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New Optimized Laboratory Testing Methods to Study the Effectiveness of Surface Modification Agents

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Abstract

Formation sand and fines can be released during production as a result of shear failure if drawdown pressures exceed the yield strength of the rock. Gravel-pack completions are typically designed to control formation-sand production. However, fines often begin to migrate into the pack, resulting in permeability damage. Surface modification agents (SMAs) were developed to agglomerate proppant to reduce proppant flowback, prevent fines invasion and migration, and improve fracture conductivity.

Different laboratory testing methods have been developed to test for the effectiveness of different SMAs. Some tests are difficult and time-consuming to set up, making them expensive. Other tests are oversimplified, where critical downhole conditions are completely omitted, causing unreliable results. Conversely, because of the nature of the test, such as in the case of testing with unconsolidated sand, reproducible results after treatments from one pack to another vary widely. This paper presents some new laboratory testing methods to evaluate the effectiveness of SMA coating on proppants. These testing methods are not only robust, but also highly reproducible, where critical downhole conditions are considered.

Introduction

SMAs

SMAs were developed more than 15 years ago to agglomerate proppant to reduce proppant flowback, prevent fines invasion and migration, and improve fracture conductivity. SMAs are water- and oil-insoluble resinous materials that provide cohesion between proppant grains and do not harden or cure under reservoir conditions. The tackiness of SMA-coated proppant has been used to immobilize the movement of formation fines from invading proppant packs to maintain the propped-fracture conductivity, and thus, well productivity.

This paper addresses both a solvent-based SMA (SMA 1) and an aqueous-based version of a tacky SMA 1 (ASMA), as well as a non-tacky SMA (SMA 2). An additional advantage of SMA-coated proppant is its enhancement of conductivity by aiding the cleanup of fracturing gel in the proppant pack. SMAs help prevent the proppant surface from being coated with fracturing gel, which enhances the breaker's effectiveness by reducing gel viscosity and enhancing fracture cleanup after the fracture stimulation. In addition to rendering mineral surfaces tacky so that the coated particles tend to stick together, the coating changes the mineral surface from a normally hydrophilic and water-wet condition to a hydrophobic condition. Recent observations have demonstrated that hydrophobic coatings on proppants can extend their useful life by inhibiting diagenetic pressure-solutions and compaction reactions.[1,2]

The SMA is coated onto the proppant on-the-fly during the fracturing treatment, preferably throughout all the proppant stages. It can be coated using a dry-coat or wet-coat process. During the dry-coat process, the SMA is added directly onto the proppant using the liquid-metering systems to deliver the SMA material to the sand as it is in the sand hopper. As the proppant proceeds from the sand hopper, it is augered up the sand screw, which completely distributes the coating onto the proppant before entering the blender tub.

During the wet-coat process, the SMA is added to the downstream side of the blender tub, where it is coated onto the proppant by displacing the water or gel coating. The uniformity of this coating is further assisted by the mixing action of the proppant slurry passing through the centrifugal pump as it is being boosted to the high pressure pumps to be injected downhole.

The next section provides a brief review of various methods that have been developed for evaluating the cohesion between solid particulates.

Interparticle Cohesion Measurements

Previous Device No. 1: In U.S. patent 4,279,165, Asakura et al.[3] described an apparatus for measuring the cohesion force between particulate material. The apparatus comprises a bottomed container composed of a fixed container segment and a movable container segment for containing the particulate material. There is also a driving device for moving the container segment perpendicularly to the plane of separation of the container for dividing the particulate material in the container into two parts. Additionally, there is a unit for detecting the external force to be applied to the movable container segment by the driving device. At least the movable container segment is suspended from and retained by swingable or deflectable support members. Because the movable container segment is retainable in suspension, there is no need to use ball bearings that would require a precision-finish rolling surface; nor is it necessary to consider any rolling friction. The apparatus can therefore be manufactured at a relatively low cost with high precision. Because the particulate specimen can be compacted with an application of a considerably large load, the apparatus is usable for a wider variety of particulate materials and settable for widely varying measuring conditions; additionally, it has a greatly increased range of applications to the measurement of properties of various particulate materials.

Previous Device No. 2: In U.S. patent 8,429,960, Landru[4] provided an invention describing a structure and process for measuring an energy of adhesion between two substrates bonded in a transverse direction. The method involves allowing at least one of the two substrates to have a plurality of elementary test cells within a test layer. Each of which are made capable of locally applying (in the transverse direction) a preset mechanical stress, dependent on temperature, to a bond interface between the substrates in a direction tending to separate them. This allows application of a test temperature to the substrates and identification of debonded regions of the bond interface so that the local adhesion energy at the test temperature in the regions can be deduced therefrom. The local adhesion energy in a region of the bond interface is deduced from the stress applied by the test cells that caused debonding in the region.

Previous Device No. 3: In U.S. publication 2011/0281294 A1, Pudas et al.[5] claimed an invention that provides a measurement head for measuring the adhesion force between a surface and particle attached to the surface. This invention also provides a force measurement system and method for measuring the adhesion force between a surface and particle attached to the surface.

However, none of the methods and apparatuses described previously were specifically designed to measure the cohesion of the precipitate SMA-coated particulates in a wet environment (i.e., the SMA-coated particulates are contained and suspended together in a liquid).

Method of Testing Degree of Tackiness of Liquid SMA on Proppant

TA-XT Plus texture analyzer is commercially available as an instrument for measuring the cohesion or tackiness of tackifying agents or pressure-activated tackifiers. However, this device is not designed to determine cohesion or tackiness between solid particulates.

Flow tests through various flow apparatuses were used to indirectly obtain the tackiness levels of the coated proppant to when the treated grains were detached from the aggregated proppant pack by observing the flow rate at which the proppant grains were produced. Often, the flow tests are time consuming. The flow rates corresponding to the detachment of the coated proppant grains are not precise because they cover a wide range. The fluid flowed through the treated proppant pack must be captured and disposed of properly.

T-Tube Flow Test

In U.S. patent 5,787,986, Weaver et al.[6] described an indirect method of measuring the cohesion of coated particulates in a wet environment by evaluating a liquid or solution of a compound for use as a tackifying compound using the following test. A critical resuspension velocity is determined for the material on which the tackifying compound is to be coated.

