



Validating the Quality of Mud-to-Brine Displacements

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Abstract

Mud-to-brine displacement efficiency can be difficult to quantify. The most common metrics used for this purpose include brine clarity, the number of filtration cycles required (or the quantity of filter media used), and the volume of mud or brine interface created during the displacement. Despite their widespread use, however, these factors may not adequately characterize the quality of displacements in critical wells.

The purpose of this paper is to assess the value of post-mortem laboratory analyses of field samples to help validate the quality of mud-to-brine displacements. Fluid samples were collected at critical stages during the initial circulations on three displacement projects in the Gulf Coast area. They subsequently were analyzed in the laboratory in order to compare predicted and actual return volumes, interface volumes, and fluid compositions. Observations presented in this paper can be used to help refine the procedures and computer programs used to design displacements and evaluate quality, especially with regard to spacer volumes and surfactant/solvent concentrations.

Introduction

The mud-to-completion brine displacement is an important operational component for most completions. A poor displacement can cause production impairment, problems with a gravel pack, loss of mud or brine, and loss of rig time, among others. However, unless these problems are encountered or even identified, it is difficult to determine the relative quality of the specific displacement. This is critical for avoiding problems on subsequent wells and for optimizing displacement operations.

Opportunities for improvement are largely affected by how well the displacement process can be characterized and understood. This can be difficult with the few direct and indirect parameters traditionally used to evaluate mud-to-brine displacement quality. Sometimes they are not completely indicative of the true downhole performance in critical wells. The most common indicators include brine NTU, the number of filtration cycles (or quantity of filter media) required to achieve a target NTU level, and the total volume of mud or brine interface created during the displacement. While these factors,

either individually or collectively, are of significant value as overall indicators of efficiency, they lack the resolution necessary to adequately characterize the process, discriminate among different design techniques, and affect continuous improvement.

Displacements are often designed according to empirical analyses of prior job performance.¹ For example, typical design criteria include:

- a. Displace at the maximum rate allowable so that the cleaning spacer (with solvent or surfactant) is in turbulent flow.²
- b. Viscous spacers should cover 500, 1000 or 1500 ft. in the largest annulus.
- c. Cleaning spacers require 4 to 10 minutes of contact time, depending upon the job designer.
- d. Drillpipe should be rotated at least 40 rpm, 80 to 100 rpm or maximum allowable rpm.

One of the key opportunities is to integrate data derived from return fluids collected during different displacements in order to compare predicted and actual return volumes, interface volumes, and fluid compositions. Results from such an effort are presented in this paper. Fluid samples were obtained on two offshore and one land well in the Gulf Coast area. The fluid samples were strategically collected at critical stages during each of the initial circulations and subsequently analyzed in the laboratory.

The purpose of this paper is to present results from this study in order to help assess the role of post-mortem analyses for validating the quality of mud-to-brine displacements. The observations can be used to refine the procedures and improve the related tools used to design and engineer displacements, especially with regard to spacer volumes and surfactant/solvent concentrations.

Current Evaluation Practice

Displacement quality is usually judged according to empirical analysis of various field data. These data are enumerated below, not necessarily in order of significance.

- The volume of mud and/or brine disposed as part of the interface can indicate insufficient pump rate, improper spacer rheology, or an operational shutdown during the displacement. This volume

relates directly to cost. A rule of thumb might be that 15 or less barrels of mud or brine lost to interface is very good, whereas between 15 and 45 barrels lost to interface is fair and acceptable. Greater than 45 barrels of interface can indicate design or operational problems.

- The volume of brine circulated with the bit on bottom while filtering the brine to the desired level of clarity is related to rig time. The lower the volume required filtering to the desired level, the less costly the overall operation. Completion fluid clarity is typically measured in Nephelometric Turbidity Units (NTU), a technique that indicates light refractivity of the fluid. The lower the number the better. Brand new brine batches are accepted at the stock point with an NTU <10. In completion operations, operators will strive to achieve NTU levels of <20 or <40, depending upon their own standards, following the displacement and prior to perforating. Having to circulate a large volume of fluid to achieve the required NTU level indicates poor displacement practices, which can be related to insufficient pipe rotation, low pump rates or poor spacer design. Rule of thumb numbers for volume circulated to filter might be a) <1 hole volume, very good; b) 1 – 2.5 hole volumes, fair; c) >2.5 hole volumes, problematic.
- The number of times the diatomaceous earth (DE) filter aid must be replaced or the number of filter cartridges used during circulation to achieve the desired level of brine clarity is another measure of displacement efficiency. If circulation of the hole is shut down to keep from putting dirty brine into the clean suction pits, additional rig time is required. Costs, therefore, are not only related to DE and filter media but to rig time and spreadrate. Several changes of the filter press DE medium during a single displacement process indicate inefficient solids removal and may suggest lack of pipe movement, insufficient density and viscosity in the spacer design or stringing out of the viscous spacers into the displacing fluid. Expressed as a function of the number of filter press cleanings required, the rule of thumb might be that <1 is very good, between 1 and 2 cleanings is fair and acceptable and >2 cleanings is poor and problematic.
- The condition of the surface of the drillpipe as it is pulled from the hole following displacement is the final evaluation criteria.³ A primary function of the spacer system is whole mud and mud film removal. Water-wetting the casing and drillpipe when oil or synthetic mud is displaced is required. If not successfully performed, the drillpipe is pulled from the hole with a mud film on its surface, indicating that the casing is also oil-wet and that

the treatment may have to be redone. Heavy accumulations of mud on the pipe after displacement may be symptomatic of lack of or insufficient pipe movement, poor spacer chemistry or insufficient spacer density or rheology. As a rule of thumb, the drillpipe should be pulled from the hole with no film and water-wet.

There are other empirical indicators of displacement success or failure, such as whether or not perforating guns or other wire-line tools are recovered from the hole with mud on them, or the ability to set or retrieve packers from the hole because of debris. Evidence is limited to supporting subjective judgments as to whether a displacement was performed to expectation, and in many cases the evidence can support judgments at opposite poles. One may hold that 30 barrels of interface is too much while another may feel that 80 barrels is OK as long as the hole gets cleaned quickly.

Sampling and Laboratory Technique

Samples were collected during three displacement recoveries. Well, sample collection, and spacer design data are shown in Tables 1 and 2. Samples were taken at the flowline or at the shakers when the flowline was not accessible. Field personnel were instructed to take samples of the mud prior to spacer recovery and continue sampling until spacers were fully recovered and completion brine or seawater was returned to surface. In one instance (Case 3), samples were not obtained until the first spacer (base oil) was recovered. However, the information gathered is beneficial to this analysis and the case is included. In each case, samples were obtained every 15 to 25 barrels.

