USF UNIVERSITY OF SOUTH FLORIDA
Civil & Environmental Engineering

EVALUATION OF HYBRID SLURRY RESULTING FROM THE INTRODUCTION OF ADDITIVES TO MINERAL SLURRIES

BDK-84-977-08

FINAL REPORT

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The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the State of Florida Department of Transportation.

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
bbl	Barrel	0.159	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
TEMPERATURE (exact degrees)				
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS TO U.S. CUSTOMARY UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	6.2898	Barrels	bbl

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	$candela/m^2$	0.2919	foot-Lamberts	fl

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

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16. Abstract

Drilled shaft construction often requires the use of drill slurry to maintain borehole stability during excavation and concreting. Florida Department of Transportation (FDOT) specifications require the use of mineral slurry for all primary structures. Contractors have occasionally requested permission to use polymer additives or polymer modified mineral slurries, to which no clear response could be provided. This study investigated the use of polymer additives in mineral slurries to assess their properties and if present specifications were sufficient for their use.

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Drilled shafts, mineral slurry, polymer additives, polymer slurry	No restrictions.

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Executive Summary

Construction of drilled shafts in the state of Florida generally requires the excavation to be stabilized either mechanically through the use of permanent or temporary casing or hydraulically by hydrostatic mineral slurry pressure. Depending on the slurry type (mineral, polymer, or natural), a lower to higher differential fluid level is required,. When compared to casing, slurry tends to use less expensive equipment (making it more attractive) but is more prone to complications associated with maintaining the borehole stability.

Until recently, FDOT allowed only mineral slurry to be used to stabilize the drilled shaft excavations during the installation of drilled shafts foundations. Specification changes made in July 2008 allowed for the use of polymer slurry but limited its use to drilled shaft excavations up to 60 inches in diameter installed to support mast arms, cantilever signs, overhead truss signs, high mast light poles or other miscellaneous structures. As a result, slurry properties for pure mineral slurry and pure polymer slurry usages were established. However, hybrid slurries made from polymer-fortified minerals or admixtures intended to enhance the mineral slurry performance are not yet permitted as questions remain as to the effect of these products. To that end, it was unclear if either set of the present slurry property specifications (viscosity, density, pH, and sand content) is more appropriate for hybrid slurries. This formed the basis of the study.

Two types of tests were undertaken to assess the effect of polymer additives on hybrid slurry performance. These tests were sand settlement / suspension tests and the API filter press test, to assess filter cake development. The results of these tests concluded that polymer additives do not drastically affect mineral slurry mix ratios but do enhance the working properties of the slurry. Sufficient quantities of mineral are still needed to achieve minimum density values, and excessive quantities of additives drive the slurry out of conformance with viscosity specifications. Provided that the minimum density and the maximum viscosity are satisfied, polymer additives can aid in sand suspension. In all cases tested, only small concentrations of additive were needed and / or could be used.

Finally, API filter press tests showed that the current specification for minimum viscosity does not produce a stable flow rate and, hence, unsuitable filter cake performance. These findings suggest that a minimum viscosity value of 30 sec/qt would be more appropriate for bentonite-based mineral slurries and a value of 32 sec/qt would be more appropriate for attapulgite-based mineral slurries.

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Chapter One: Introduction

Construction of drilled shafts in the State of Florida generally requires the excavation to be stabilized by either mechanical (casing) or fluid pressure (slurry) systems. Therein, lateral pressure is radially applied to the excavation walls by the lateral compressive strength of the casing or by the net fluid pressure of a slurry level maintained above the ground water table. Depending on the slurry type (mineral, polymer, or natural), a lower to higher differential fluid level is required. When compared to casing, slurry tends to use less expensive equipment (making it more attractive) but is more prone to complications associated with maintaining the borehole stability. General complications include, but are not limited to, the following: fluid property maintenance (viscosity, density, sand content, etc.), proper head differential, loss of fluid, and storage/handling/disposal issues. Figure 1.1 shows the slurry level maintained at the surface for a 25 ft deep, 9 ft diameter shaft excavation stabilized with a combination of a temporary surface casing and slurry.