In **Fig. 1**, a test apparatus is illustrated for performing the test. The apparatus comprises a 1/2-in. glass tee 10, which is connected to inlet water source 12, and outlet disposal line 14, which is blocked off. A slurry of particulate is vacuum aspirated into tee 10 through inlet 12 and collected within portion 16 by filtration against screen 18. When portion 16 of tee 10 is full, the vacuum source is removed, and plug 20 is used to seal the end of portion 16. The flow channel from inlet 12 to outlet 14 is then swabbed clean. A volumetrically controlled pump, such as a MOYNO pump, is connected to inlet 12, and a controlled flow of water is initiated. The velocity of the fluid is slowly increased through inlet 12 until the first particle of particulate material is picked up by the flowing water stream. This determines the baseline for the beginning of the resuspension velocity. The flow rate is further increased until the removal of particles becomes continuous. This determines the baseline of the continuous resuspension velocity.

The test is then terminated, the apparatus is cleaned out and the apparatus is refilled with the same particulate except having a coating to be tested corresponding to approximately 0.1 to 3% material by weight of the particulate. The test is repeated to determine the beginning point of particulate removal and the velocity at which removal becomes continuous. The percent of velocity increase (or decrease) is then determined based on the initial or continuous baseline value comparisons.

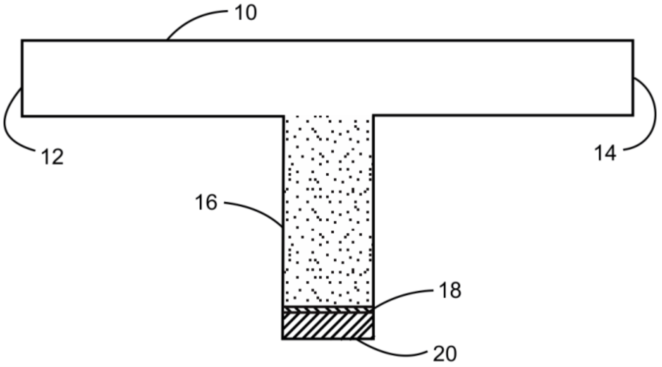


Fig. 1—Schematic illustration of the test apparatus used to determine the critical resuspension velocity for a coated substrate material.

Table 1[6] shows the results of velocity increase (or decrease) of water flowing through the T-tube compared to the initial or continuous value of the baseline.

Table 1— The Percent of Velocity Increase (or Decrease) Determined Based on the Initial or Continuous Baseline Value

Test No.	Particulate Size (mesh sand)	Coating Agent, % V/Wt Particulate	Percent of Velocity Change at	
			Starting	Continuous
1	20/40	none	0	0
2	20/40	1/2 percent polyamide	192	222
3	20/40	1 percent polyamide	271	391
4	20/40	1/2 percent phenolic	-0.5	-6.5
5	20/40	1 percent phenolic	-9	-6.8
6	20/40	1/2 percent epoxy	-9	-1.2
7	20/40	1 percent epoxy	5.2	12.2
8	12/20	1/2 percent polyamide	228	173
9	12/20	1 percent polyamide	367	242
10	12/20	1/2 percent phenolic	42	22
11	12/20	1 percent phenolic	42	13
12	12/20	1/2 percent epoxy	48	30
13	12/20	1 percent epoxy	38	15

Effect on Erosion Velocity

Nguyen et al.[7] designed a high-temperature flow cell to determine the critical fluid velocity that would cause proppant erosion of non-coated or coated particles, particularly for testing at high temperatures **(Fig. 2).** Constructed entirely of aluminum to achieve rapid heat transfer during high-temperature tests, the cell consists of a flow slots 1/4-in. (0.635-cm) wide, 1/4-in. (0.635-cm) high, and 12-in. (30.5-cm) long. Approximately 4 in. (10.2 cm) from the inlet and 2 in. (5.08 cm) from the outlet, a 6-in. (15.2-cm) long recess slot, measuring 1/4-in. (0.635-cm) wide and 1/4-in. (0.635-cm) deep, is positioned within the flow slot.

During the test procedure, this inner slot is hand-packed with plain proppant or SMA treated proppant to the same level as the surface of the flow slot. A high-pressure visual cell is attached to the outlet of the flow cell. This cell shows the proppant produced under flow from the proppant pack in the recessed slot inside the flow cell. During testing, flow rates are incrementally increased and the onset of proppant production is recorded. **Fig. 3** shows example data from the cell.

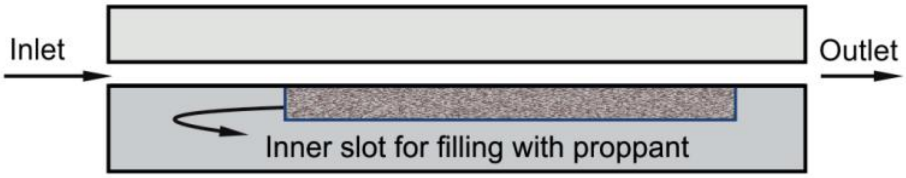


Fig. 2—Schematic of a high-temperature flow cell with an inner slot for filling using a plain proppant or SMA 1 treated proppant (the schematic was not drawn to scale).

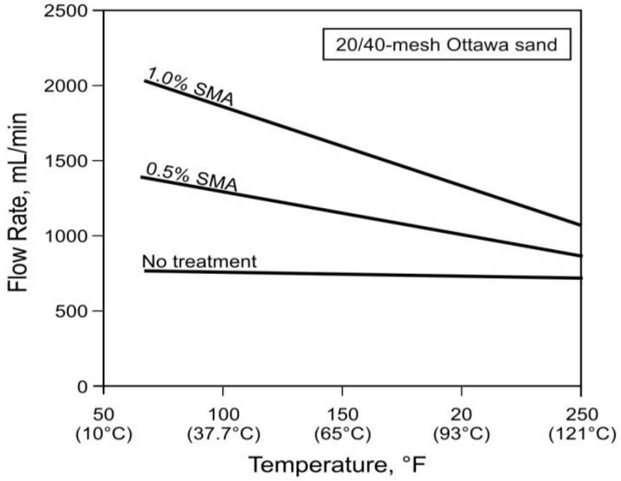


Fig. 3—Effect of temperature on fluid flow rates when proppant grains begin to erode and flow out of the flow cell.

Effect on Proppant-Free Flow Rate

Nguyen et al.[8] described a testing method using a large transparent perforation model to perform proppant-flowback tests for examining SMA characteristics. The slot used was 1-ft high and 8-ft long, with a simulated fracture width of 3/8 in. **(Fig. 4)**. The SMA system can stabilize the proppant bed by increasing cohesive forces between individual proppant grains and the fracture wall, and the result of these increases of cohesive forces is a proppant pack that can withstand increased fluid velocity. When the proppant is coated with the SMA, the rate of proppant flowback can be significantly reduced when compared to the rate of flowback for untreated proppant, even at aggressive flowback rates **(Fig. 5).** For untreated proppant, the flow is initiated at low production rates, and the proppant production rate dramatically increases when the fluid rate is increased.