Upon arrival in the laboratory, photographs were taken of the samples as received. The samples were then thoroughly mixed using a single spindle overhead mixer and composites removed for further analysis. Density of composite samples was determined using a 25-mL standard picnometer. The pH (direct reading) was determined with an Orion (Model 290) pH meter. Plastic viscosity (PV) in centipoise and yield point (YP) in lb/100 ft² were determined at ambient temperature using a Fann 35 viscometer. To determine the composition, each sample was centrifuged (IEC Model CL centrifuge) at high speed for 20 minutes and then photographed. This centrifuge technique will separate oil and water phases but will not generally break the oil mud emulsion. This technique is also capable of distinguishing high gravity solids (i.e., barite) from low gravity solids (i.e., drill cuttings). The volume percent of each separated phase was recorded and correlated to percent mud by rationing percent solids/oil in the sample to the percent solids/oil in the drilling mud. The remaining oil and other fluids in the sample are reported as base oil, spacer or completion fluid, based on visual impression and their likelihood of appearing in the sample. It is sometimes

difficult to distinguish between a spacer and completion fluid, or between base oil and a solvent added to a spacer. In these cases, mass balancing is used to validate the interpretation. In most cases, this analysis was able to identify a fluid with greater than 90% accuracy.

Once the lab data is collected, each sample is correlated to a specific volume of fluid recovered. A graph is generated by an overlay of "actual" spacer content, as determined by the analytical methods, upon a background of the "ideal" flowback conditions. This overlay allows the analyst to view what actually returned to surface versus what was anticipated and gives important information such as interface volumes. Figures 1 through 3 show these overlay graphs for all three case wells.

The "ideal" flowback conditions represent the point at which fluids should return to the surface by calculated volume and assume 100% ideality, *i.e.* no interface. The hole volume in case well #1 was 588 barrels. As shown in Figure 1, the first barrel of spacer (15 barrels of base oil) is "ideally" expected to arrive at the surface at 589 barrels and the last barrel should arrive at 603 barrels. Such an "ideal" flowback would then account for 100% of recovered spacer and a mass balance calculation would be 1500 bbl%. The red line on the graph identifies the samples in which base oil was found. Using the same mass balance calculation on the "actual" base oil spacer identified in the samples shows a recovery of about 90%, which is acceptable for this analysis. Other correlations were in this same range with deviations as much as 20% due to interpretive complexities, such as distinguishing between base oil and solvent in spacers or between seawater (or brine) and spacers made up in seawater (or brine).

Data Analysis and Case Histories

Case No. 1. This direct displacement operation was performed on an 18,500-ft vertical well at a land location. Production tubing with a production packer was run in the hole in 17.3-lb/gal OBM and the packer was set. The tubing was unlatched from the packer and the displacement was performed above the packer to 11.6-lb/gal CaCl₂. The objective was to displace the mud from the annulus and then to latch up the production seal assembly into the packer. On a later date, drilling mud inside the small liner below the packer was displaced using coil tubing. To limit differential pressure while circulating spacers and completion fluid, all spacers (except the base oil) were prepared in 13.0-lb/gal CaBr₂ brine and the pump rate was limited to 2.6 bbl/min. This flow rate provided an annular velocity of about 100 ft/min, which sufficed to put the wash spacer into turbulent flow. The spacer system consisted of 15-bbl base oil, followed by 50-bbl viscous spacer, 50-bbl wash spacer, 25-bbl viscous spacer and finally 11.6-lb/gal completion fluid. See Table 2 for details.

Of the evaluation criteria cited in the previous section, this well provided only one data point, *i.e.*, 15 bbl of mud interface was disposed. Filtration was not performed on the displacing CaCl₂ brine, since a subsequent displacement below the packer was planned. Therefore, two evaluation criteria, fluid NTU and time/volume to filter completion fluid were unavailable. Furthermore, because the production string was run in the cleanup trip, pipe was not pulled from the hole for visual inspection. No brushes or scrapers were run and the pipe was neither rotated nor reciprocated.

Twelve displacement samples were taken over 235 barrels in 15-30 barrel intervals. A photo of the centrifuged samples is shown in Figure 4. Sample viscosity (PV and YP) is shown in Figure 5. Figure 1 shows the actual vs ideal flowback schematic. The first four samples are clearly mud and base oil. The first spacer (15 bbl of base oil) arrives at the surface about 30 bbl early, and continues for about 60 bbl into the spacers that follow. Mass balancing the base oil spacer in the return samples account for about 15.7 bbl, *i.e.*, 105%. This value provides a certain level of credibility to the analytical technique.

Whole mud is removed by Sample #6 (611 bbl), 23 bbl after hole volume and barite mud solids are completely removed by Sample #8 (665 bbl), 77 bbl after hole volume. These data suggest that a 23-bbl mud interface of mud plus base oil is available to return to the mud pits and another 54 bbl of contaminated mud-spacer interface can not be recovered. The volume of mud between the last sample containing whole mud interface (Sample # 7 at 637 bbl) and the last sample to contain a trace of mud solids (Sample #8 at 665 bbl) can be considered residual mud brought to surface by the aqueous spacer system. A mass balance calculation of this volume accounts for about 1 bbl of mud. The solids at the bottom of Sample #8 through #12 are low-gravity solids (LGS) and precipitated iron hydroxides.

To evaluate the efficiency of the spacer system, it is possible to estimate the volume of mud residing on the surface of the drillpipe and casing if one assumes a certain mudwall cake thickness. Simulation of wallcake (or film) thickness in the laboratory suggests that a value of 1/64-1/100 of an inch is a reasonable approximation. Using this technique, a total volume of 7 bbl of mud cake/film is calculated for Case 1. The fact that the post-job analysis accounts for only 1 bbl of mud film suggests that the spacer system removed only about 14% of the mud film from the pipe surface.

The last two samples appear to be completion fluid with traces of synthetic polymer. This is confirmed by the density data (Figure 6) Comparing Figure 7, which shows results of a colorimetric technique that determines the presence of HEC polymer, with the PV and YP data (Figure 5), clearly demonstrates that the first viscous spacer arrives at surface between Sample #6 (611 bbl) and Sample #10 (719 bbl). These data show the 50-bbl

viscous spacer returned over 104 bbl and arrives at surface 14 bbl early, *i.e.*, in the mud-base oil-spacer interface. This is in good agreement with the interface volume reported from the rig.