Figure 1.1 Slurry-stabilized drilled shaft excavation with temporary surface casing.

Until recently, FDOT allowed only mineral slurry to be used to stabilize the drilled shaft excavations during the installation of drilled shaft foundations (FDOT, 2007). Specification changes made in July 2008 allow for the use of polymer slurry but limit its use to drilled shaft excavations up to 60 inches in diameter installed to support mast arms, cantilever signs, overhead truss signs, high mast light poles or other miscellaneous structures. As a result, slurry properties for pure mineral slurry and pure polymer slurry usages were established in the 2009 specifications (FDOT, 2009). However, hybrid slurries made from polymer fortified minerals or admixtures intended to modify the mineral slurry performance are not yet permitted as questions remain as to the full effect of these products. To that end, it is unclear if either set of the present slurry property specifications (viscosity, density, pH, and sand content) is more appropriate for hybrid slurries. This formed the basis of the study.

1.1 Background

The most widely utilized slurry type is mineral slurry formed by mixing dry clay powder with water. Depending on the environmental conditions, either bentonite or attapulgite powder may be used (attapulgite being used in saline water conditions). Recently, however, polymer modified and polymer based drilling slurries have become popular.

Although both mineral and polymer slurry have been shown to be effective in stabilizing an excavation, the mechanisms by which they provide this stability are quite different. Mineral slurries depend on a minimum density (clay mineral concentration) to provide a sufficient lateral pressure on the excavation walls coupled with the impervious barrier (filter cake) that quickly forms containing the slurry within the excavation. Without adequate clay mineral concentration, the filter cake will not form. Therein, the slurry density provides a measure of slurry suitability prior to being placed in the excavation. The effectiveness of mineral slurries to form a filter cake/layer and sufficient lateral pressure allows the required fluid head to be the least of all slurry types.

Equally important is the effectiveness of mineral slurry to manage cutting debris. Mineral slurries should maintain a minimum viscosity which in turn is intended to suspend soil particles long enough for concreting to expel the particle laden slurry. Without such a suspending action, debris will fall out and accumulate on the rising concrete surface increasing the potential for entrapment or soil inclusion-type anomalies. Conversely, excessively high viscosity causes gelling which prevents the slurry from being easily displaced and flowing upward without encapsulation during concreting. Additionally, if too high a concentration of cuttings are retained by the slurry the density will rise making it less susceptible to displacement by concreting (i.e. unit weight of fluid concrete should be markedly higher than the slurry to affect adequate displacement of the lighter slurry). Further, recent studies (Mullins 2005) have shown that high sand contents in mineral slurries (approaching 4 percent) produce excessive debris accumulation on the surface of the rising concrete. Consequently, a range of acceptable densities and sand contents have been prescribed for mineral slurries that produce the desired effects.

Polymer slurries must also maintain both a manageable viscosity and density, but for different reasons. Polymer slurry maintains excavation stability by the long polymer strands clinging to and flowing into the surrounding soil strata. No filter cake is formed; rather, a constant flow of viscous polymer fluid pulls the soil particles into the surrounding excavation walls and likewise binds the soil from erratic reverse flow during tool extraction. Viscosity is the primary measurement for polymer effectiveness although excessive viscosity can result in clumping and counterproductive performance. Although density and viscosity are related in clean slurry, the density and viscosity in the field can be artificially affected by sand content. However, unlike mineral slurries, polymer slurry is designed not to suspend cuttings/debris, but rather to permit quick sedimentation of particulates. Therein, flocculating admixtures can be used in conjunction with the polymer slurry to expedite the removal of suspended solids. As sand sedimentation occurs rather quickly, much lower slurry sand content must be achieved prior to concreting.