The SMA-coated proppant can withstand erosion at higher flow rates. This characteristic retards proppant flowback during cleanup and production operations.

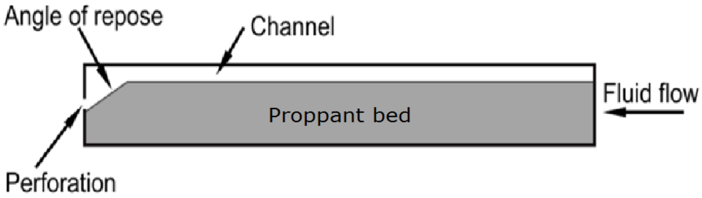


Fig. 4—Generalized schematic to depict large, transparent slot model (1 × 8 ft), with a simulated fracture width of 3/8 in.

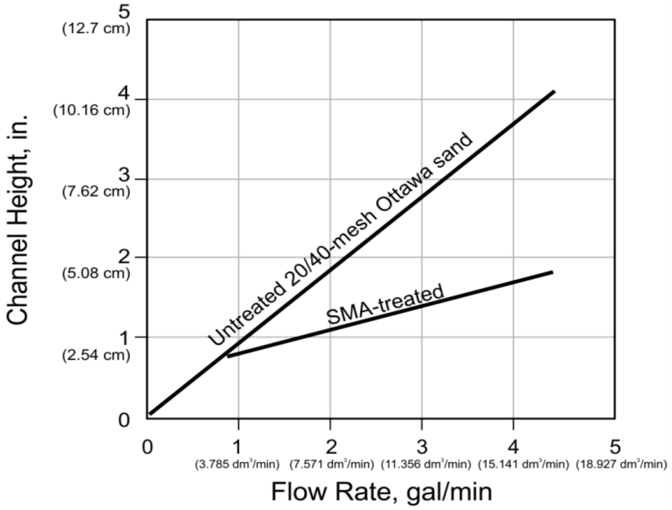


Fig. 5—Effects of water flow rates on heights of channels formed in sand packs with and without SMA treatments.

Rather than depending on the judgment of a person who subjectively determines the tackiness level of proppant grains that have been coated with a SMA (based on when the proppant grains are detached and produced using the flowing fluid), this paper introduces an apparatus that can be used to directly and quantitatively measure the level of this cohesion or tackiness.

Fines Migration

Formation sand and fines can be released during production as a result of shear failure if drawdown pressures exceed the yield strength of the rock. Gravel-pack completions are typically designed to control formation-sand production. However, fines often begin to migrate into the pack, resulting in permeability damage. For the gravel matrix, efforts are often focused on removing the fines from the gravel, without allowing for the need to prevent fines production at its sources. Often, an acid treatment, such as hydrofluoric (HF) acidizing, used in the workover to remove the bridging fines, can actually further weaken the formation and enhance the production of fines, making the problem worse.[9]

In addition to fines damage in the gravel, the sand screens used to retain the gravel can also experience a plugging problem caused by the fine particles. Conversely, if these fine particles pass through the screen, local erosion of the screen can become an additional concern. Various cleanup methods have been implemented to remove screen plugging and increase productivity.[9,10] Submersible pumps are also susceptible to damage by produced fluids that contain formation fines and sand particulates.

A brief review of various methods that have been developed for evaluating the fines migration control of different SMAs and their testing results is presented next.

Bottle Test for Determining Fines Control Capability

of SMAs

Typically, to test for the fines-catching capability of an SMA, a quick visual bottle test was conducted. Sand or proppant was typically dry-coated using the SMA at various coating concentrations. The SMA-coated sand was rinsed with tap water. Fines particles (200 mesh and below) were then added to this SMA-coated sand suspension. The mixture was shaken, and observations were noted. **Fig. 6** shows an example of the sufficient fines-catching capability of the SMA-coated sand.

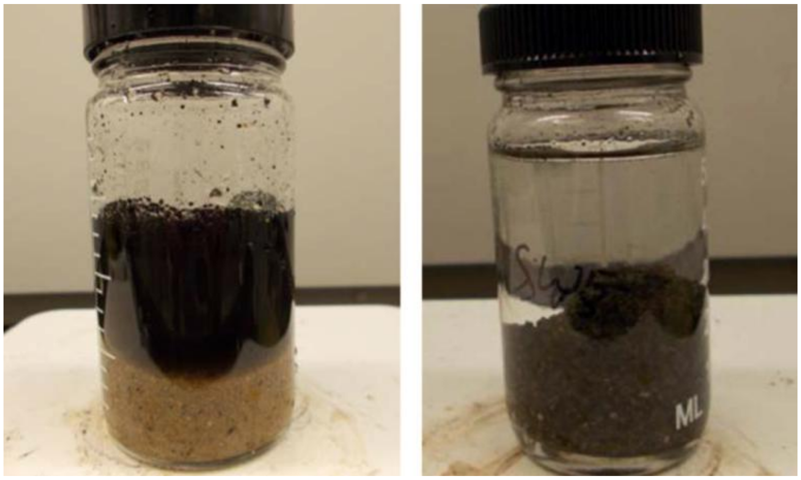


Fig. 6—Addition of 0.5 g of coal fines in both jars; jar (left) mixed with untreated 20/40-mesh Brady sand; jar (right) has 20/40-mesh Brady sand coated with the SMA.

Stabilization of Formation Fines in API Conductivity Cell[11]

In a more extensive testing procedure, the performance of aqueous SMA 1 (ASMA 1) solution on the capability to control or mitigate the invasion of formation fines into the proppant pack was conducted during an API conductivity experiment. During this experiment, silica flour with particle sizes of 325 mesh or smaller was used to simulate unconsolidated formation faces. Core wafers were prepared with silica flour and frozen before they were installed in the API conductivity cell. A 5-lbm/ft^2 proppant pack of 20/40-mesh ceramic proppant was sandwiched between the unconsolidated frozen silica wafers; this was assembled between Ohio sandstone core wafers inside the API conductivity cell.