Table 3 shows the rheology for the lead and tail spacers before they were pumped. It is evident that the lead spacer retained good viscosity despite relatively high bottom-hole temperature. The viscous tail spacer, which was formulated with a synthetic polymer, lost almost all of its viscosity while in the hole.

Case No. 2. This well in an offshore location in about 1000 ft of water was displaced indirectly to seawater. A 14.9-lb/gal SBM was displaced from the 48° angle well at 5.25 bbl/min. A workstring with scrapers and brushes was run to bottom and spacers pumped. Clarity of seawater following 1½ hole-volumes pumped behind the spacers was less than 100 NTU. The DP was short-tripped while the rig pits were cleaned. One day was spent waiting on weather to get the completion brine on board. Another series of spacers was pumped prior to filling the hole with brine. (This displacement was not sampled.) One hole-volume of 13.0-lb/gal CaCl₂/CaBr₂ brine was filtered to obtain an NTU reading of 17.

Judged by the standards stated above, the displacement was a moderate success. Little time was spent circulating after the displacement to clean the well, *i.e.*, ½ hole-volume of seawater following the mud displacement and 1 hole-volume of brine after the seawater displacement. A single DE filtration cycle sufficed to clean the brine. No residual mud was reported on the pipe as it was pulled from the hole during the short-trip. However, a sizeable volume of mud, 50 barrels, was disposed as interface in the initial displacement.

Twenty-five samples were taken over 515 barrels at intervals of 15-25 barrels each. Photos of these are provided in Figure 8. Figure 2 shows the actual vs ideal flowback analysis. The base oil spacer returned about 30 barrels early and is cleaned up by the first viscous spacer. Mass balancing the analytical data indicate that base oil is accounted for at about 78% of volume pumped. Unlike Case 1, the appearance of mud solids far outlasts that of the base oil. Furthermore, the spacers were more effective at bringing mud to surface. Twenty six barrels of mud can be accounted for in the spacers behind the base oil. According to the volume calculation results in Table 4, four times the minimum amount of mud film available was removed from workstring and casing.

From Sample #17 on, barite is no longer seen and solids contained in the fluid are LGS, indicating that they are somehow separated from the heavier mud solids during the displacement. Although not shown in the graph in Figure 2, Sample #17 through #23 contain between a trace and 1% LGS. These drill solids are not

reported as mud, but are an evident part of the clean-up. Sample #8 through #12 were analyzed for wettability of the entrained solids because of the unusual spacer sequence. In this displacement the base oil was followed by a volume of seawater containing a surfactant, then by a volume of seawater containing a solvent. This was followed by a viscosified spacer. The wettability analysis determined that the solids in Sample #8, which had 17% base oil and 68% spacer, were oil-wet. The solids entrained in Sample #9, which had 19% base oil and 66% spacer, were water-wet, as were all remaining solids in later samples.

Case No. 3. This well in 3000 feet of water in the OCS G was displaced directly from 14.8-lb/gal SBM to 13.1-lb/gal CaCl₂/CaBr₂ completion brine. Spacers mixed in 14.2-lb/gal CaBr₂ cut-back with freshwater were pumped at 8 bbl/min. The well is angled 62° from vertical. While still working in mud, an unsuccessful attempt was made to plug a ¼-in. hole that had been punched in casing for formation fluid sampling. The displacement was performed with slightly higher density brine than originally planned in the event that the hole remained open after the well was cleaned up. Following the displacement, pump pressure applied to the casing showed that a squeeze was necessary. For this reason, brine was not circulated and filtered until after the squeeze job several days following the displacement.

According to the rule of thumb indicators of displacement success, the displacement was performed as anticipated. Brine clarity was at a filterable level (101 NTU) after 230 barrels of circulation (about ¼ hole-volume). As mentioned above, filtration was not performed, so there is no indication of how much DE or time was required to clean the brine to completion fluid specification (usually < 30 NTU for perforating). No mention was made of mud clinging to the pipe after it was pulled from the hole to get the squeeze packer. The mud report indicates that 17 barrels of mud was lost to interface.

Fourteen samples were taken over 195 barrels at intervals of 15 barrels. Photos are shown in Figure 9. Figure 3 contains the actual vs ideal flowback scenario. Sampling was initiated 45 barrels after the beginning of ideal recovery, so samples of the mud and much of the base oil were missed. The first two samples, however, show that the base oil was recovered well into the initial spacer. Mass balance calculations show that our analysis accounts for 15% of the total base oil volume in the first spacer. As we assume that the base oil also blended with the mud on the front end, this indicates a high degree of intermixing during the pump operation.

Mud is seen deep into the spacer train. While significant mud volume is recovered in the first sample, mud remains are seen more than 100 barrels later in the completion fluid. Rheology of viscosified of spacers 1

and 3 are shown in Table 3. It is expected that a viscous fluid with excellent suspension properties moving at >200 ft/min in the annulus will carry a large load of solids out of the hole, leaving little volume to be carried out later.⁴ The fact that 8% to 10% solids are seen into the completion fluid stage of the displacement may be indicative of mud build-up on the low-side of the hole that was not adequately disturbed by pipe movement. Mass balance calculations show that 18 bbl of mud was removed in the spacer train, or about twice the minimum calculated volume for residual film.

Discussion

The purpose of this exercise was to test a system of displacement analysis that is repeatable, scientific and which can be carried out without great expense. These analyses relied upon centrifugation, visual inspection and relatively simple analytical techniques. The data obtained using these techniques can supplement field data / criteria to allow a better evaluation of the quality of the displacement design and the performance in the field. Although the post-job analyses presented here did not provide all the necessary information to quantify an evaluation, nor did these data support a conclusive outcome, we believe the process is valuable and can be improved to bring the industry closer to the goals stated here.

The inefficiency of the wash spacers in Case 1 may be due to insufficient chemistry, i.e., the lack 'free' water in the wash spacer reduced its ability to solvate. One might consider a whether a larger spacer volume, which would provide longer contact time, would have provided additional mud-film removal, but the poor removal efficiency seen in Figure 1 suggests that this is not the case. (It should be restated that the primary objective of this displacement was not washing the casing and tubing, but removing the whole mud from the annulus.) A calculation of the mud content in the spacers in Case 1 lends support to the position that the use of brushes and scrapers and pipe movement are critical to getting mud off the casing wall. Good annular velocity, turbulent flow and adequate contact time (in this case ~100 ft/min and 10 minutes) may be insufficient to clean casing when using weighted brine in cleaning spacers.