Summarizing, mineral slurries form filter cakes (requiring sufficient clay content) and high lateral pressure to support excavation walls while also suspending cuttings/soil particles (requiring minimum viscosity) until concreting is completed. Polymer slurries do not form filter cakes and cling to the soil, pulling the soil into the excavation walls. In contrast to mineral slurries, polymer slurry will release suspended solids readily allowing the particles to be captured by a clean out bucket either left to rest at the bottom of the excavation or reinserted to remove this debris. As these two products/approaches have disparate mechanisms, it may be difficult to assign one single set of parameters to best manage hybrid slurries.

1.2 Report Organization

The overall organization of this report is outlined below wherein four chapters provide the following: a comprehensive background, slurry filtrate testing, examination of sand suspension properties, and the study findings.

Chapter 2 introduces the original problem as outlined in the University of South Florida (USF) proposal submitted to the Florida Department of Transportation (FDOT). An overview of currently publicized subsurface drilling techniques, equipment, and practices is presented, along with generalized drilling fluid descriptions. The products utilized for testing are discussed, FDOT 455-Standard Specifications for Road and Bridge Construction 2010 is reviewed, and slurry testing methods and equipment are described.

API filter press testing performed on pure mineral, polymer modified (high yield) and polymer enhanced mineral (hybrid) slurries is presented in Chapter 3. Results from comparative tests conducted on several different mineral, polymer, extra high yield and hybrid slurries are presented.

Chapter 4 contains, in addition to a brief discussion of the products tested, test procedures and results pertaining to sand suspension testing. Results from both large and small scale testing are presented.

Chapter 5 contains a summary of project findings and trends discovered in testing discussed in Chapters 3 and 4 and provides recommendations from the findings of the study.

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Chapter Two: Background

This chapter provides an overview of drilling applications and how practice pertains to slurry usage and selection.

2.1 Problem Statement

The purpose of this study was to identify potential problems that may arise as a result of polymer additives being introduced to mineral slurries. The objectives of the proposed research were (1) to determine the optimum amount of different additives that can be added to the mineral slurry before the hybrid slurry is no longer considered a mineral slurry, (2) to establish criteria, if any, for the additive components and (3) to evaluate suitability of the American Petroleum Institute (API) Filter Press Test (that provides information in relation to hole stability), as a hybrid slurry performance evaluation test.

The project stemmed from a Request for Research Proposal (RFRP) defined by FDOT wherein the following proposed tasks were identified:

> *The proposed study will undertake four general tasks: (1) perform a literature search of present foreign and domestic methods as well as pertinent parameters (e.g. available minerals, clay chemistry, equipment, field practice, and possible admixtures), (2) lab and/or field slurry preparation and testing of hybrid slurry combinations, (3) review and conduct API filter press tests, and (4) develop recommendations/guidelines, quarterly reporting, and final report preparation.*

2.2 Types of Subsurface Drilling

Subsurface drilling methods, equipment, and involvement vary depending on the type of drilling at hand. Although the type of drilling depends on application, the main types of subsurface drilling all make use of a variety of slurry products. A summary of drilling applications are discussed below that make use of these products.

2.2.1 Petroleum Applications

The oil exploration and recovery field is undoubtedly the foremost leader in subsurface exploration and the associated drilling techniques. Therein, virtually all of today's drilling technology originated in the oil drilling industry. The need to produce large, stable boreholes at great depths has driven the industry to develop new and creative means to achieve their goals. Techniques and applicable approaches (e.g. boring logs, drilled shafts, etc.) have trickled down over time to the civil engineering / construction industries. As a result, it behooves civil engineering research to stay abreast of new developments or at least readily available information of the state-of-the-art in that arena.

It should first be noted that oil field drilling seldom produces vertical boreholes; rather, boreholes may start out vertical, but may make several turns before reaching their final destination. This is known as “Directional Drilling”. To accomplish directional drilling, several tools are available. Some bits are simply stationary heads with an angled tip, as shown in Figure 2.1.

Figure 2.1 Simple directional drilling assembly (Horizontal Technology, Inc., 2011).

The bit shown in Figure 2.1 is a “Jetting Assembly”, and is useful when cutting through alluvial soils. High pressure fluid is pumped through the drill rod (sometimes referred to as drill string or drill stem), and exits the head, pushing material aside. The fluid then circulates back through the annular space between the drill string and the borehole walls, providing lubrication and cooling while suspending and transporting cuttings to the surface. The suspended cuttings, in some cases, may travel long distances along a horizontal borehole.