Procedure for Forming API Linear Cell Wafers from Silica-Flour Materials

1. Begin with 150 g of dry silica flour.
2. Add 10 to 20% by weight of 2% KCl water to the dry material to create a damp paste.
3. Prepare the mold and place all the material into it to form the wafer shape.
4. Place the mold into a press and apply 1,000-psi closure stress for 30 min to compress and consolidate the material.
5. Remove the mold from the press and place it in a freezer to freeze the sample and maintain its shape.
6. Remove the frozen sample from the mold after 3 hr. Note that the wafer should be maintained in a frozen condition until it is to be used during a test.

Procedure for Conductivity Test using Unconsolidated Materials

1. Load the test cell containing a bottom piston, then an Ohio sandstone wafer followed by a frozen artificial soft formation wafer, a leveled 5-lbm/ft^2 lightweight ceramic proppant pack and then another frozen wafer, another Ohio sandstone wafer, and the top piston. **Fig. 7** illustrates the order of proppant pack and core wafers between the pistons.
2. Place the test cell into the press, attach all required plumbing, and apply closure stress and temperature to specified test conditions.
3. Initiate flow through the proppant to take initial conductivity measurements using 3% KCl water.
4. Perform the treatment-fluid step by flowing into the test cell proppant pack and out through the wafers with effluent outlet closed (reverse of flow arrows marked “Simulated formation flow” in Fig. 7).
5. Flow through the core wafers into the proppant pack and out the effluent outlet (proppant pack inlet closed) as arrows shown in Fig. 7 for the preset timeframe and as discussed below.
6. After the treatment step, again initiate flow through the proppant pack with 3% KCl water and measure conductivity using a routine procedure and capturing solids.

The frozen, unconsolidated wafers and proppant packs were loaded into the API linear conductivity cell without treatment. After the temperature (180°F) and initial stress (2,000 psi) for the test were set and stabilized, the flow was initiated. Following the initial conductivity measurement of each cell, the treatment step was performed. The treatment procedure was identical for each conductivity cell, with the exception that each treatment fluid was different in each cell. The treatment fluid was 3% KCl brine (e.g., control) or ASMA solution.

Following the treatment step, initiate the fluid flow through the wafers to simulate production from the formation into the packed fracture (Fig. 7). The initial flow rate through each wafer is 2 mL/min. Observe and document the effluents and pack width to determine if fines are being produced through the proppant pack and out of the test cell.

The cells during the conductivity test were subjected to the same testing conditions, including the closure stress, flow rate, and temperature. After reaching stable conductivity measurements at a 2,000-psi closure, the stress load was increased to a 4,000-psi closure. After reaching a stable conductivity measurement, the stress load was decreased back to a 2,000-psi closure. This stress cycle was repeated several times.

The result indicated that the ASMA 1 treatments effectively stabilized the unconsolidated fines (silica flour) that made up the formation. **Fig. 8** illustrates the stable conductivity for each cell receiving the treatment and the failure of the untreated cell. **Fig. 9** provides the concentrations of total suspended solids (TSSs) obtained in the effluents collected from the conductivity cells during the conductivity flow tests initially and then after flow through the synthetic core wafers, thus simulating fluid production. Both the conductivity and TSSs of effluents confirm the effectiveness of the ASMA when stabilizing unconsolidated formation fines.

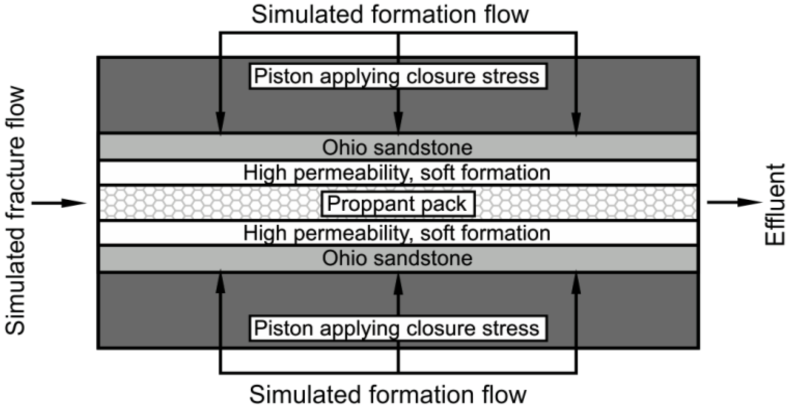


Fig. 7a—Schematic layout of sand packs inside the modified API conductivity cell with directions of treatment fluids.

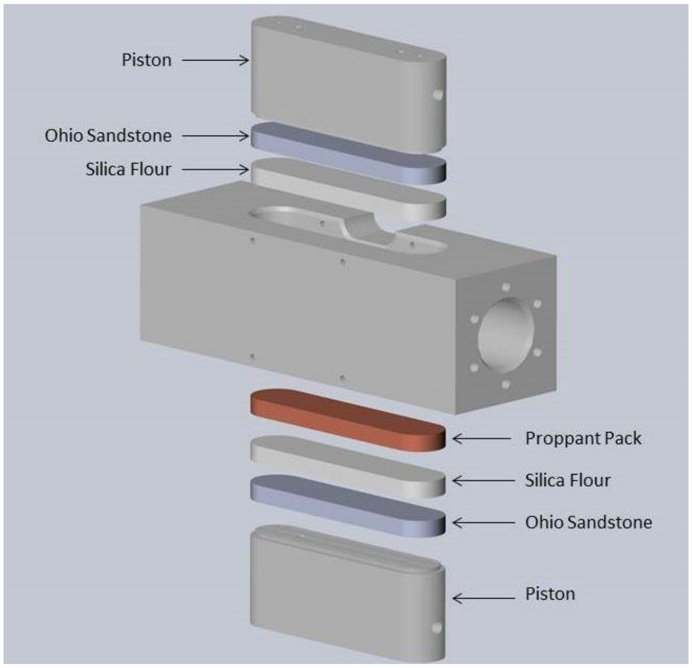


Fig. 7b—Conductivity core assembly.