Theoretical models suggest that base oil following mud and preceding spacers, whether viscous or not, should tend to blend in with the mud, thinning it and making it more mobile. The analysis provided here shows that significant mixing occurs at the back end of the base oil spacer with the spacers that follow it in the hole. This has two effects, among others: viscous spacers are rheologically lessened by the oil contact, and solids removed in the base oil-contaminated spacer tend to be oil-wet. The effects of this latter are mitigated and reversed as soon as a water-wetting surfactant contacts the solids. One suggestion is that, following the

base oil, the spacer volume (which in our opinion should be viscosified) is increased to overcome the effects of contamination.

The phenomenon of low-gravity solids showing up late in the displacement train was another insight we did not anticipate. Barite can be expected to move more slowly than the lighter solids, but in two of three cases, LGS were observed unassociated with barite in the latter spacers and even into the completion brine well after all the barite was removed. These dissociated LGS could be an indicator of barite solids left in the hole.⁵

In one case, non-viscous surfactant and solvent spacers were run between the base oil and viscous spacers. It was observed in contiguous samples of nearly identical make-up that the solids closest to the base oil spacer were oil-wet and those closest to the surfactant spacer were water-wet. This suggests that a water-wetting surfactant spacer, whether viscous or non-viscous, is beneficially inserted at the beginning of the displacement to make the solids mobile in the aqueous spacers.

Conclusions

1. Data from samples of recovered fluids taken during displacement can inform as to the effectiveness of spacers and method. Judgments support data gathered in field for post-well analysis.
2. By indicating percentage of whole mud removal, post-job analysis data can yield judgments about cleaning effectiveness of individual spacers and the tendency of spacers to interact.
3. High rate and fluid velocity are not sufficient to clean mud from the wellbore when the cleaning spacers are formulated in heavy brine.
4. Mud appears in recovered spacer samples throughout the displacement trains when pipe rotation and reciprocation are performed. Pipe movement assists in mud removal.
5. Base oil tends to be assumed into the mud ahead and the spacer behind. Since a degree of contamination can be expected in the initial spacer adjacent to the base oil, the size of the initial spacer may be increased to accommodate the contamination.

Acknowledgments

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	Well No. 1	Well No. 2	Well No. 3
Location	Land	OCS G	OCS G
Type of displacement	direct	indirect	direct
Mud type	OBM	SBM	SBM
Mud weight (lb/gal)	17.3	14.6	14.8
Displacing fluid density (lb/gal)	11.6	8.6	13.3
Displacement pump rate (bbl/min)	2.6	5.2	8
Hole angle	0	48	65
Hole volume (bbl)	588	~ 830	~ 850
Total Depth (ft - measured)	18500	16000	20850
Bottom hole temperature (°F)	350	205	194
Sample range	235	520	195
Sample frequency	15-30	15-25	15
No. of samples	12	25	14
Rig Report: Bbl of mud interface	15	50	17
Calculated Bbl of mud film in wellbore	7	6.5	9.7
Lab Analysis: Bbl of mud removed	1.2	23	18

	Contact		Contact		Contact	
	Well No. 1	Time	Well No. 2	Time	Well No. 3	Time
Base fluid for spacers	13.0 lb/gal CaBr ₂		Seawater		13.1 CaBr ₂	
Spacer components and pump sequence	15 bbl base oil	6 min	25 bbl base oil	4.5 min	25 bbl base oil	3
	50 bbl HEC with surfactant and solvent	19 min	50 bbl surfactant	9	50 bbl xanthan with surfactant and solvent	6.25
	50 bbl surfactant	19 min	100 bbl solvent	18	50 bbl surfactant and solvent	6.25
	25 bbl synthetic polymer	10 min	50 bbl xanthan	9	25 bbl xanthan	3
	11.6 lb/gal CaCl ₂		50 bbl flocculant	9		
			50 bbl xanthan	9		

Table 3. Rheology of Viscous Spacers in Case 1 and 3 (120°F)

Dial Reading	Case 1 lead	Case 1 tail	Case 3 lead	Case 3 tail
600	292	125	171	180
300	296	75	117	141
200	142	51	94	122
100	90	25	59	95
6	30	9	10	27
3	20	2.0	6	18
PV	96	50.0	54	39
YP	100	25.0	63	102
10 sec	24	3	10	27
10 min	26	3	11	30

Table 4. Volume Accounting

	Case 1	Case 2	Case 3
Amount of Mud Found in Spacers (bbl)	26	23	14
Amount of Mud not found in spacers (bbl)	28	87	0
Amount of Spacer Recovery (bbl)	75	320	107
% Spacer Recovered	100%	106%	86%
Amount of Oil Found in Spacers (bbl)	13	39	2
Volume of Oil pumped (bbl)	15	50	25
% Oil Recovered in Spacer	87%	78%	8%
Amount of Seawater/Completion Fluid Found in Spacer (bbl)	22	45	72.0
Total Volume of Mud, Oil, Spacer, and Seawater/Completion Fluid Found in Samples	164	515	195
Volume Over Which Samples were collected	235	520	195
% Accountability	70%	99%	100%

