	.111	.174	0.04	1.07	2.98	1	1.26	-	-	-	-	49300	2130	-	-	-	2
.119	.111	.174	0.06	1.07	1.98	1	1.26	-	-	-	-	14500	938	-	-	-	2
.119	.111	.174	0.08	1.07	1.49	1	1.26	-	-	-	-	6230	533	-	-	-	2
.119	.174	.111	0.04	0.68	2.98	1	1.26	-	-	-	-	195000	5300	-	-	-	2
.119	.174	.111	0.06	0.68	1.98	1	1.26	-	-	-	-	57800	2350	-	-	-	2
.119	.174	.111	0.08	0.68	1.49	1	1.26	-	-	-	-	24500	1300	-	-	-	2
.174	.119	.111	0.04	1.46	4.35	1	1.26	-	-	-	-	64000	2520	-	-	-	2
.174	.119	.111	0.06	1.46	2.90	1	1.26	-	-	-	-	19000	1120	-	-	-	2
.174	.119	.111	0.08	1.46	2.18	1	1.26	-	-	-	-	7990	630	-	-	-	2
.174	.111	.119	0.04	1.57	4.35	1	1.26	-	-	-	-	30900	2160	-	-	-	2
.174	.111	.119	0.06	1.57	2.90	1	1.26	-	-	-	-	21300	958	-	-	-	2
.174	.111	.119	0.08	1.57	2.18	1	1.26	-	-	-	-	6360	541	-	-	-	2
CRUSHED COAL: E=210 psi E=1880 psi S/E=0.11										Degraded Particle Dimensions: 0.123 0.084 0.079							
L (in)	h (in)	d (in)	v (in)	L h	L v	Bridge Type	P ₁ (Fig.3)	P ₂ (Eq.6)	P ₄ (Eq.11)	$\sigma_{\text{max}}^{\text{EP}} \frac{S}{E}$ (Fig.7)	P ₂ θ ₀ (Fig.5)	(P _{max}) _{1E} (Eq.2)	(P _{max}) _{1I} (Eq.1)	(P _{max}) _{2E} (Eq.9)	(P _{min}) _{2E} (Eq.10)	(P _{max}) _{2I} (Eq.14)	REMARKS
.123	.084	.079	0.04	1.44	3.08	1	1.26	-	-	-	-	21937	1235	-	-	-	2
.123	.084	.079	0.06	1.44	2.05	1	1.26	-	-	-	-	6300	549	-	-	-	2
.123	.084	.079	0.08	1.44	1.54	1	1.26	-	-	-	-	8631	309	-	-	-	2
.123	.079	.084	0.04	1.36	3.08	1	1.26	-	-	-	-	18388	1098	-	-	-	2
.123	.079	.084	0.06	1.36	2.05	1	1.26	-	-	-	-	5448	488	-	-	-	2
.123	.079	.084	0.08	1.36	1.54	1	1.26	-	-	-	-	2298	374	-	-	-	2
.084	.123	.079	0.04	0.68	2.10	1	1.26	-	-	-	-	70569	2691	-	-	-	2
.084	.123	.079	0.06	0.68	1.40	1	1.26	-	-	-	-	21937	1235	-	-	-	2
.084	.123	.079	0.08	0.68	1.05	1	0.93	-	-	-	-	6384	664	-	-	-</

Figure 1 Single-particle bridging at the entrance to a fracture.

ACTUAL

**DEPTH d NORMAL
TO PLANE OF
FIGURE**

IDEALIZED

**EQUIVALENT
BEAM**

Figure 2 Incipient failure of a single-particle bridge due to elastic deformation.

Figure 3 Dimensionless elastic failure pressure, P_1 , for single-particle bridges.

Figure 4 Two-particle bridging at the entrance to a fracture

Figure 5 Particle equilibrium orientation angle, α_e , as a function of applied dimensionless differential pressure, P_2 , for a two-particle bridge.

Figure 6 Dimensionless elastic failure pressure, P_3 , and minimum required pressure, P_4 , for a two-particle bridge.

Figure 7 Dimensionless particle stress, P_5 , for a stable two-particle bridge.

ACTUAL

DEPTH d_e
NORMAL TO
PLANE OF FIGURE

IDEALIZED

**EQUIVALENT
BEAM**

Figure 8 Two-particle bridging inside a fracture

Figure 9 Minimum required particle/fracture wall friction coefficient for a stable two-particle bridge inside a fracture.

Figure 10 Modified API bridging materials tester.

Figure 11 Lost Circulation Test Facility (LCTF).

Figure 12 Particle Materials Property Tester (PMPT).

Figure 13 SAN-2 engineered particle distribution.

Figure 14 Differential pressure record from a typical LCTF test.

Figure 15 Filtrate loss record for a typical LCTF test.

Figure 16 Softening temperature results for thermoset rubber in the PMPT.

Figure 17 Plugging performance plot for thermoset rubber in the modified API tester.

Figure 18 Filtrate loss for thermoset rubber in the modified API tester.

Figure 19 Plugging performance plot for a combination thermoset rubber:thermoset plastic flake (SAN-1 distribution) in the LCTF and modified API tester

Figure 20 Comparison of experimental and theoretical plugging pressure for thermoset rubber.

Figure 21 Effects of temperature on thermoset rubber plugging capability.

Figure 22 Effects of expanded aggregate on the thermal softening of thermoset rubber in slot-plugging tests.

Figure 23 Relative filtrate loss for three fiber additives to thermoset rubber granules in the modified API tester.

Figure 24 Plugging performance plot for expanded aggregate in the modified API tester and the LCTF.

Figure 25 Plugging performance plot for crushed coal in the modified API test before and after thermal aging in a roller oven.

Figure 26 Comparison of experimental and theoretical plugging pressure for crushed coal.

Figure 27 Comparison of plugging performance curves for LCMs tested in the modified API tester.