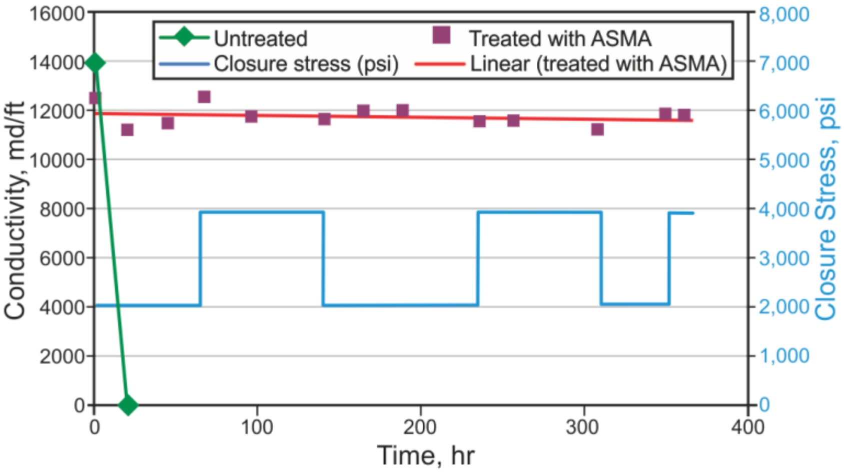


Fig. 8—Conductivity comparison between unconsolidated sand packs with and without treatment of the ASMA solution. Silica flour was used in simulating the unconsolidated formation. Lightweight ceramic proppant was used as a propping material with a loading concentration of 5 lbm/ft^2. Testing was performed at 180°F and closure stresses of 2,000 and 4,000 psi.

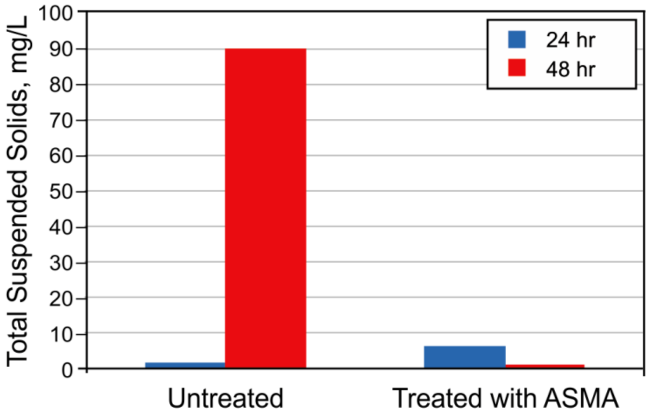


Fig. 9—Amounts of silica flour fines produced in the effluents of conductivity cells after 24 hr and 48 hr they have been treated with ASMA solutions (right) or without a treatment (left).

Degree of Cohesion between Grains and Trapping of Fines

The following part of this paper will first introduce a quick, easy, and reliable testing method for the study of the grain-to-grain interaction of the SMA-treated proppant, as well as a new method for testing fines migration control. As a result of the efficiency of the testing procedures, the tests can be run in the field with minimal training and equipment requirements. The final part will illustrate a method to evaluate the ability of a treated proppant bed to trap/remove fines from a fluid containing fines.

Experiments and Results

Part A—Method for Determining Degree of Cohesion between Grains of the SMA-Treated Proppant

The degree of tackiness of the liquid SMA does not reflect on how well the SMA is coated on the proppant as well as does the degree of grain-to-grain cohesion the SMA provides once coated on the proppant surface. This level of cohesion/tackiness can be used to determine the coated concentration of the SMA. The ability to quickly and reliably determine the degree of cohesion between grains is highly desired. The next section in this paper provides a description of the apparatus and method for directly determining the levels of cohesion or tackiness of the proppant grains, which offers several important insights: (1) the effectiveness of the SMAs as being coated on the proppant and how the SMAs provide interactions between grain-to-grain and (2) the effectiveness of the coating process itself.

Apparatus Description and Test Procedures

The apparatus used during the testing was a Brookfield RVDV-II+ viscometer. During this test, the Spindle C from the Helipath spindle set was used. The spindle has a crossbar at the lower end **(Fig. 10a).** The upper end of the spindle is affixed to the bottom of a torsiometer so that the cohesion or tackiness between sand grains can be measured in terms of a torque-resistance measurement **(Fig. 10b).**

To measure the cohesion between the proppant grains, with or without coating of the SMA, the spindle is lowered into the water covered proppant pack until the crossbar is just beneath the top layer of proppant grains. The torsiometer is turned on to begin the measurement of the torque-resistance, which provides a direct reading of the cohesion value.

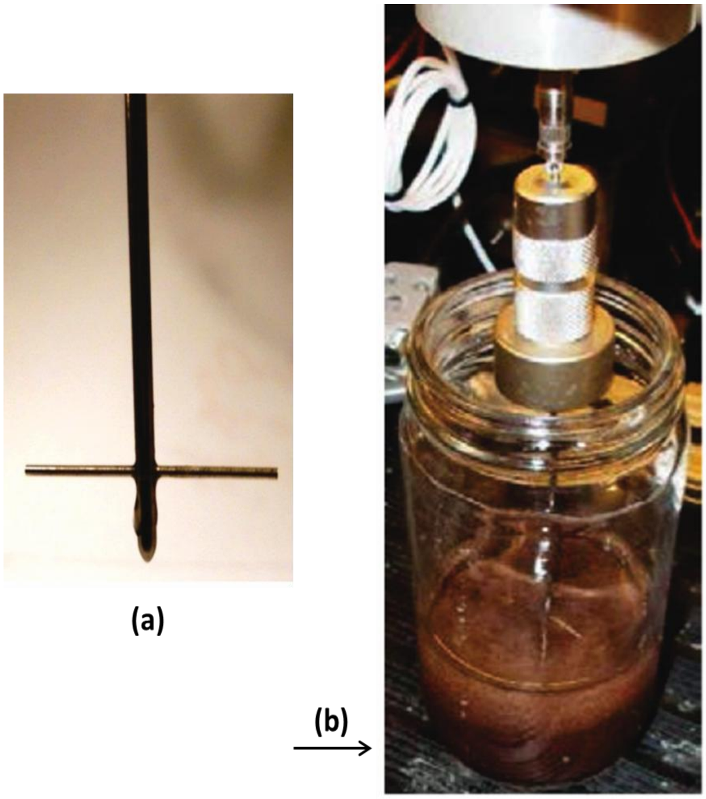


Fig. 10—Photographs of the (a) crossbar and (b) apparatus.

The crossbar is immersed below the top layer of the proppant pack and rotates in a water covered sample (coated or not) settled in the container **(Fig. 11).** As the spindle rotates, the crossbar sweeps across the sand grains that resist the rotation. The torque resistance is registered by a spring that winds up while rotating inside the instrument. A digital torsiometer has an electronic sensing system that reads the spring deflection. The on-board firmware then converts the torque reading into a cohesion reading, thus accounting for the instrument's spring torque range, spindle, and speed (in rev/min). The measured apparent cohesion is a function of the shear rate. The shear rate, in turn, depends on (1) the geometry, including the cross-bar size and (2) the test (rotational) speed. The yield stress is the stress at which the coated sand grains begin to move or detach as a liquid sand. The degree of slip is basically a measurement of significant tackiness or a complete lack of tack or grip between the coated sand grains and crossbar.