Figure 1: Actual vs Theoretical - Case 1

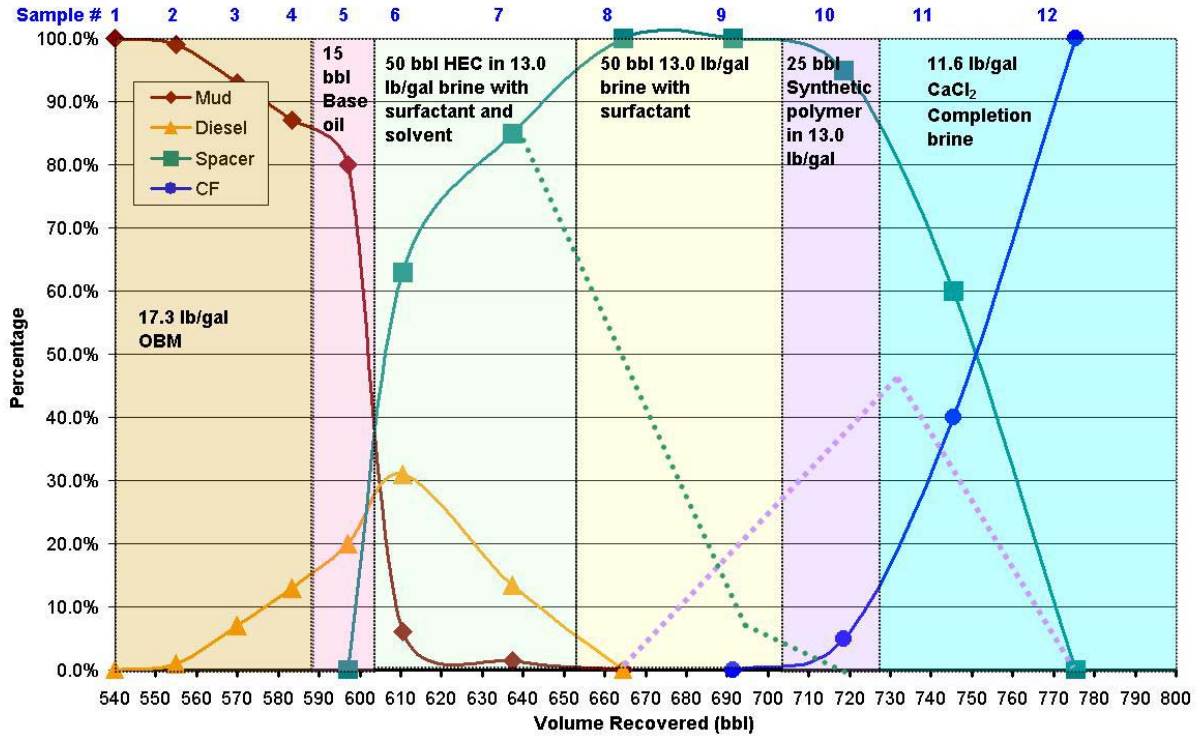


Figure 2. Actual vs Theoretical - Case 2