When a straight borehole is needed, the entire drill string is rotated, causing the bit, which is angled, to produce a larger diameter hole than itself. When the drillers wish to make a turn, rotation of the drill rod ceases, and the string is directly pushed, making use of the pressurized drill fluids to remove soil from the intended path. When the turn is complete, the entire drill string is rotated once again (known as a “start-up”), and a straight borehole is produced in the new direction. During the turning process, precise knowledge of the tip orientation is required to assure the turn is progressing appropriately.

The jetting assembly shown above is not sufficient for applications which encounter heavily consolidated soils, shales, or rock formations. For these applications, the drill fluid passing through the drill stem is used to spin a turbine similar to a hydraulic motor that allows the drill bit to spin separate from the drill stem. A downward crowd force (aligned with the axis of the drill stem) is required to advance the drilling progress wherein the drilling fluid must provide sufficient lubrication while also removing the cuttings. For directional drilling a minimum radius of curvature to turn the drilling direction is established such that the drill stem can undergo high cycles without fatiguing. This curvature is likewise refined by the lubrication provided by the drill slurry and the aggressiveness of the strata in which the turn is occurring. The drill bits shown in Figure 2.2 are used when spinning on straight drill stems or on down-hole turbine-type drill motors.

Figure 2.2 More aggressive cutting bits (Varel International, 2011).

The left-most bit shown in Figure 2.2 is a stationary directional drilling bit. This bit features hardened teeth for use when encountering more formidable formation, and outlets for drilling fluid circulation. It is used in the exact same fashion as described above, whether making straight boreholes or making turns. The bits shown to the right are known as "tricone" bits, or roller bits, and make use of moving parts to simultaneously crush and cut the formation. In this application, the drilling fluid circulation not only provides lubrication and cooling to the tool, but it provides hydraulic power to the cutting head. The cutting heads rotate, cutting through stone and other extremely hard formations.

More advanced directional drilling tools are available as well. Rather than relying on a bit assembly which features a fixed angular offset to perform turns, bits with adjustable swivels are available for directional applications. An example of this type of assembly is shown in Figure 2.3.

Figure 2.3 Steerable directional drill assembly (Segofs Energy Services Limited, 2011).

By swiveling the bit, changing direction while drilling is simplified, and the radius of the bend may be varied. Directional drilling is not blind drilling; highly advanced tools are available to track the progress of the drill assembly.

To track progress, several remote monitoring tools have been implemented. These tools, known as "Measurement While Drilling" (MWD) or "Logging While Drilling" (LWD) perform a wide variety of tasks during drilling operations. The down-hole sensors are housed just behind the drill motor / drill head and are encased in a long stainless steel section of the drill stem. This eliminates magnetic interference of the on-board compass. The entire sensor set is battery powered, are contained within the drill assembly, and transmit information through digital communications, transmitting the information collected from the sensors to the operators via the drilling fluid with high pressure pulses (like Morse code).

First and foremost, the monitoring tools provide a means to monitor the direction of drilling. Inclinometers and compasses constantly take readings, transmitting information back to the drillers. By knowing the inclination and orientation of the tool, corrections to the drilling direction are made by the drillers.

Most tools are also outfitted with gamma radiation sensors which measure the natural gamma radiation of the surrounding formations. The various formations encountered provide unique gamma radiation signatures, allowing the drillers to identify the material being cut. Additionally, on board load cells allow the drillers to monitor the pressure on the tip of the bit as well as the torque applied to the bit during rotation. Some instrumentation assemblies even provide means to sample soil while drilling, and store it on board for testing after retrieval.