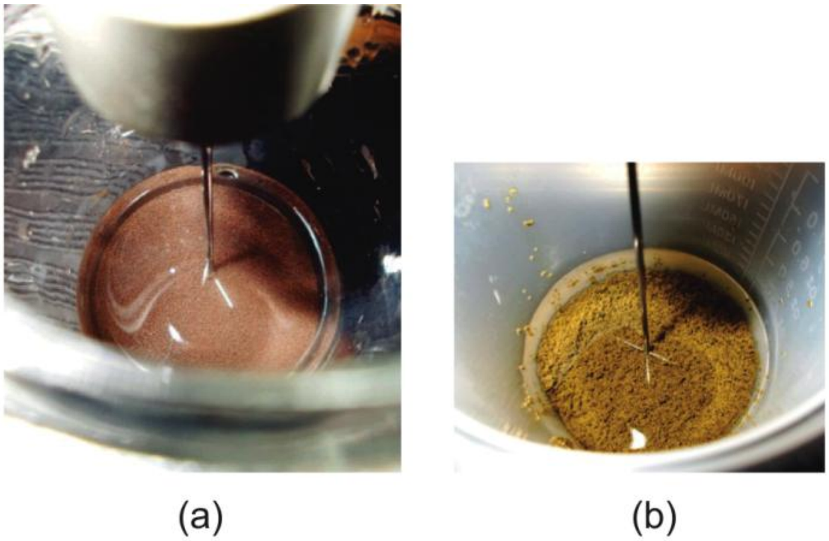


Fig. 11—Photographs of the crossbar dipping in (a) the SMA 1-coated proppant inside a glass jar and (b) SMA 1-coated sand inside a plastic beaker.

Throughout the early laboratory testing, it was observed that the use of a spindle device attached to a vane, or a half-flight auger, was not appropriate for measuring the tackiness or cohesion of the SMA-coated proppant. Once the vane or auger completed a revolution in the coated sand pack, a void space is generated by the vane or auger, causing the device to lose the ability to register the torque.

Series 1—Proppant Coated with Various Concentrations of SMA 1

During this study, all measurements were conducted in the containers with identical dimensions because variances in geometry can affect the dynamic of the proppant slurry. The proppant used in testing shown here was 20/40 Bauxite. A sample size of 100 g, was used to determine the cohesion between grains, with and without the coating of SMA 1. In each sample, a designed amount of SMA 1 was added to the proppant and hand-stirred with a spatula to help ensure the complete coating of all proppant grains. Various samples were prepared using different concentrations of SMA 1, including 0.5, 1, 2, and 4% v/w. To each proppant sample, 200 mL of tap water was added. The content was hand-stirred, and all the water was decanted. This process was repeated two more times, and then 60 cc of tap water (60 cc) was added after the third rinse. A spatula was used to level off the settled proppant pack in the case a dune might have formed in the pack. For the control test, a plain, uncoated proppant sample was used but also submersed in tap water.

Fig. 12 illustrates the results of the analyses for test Series 1, showing a good linear relationship between the grain-to-grain cohesion and coating concentration.

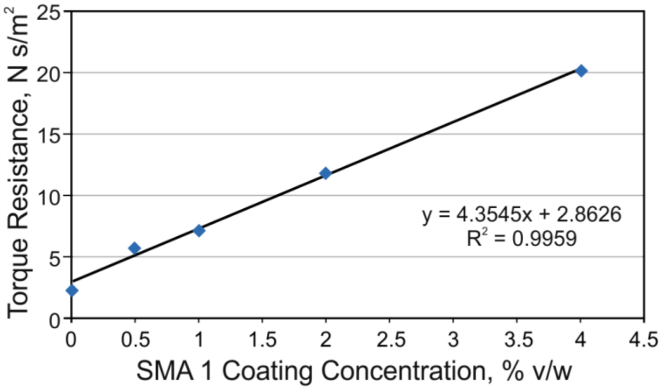


Fig. 12—Correlation between cohesion of SMA 1-coated proppant with the coating concentration.

Series 2—Proppant Coated with Various Concentrations of Non-tacky SMA 2

Similar to the testing during Series 1, various bauxite proppant samples were coated using different non-tacky SMA 2 concentrations, including 0.5, 1, 2, and 4% v/w. **Fig. 13** illustrates the results of the analyses for test Series 2.

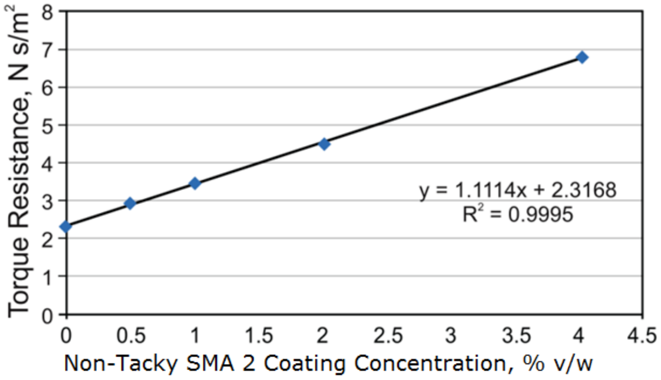


Fig. 13—Correlation between cohesion of non-tacky SMA 2-coated proppant with the coating concentration.

Part B—Method for Determining the Effectiveness of Fines Trapping of SMA-Coated Proppant: The Slurry Loop Test

Apparatus Description and Test Procedure

3-Component Slurry Loop. The apparatus or slurry loop consists of three key components: a brass cell, a peristaltic pump, and the fines slurry. The brass cell is a 5-in. long, 1 3/8-in. diameter brass cylindrical cell that contains proppant, treated or non-treated using different SMAs at different concentrations. Two samples of SMA 1treated proppant from Series 1 of the previous study were used, particularly the samples with coating concentrations of 0.5 and 2% v/w. During the second series of the study, two samples of non-tacky SMA 2-treated proppant from Series 2 of the Part A study were used with coating concentrations of 0.5 and 2% v/w.