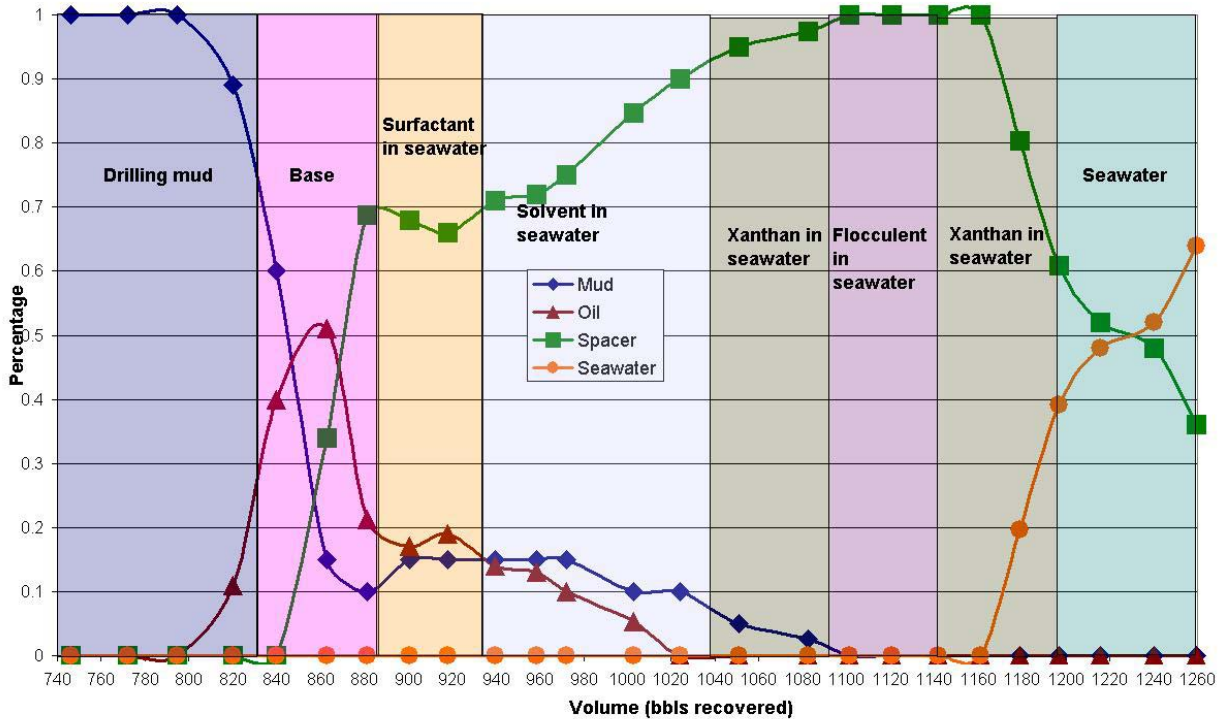


Figure 3. Actual vs Theoretical - Case 3

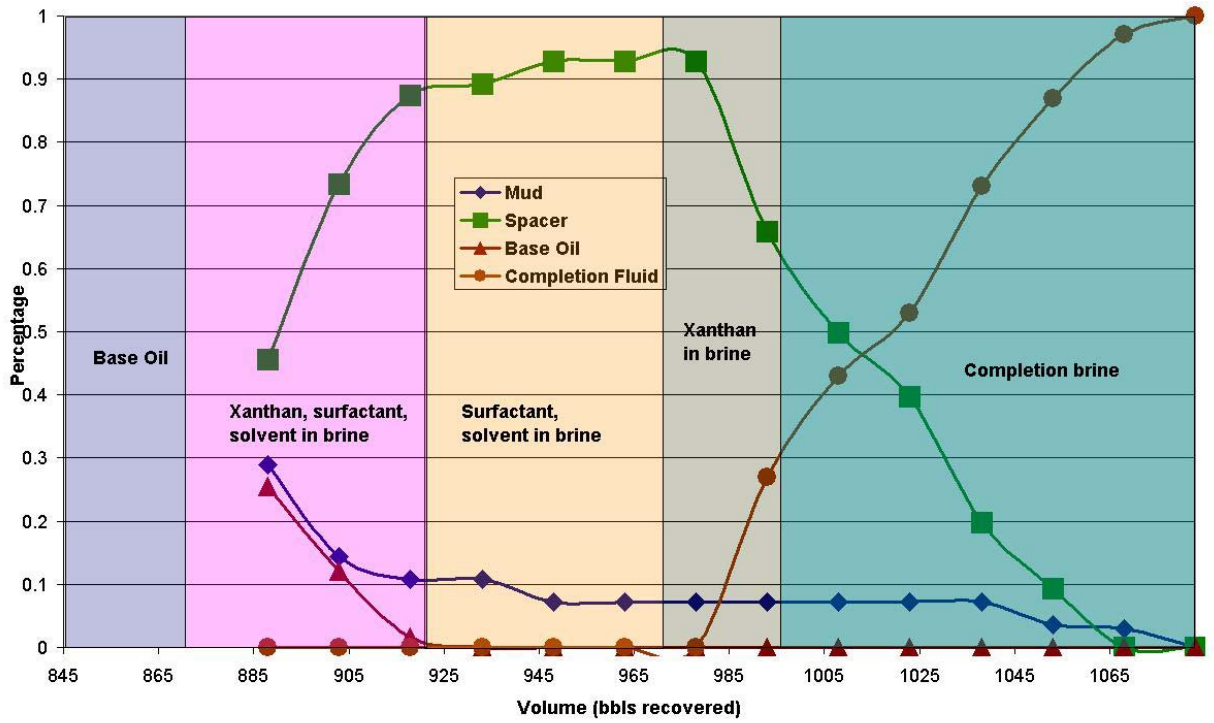
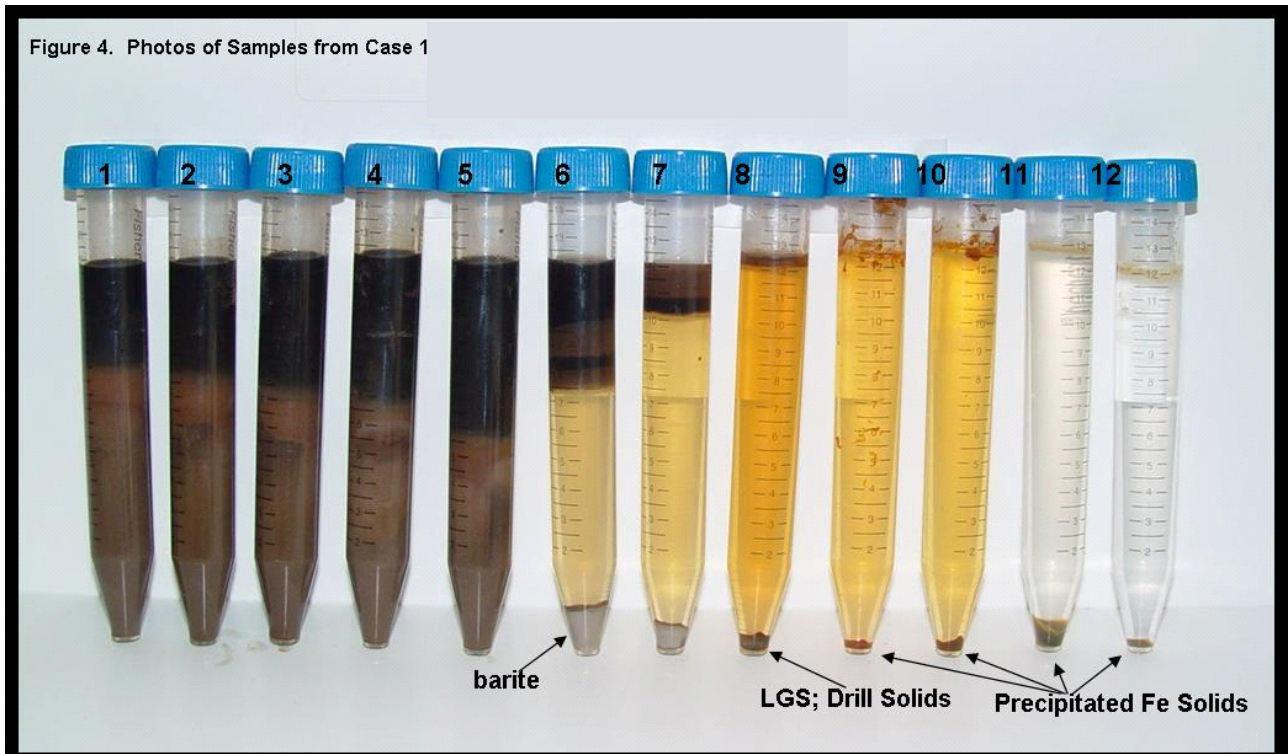
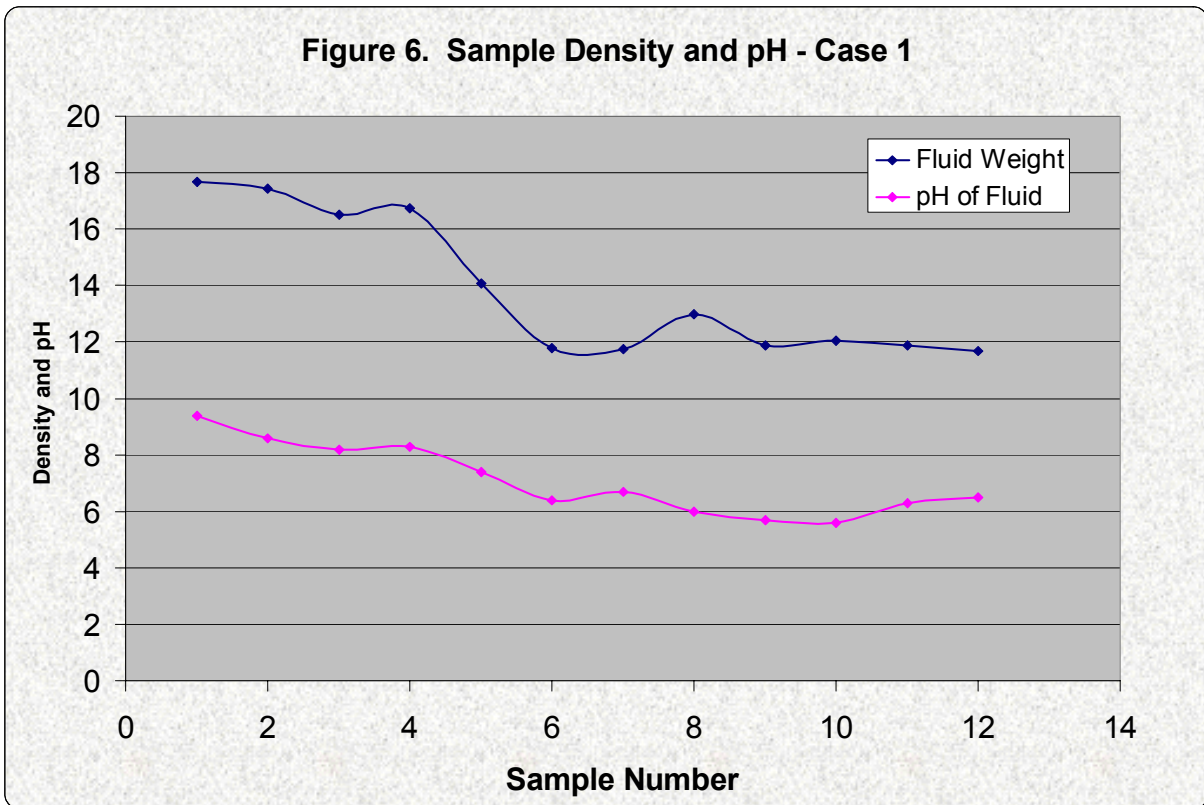
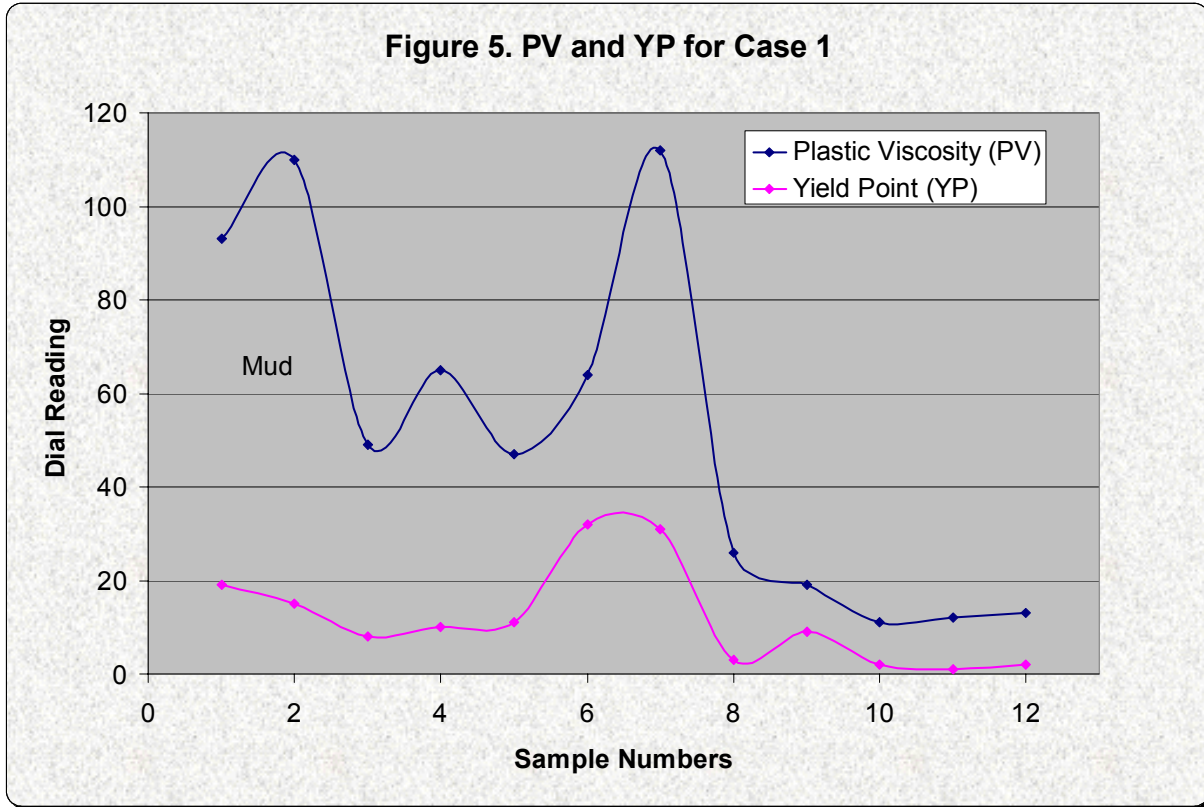