During a control experiment, the proppant was loosely packed into the brass cell without any SMA treatment. A general experimental procedure is as follows. In the brass cell, the treated or non-treated proppant is simply packed in the order of 80-mesh screen, 50-g proppant, and 80-mesh screen. First, 100 mL of tap water was flowed through the proppant pack at a 10 mL/min flow rate using the peristaltic pump. Tap water was chosen during this study to keep the procedure simple knowing there was no clay involved during the study. In the case that the formation sand or sand pack might contain clay, a brine solution, such as 3% KCl, would be used as the base solution during the testing. Omitting KCl in the base solution allowed the clearer analytical images on the post-tested proppant under the scanning electron microscope (SEM) as the samples dry. Some KCl salt residue could interfere with the visual evidence of fines on the proppant.

The second component of the slurry loop is the fines slurry. A silica flour with a particle size of 200 mesh and smaller was used to simulate formation fines. In a 1-L plastic container, 1% (w/v) of silica flour was dispersed into deionized water. A fines slurry with a concentration of 1% (w/v) was chosen because this slurry concentration allows for the most reliable comparison between treated and untreated proppant packs. The silica fines slurry, together with a Teflon®-coated stirring bar, were positioned on a stirring plate directly below the brass cell **(Fig. 14).** This slurry was stirred to keep fine particulates in suspension during the entirety of the test.

The final key component of the fines slurry loop is a peristaltic pump. A 1/8-in. inside diameter (ID) tubing was installed in the peristaltic pump and maintained at 400 rev/min. The rev/min and tubing size create a constant flow of 400 mL/sec. This high flow rate was used to create a high fluid velocity that would help prevent fines from settling in the tubing.

Fig. 14 shows the experimental setup of this study. An initial turbidity measurement was determined for the base fines slurry. The fines slurry was then passed through the proppant pack at a 400 mL/min flow rate, and the exiting solution was looped back into the original container containing the fines slurry. To determine this effectiveness of the coating, the turbidity readings of the fines solution were collected every 10 min during pumping for 60 min. The turbidity measures the cloudiness of a liquid sample; any fines material suspended in the liquid will affect the reading.

Fig. 14—Photograph of the 3-component apparatus: high-rate pump (on countertop), brass cell (above plastic beaker), plastic beaker of fines solution, and its stirring plate (bottom).

Figs. 15 and 16 illustrate the results of the study. Fig. 15 shows the effectiveness of catching fines comparison between the SMA 1 and the non-tacky SMA 2 coating at a concentration of 0.5% v/w on the proppant. Fig. 16 shows the comparison between the two SMA coatings at a concentration of 2% v/w on the proppant. Results indicated that the SMA-coated proppant could trap fines, even in a small coating concentration at 0.5% v/w. **Fig. 17** assists in visually assessing that the fines were captured within the proppant pack.

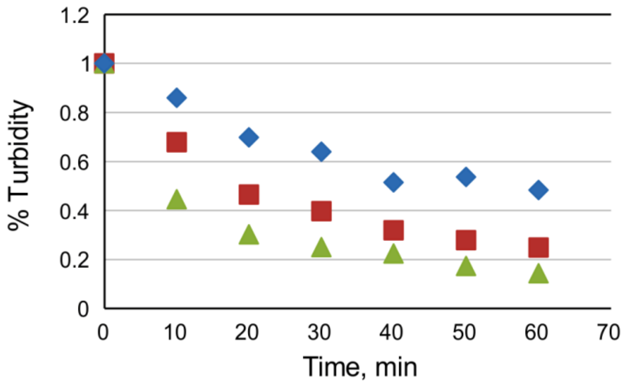


Fig. 15—Comparison between the amount of fines removed (trapped) in the proppant pack treated using different SMAs at a 0.5% v/w coating concentration. Blue = noncoated; Red = SMA 1-coated; and Green = non-tacky SMA 2-coated.

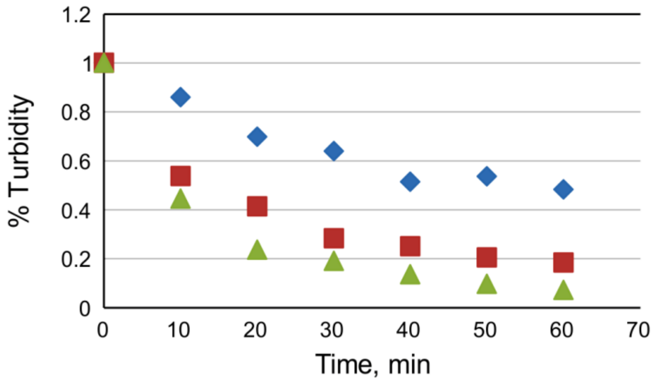
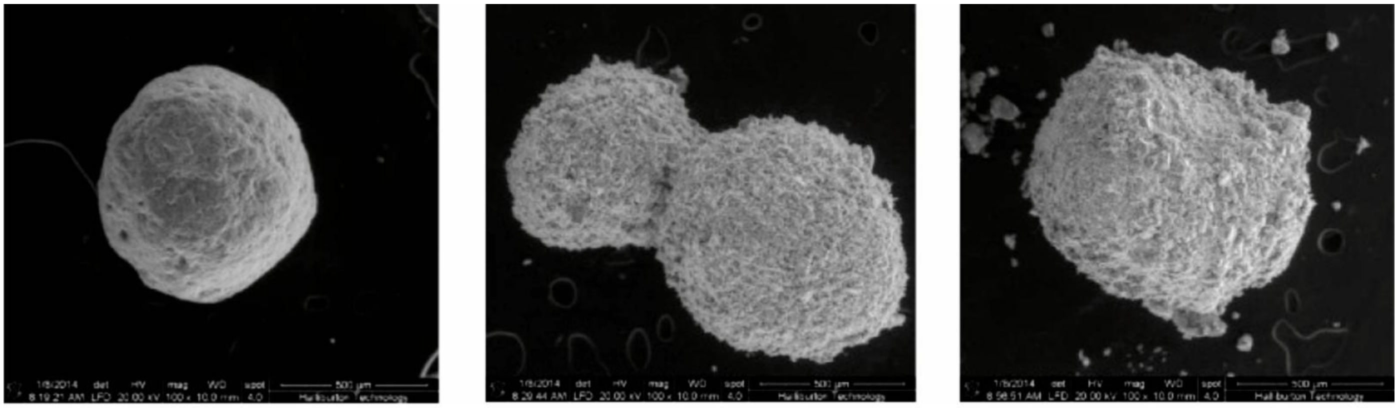


Fig. 16—Comparison between the amount of fines removed (trapped) in the proppant pack treated using different SMAs at a 2% v/w coating concentration. Blue = noncoated; Red = SMA 1-coated; and Green = non-tacky SMA 2-coated.