Figure 4. Photos of Samples from Case 1





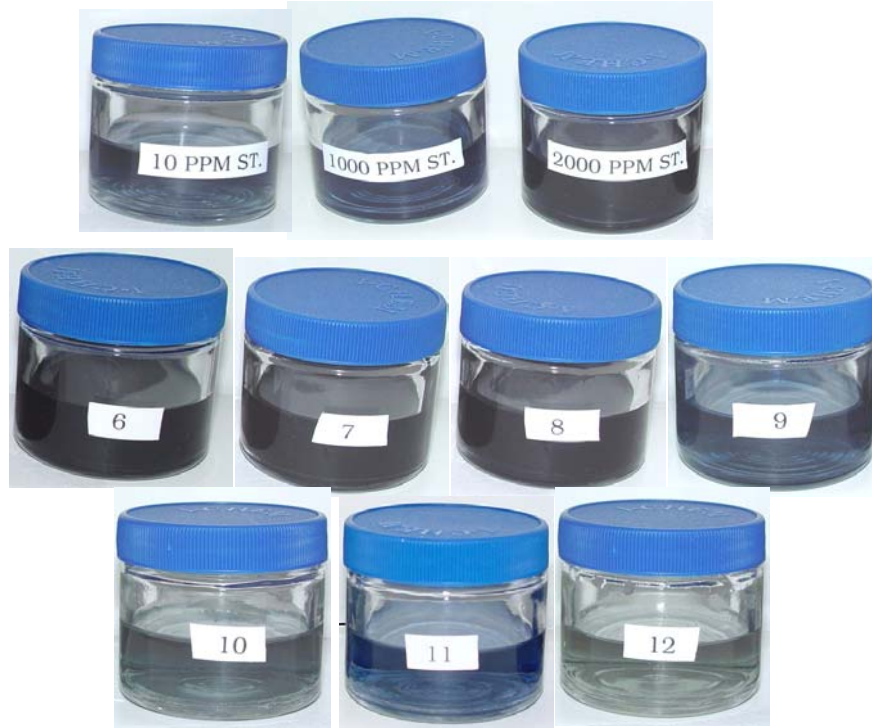


Figure 7. Colorimetric Determination of HEC in Samples – Case 1

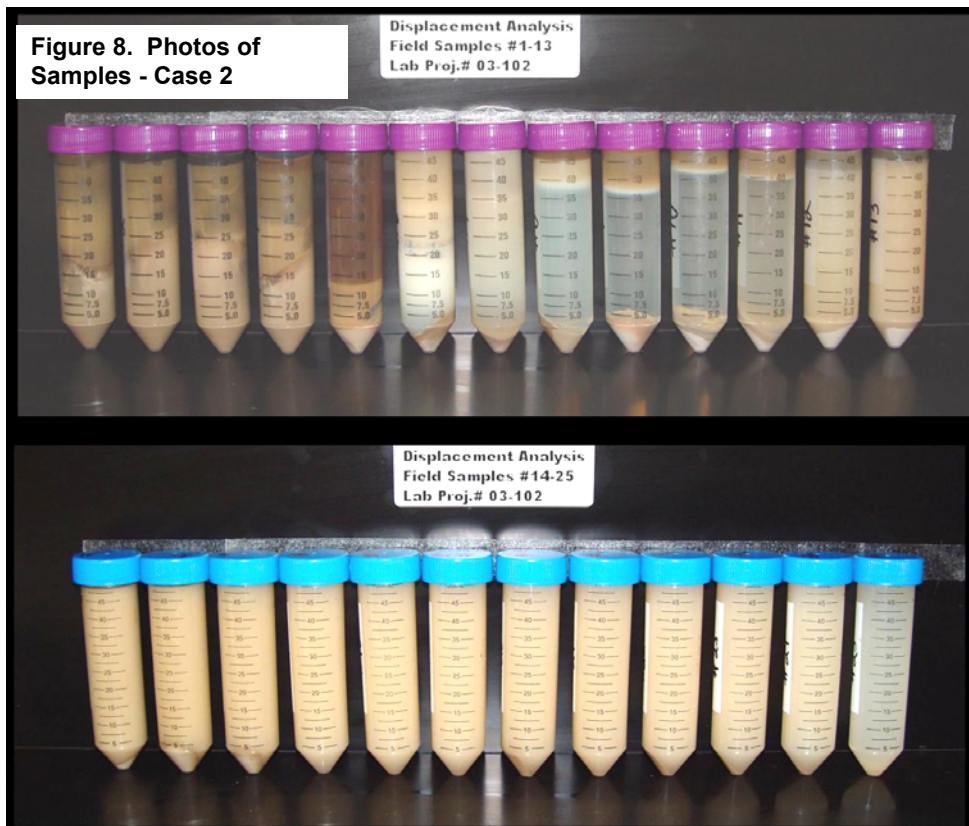


Figure 8. Photos of Samples - Case 2

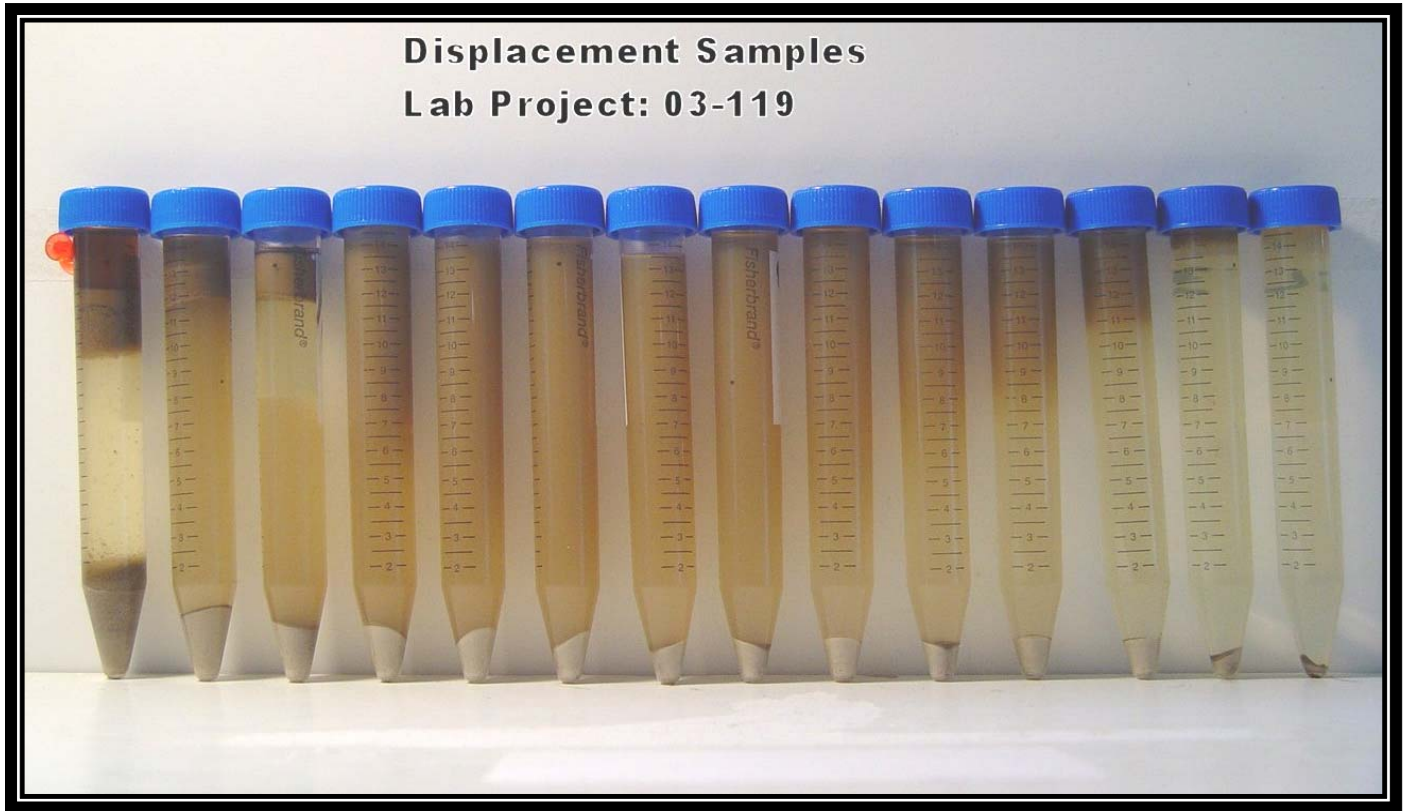


Figure 9 – Photos of samples Case 3.