Fig.17—Photograph of proppant coated with a 2% non-tacky SMA 2 after a 1% fines solution was passed through for 60 min. It is clearly visible that the coating on the proppant trapped a large amount of fines throughout the pack.

SEM images **(Figs. 18 and 19)** of the proppant samples after the test clearly showed the adhesion of silica fines on the surface of the SMA-treated proppant, while the surface of the non-treated proppant appeared to be completely clear of silica fines.



(a) (b) (c)

Fig. 18—SEM images of post-test proppant: (a) control, non-SMA-coated; (b) 0.5% SMA 1-coated, (c); 0.5% non-tacky SMA 2-coated.

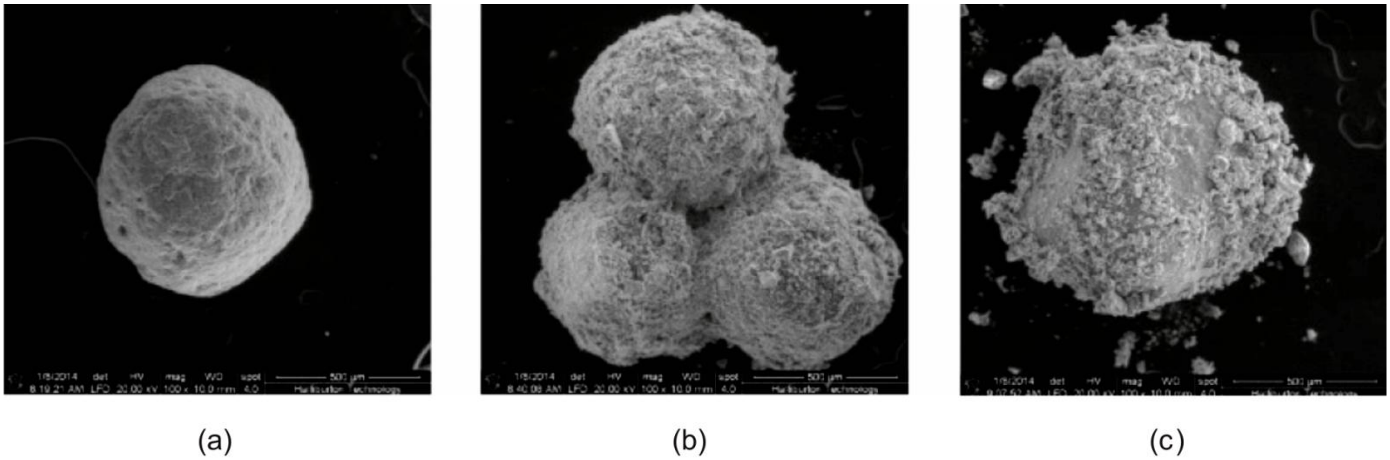


Fig. 19—SEM images of post-test proppant: (a) control, non-SMA-coated; (b) 2% SMA 1-coated; (c) 2% non-tacky SMA 2-coated.

Discussion

It is important to have a method for determining the cohesion or tackiness of the treated proppant to provide a recommendation of a proper SMA coating and its concentration for controlling fines migration, a successful forming of proppant pillars, or aggregates as part of the hydraulic fracturing treatment for generating proppant-free channels in the propped fractures.

By closely examining the torque resistance values of intrinsic properties of the SMA coated proppants, the cohesion value detected using this method also depends on the physical properties of the substrate, such as particle size, roughness, particle angularity, temperature, etc., and the chemical makeup of the substrate itself (i.e., natural sand or man-made proppants). These results are valuable because they can be used as calibration standard curves to determine the amount of SMA coated onto the proppant surface for a known torque resistance value. This can be used as a quantitative evaluation on the effectiveness of the coating of the SMA on the proppant, which can be used for either dry-coating or wet-coating methods.

During a field application, the measurements can be used to adjust the coating of SMA on the proppant with better precision by correcting the rate at which the SMA is distributed or coated onto the proppant. For a field application, having a robust testing method where the degree of tackiness can be correlated back to the treating concentration can provide a great way to gauge the coating process of the SMA onto the proppant. It is important to have a method to determine the cohesion or tackiness of the treated proppant. Knowing the effectiveness of the coating process, it is easier to confidently provide a recommendation of a proper coating of a SMA.

Fines are known to be a primary culprit of damaging proppant pack conductivity if they are allowed to freely move with the production fluids. Free-flowing fines will tend to collect near the wellbore area and reduce a well's production flow rates. Studies have shown that propped fracture conductivity can be enhanced and prolonged by effectively preventing these formation fines from invading the proppant pack. Coating the proppant pack with SMA has been proven to provide sufficient adhesion between particulates, attaching the fines particulates onto larger particles and anchoring them in place. Both laboratory studies and field results have confirmed the positive impact of SMA-coated proppant packs on fines migration control.

While there currently are laboratory methods of testing for the effectiveness of different SMAs in fines migration control, they each have their own limitations. A quick and easy method to test for the effectiveness of SMA is often qualitative; it relies heavily on personal judgment. Conversely, the API conductivity test provides reliable results, simulating real production. However, this experiment tends to be labor intensive, and therefore is an expensive test and requires significant time.

The laboratory testing method demonstrated in this paper illustrates an easy setup and use process for simulating formation fines migrating into proppant packs. It can also be set up in a mobile field lab. The effectiveness of different SMAs on controlling the migration of formation fines can be easily quantified using simple turbidity measurements of the collected effluents. By comparing the SMA-treated proppant pack to a control test where the proppant pack is not treated, the results of the study clearly confirm the effectiveness of SMA treatments in controlling the migration of fines into the proppant pack. The effectiveness of the SMA in holding fines at the interface, thus preventing invasion into the proppant pack, can be compared using the curve slope. The SMA 2-treated proppant pack appeared to control the migration of fines better than the SMA 1-treated pack and the control (Figs. 15 and 16). The results of this simple and inexpensive test agrees closely with results obtained from the API conductivity tests.[11,12]

Conclusions

Based on the laboratory test results, the following conclusions are drawn:

- The simple Brookfield testing apparatus with the crossbar offers a reliable quantitative method for testing the cohesion or tackiness of proppant treated with SMAs.
- The Brookfield testing method can be used to quantify the amount of the SMA treated onto the proppant and can easily be applied to the field application.
- The slurry loop test developed offers an inexpensive, yet reliable method with quantitative results to determine the effectiveness of different SMAs in preventing the invasion of fines into the treated proppant packs.

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