A common tool for monitoring the conditions in the borehole is to simply monitor the drilling fluid. By comparing the amount of drilling fluid provided to the borehole to the amount of fluid circulated back to the surface, soil conditions may be estimated. If large amounts of fluid are provided with little return, a porous or karst formation may have been encountered. If fluid is seen to return at an extreme rate, the tool may have encountered a high pressure formation, possibly a crude or natural gas deposit. These short returns, known as "kicks", are potential signs of a well blowout. When a well begins to kick, steps should be taken to prevent a catastrophic blowout, injuring or killing anyone nearby in addition to destroying drilling equipment. A specialized device, known as a Blowout Preventer (BOP), is usually put in place for deep wells that are likely to encounter such conditions. The BOP is designed to control the well mechanically while the drillers work to safely stabilize the hole. A schematic of a BOP is given in Figure 2.4.

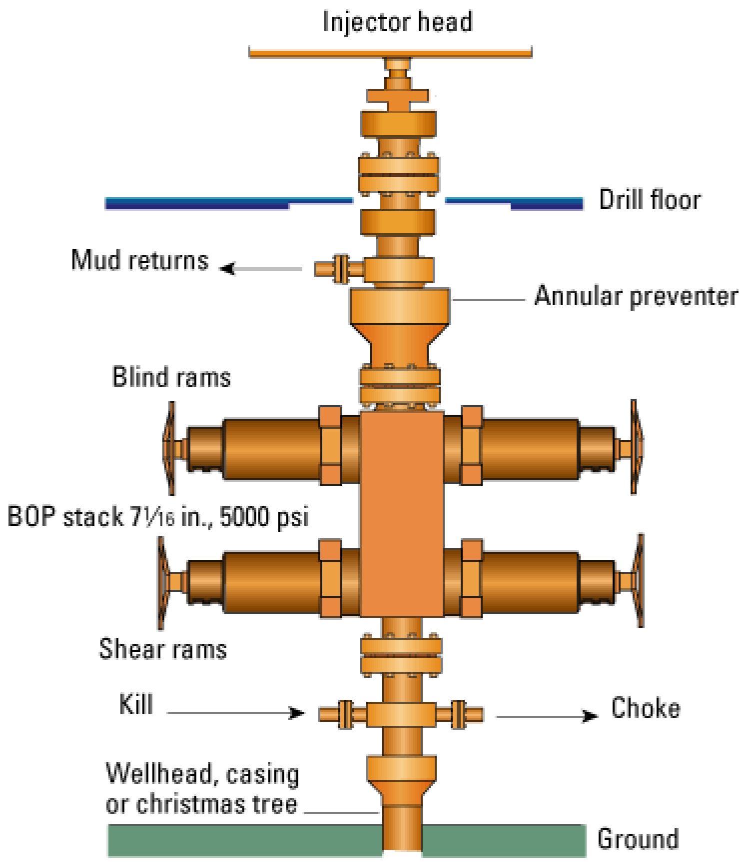

Figure 2.4 Blowout preventer (Schlumberger Limited, 2011).

From the top-down, the following components are shown:

- Injector Head: The location of fluid injection; the drill string is lowered through this port.
- Drill Floor: The drill floor is where the drillers walk about and work.
- Mud Returns: The circulated drilling fluid which has traveled to the end of the drill string and out the bit emerges here. It is monitored, cleaned, and potentially reused. Note that most systems must pass relatively clean slurry through the turbine / drill motor.
- Blind Rams: When the well is closed, the Blind Rams cut the drill pipe and seal the well.
- BOP Stack: The mechanical seal to prevent an imminent blowout. They are rated in terms of the sealing pressure that can be provided; in this figure, 5000 psi.
- Shear Rams: In case of emergency, the Shear Ram will cut the drill pipe or casing when a quick disconnect is necessary.
- Kill: A line to provide extremely dense fluid (known as “Kill Fluid”) to stabilize a wellbore.
- Choke: A line provided to control the outflow fluid rate or pressure on the well. (NY Times, 2010)

2.2.2 Horizontal Direction Drilling (HDD)

Horizontal directional drilling commonly makes use of small and large track mounted rigs, and may be used to place new subterranean pipe and wire without digging long, large ditches. HDD rigs circulate fluids through the drill string and back to the surface, and cannot function without large amounts of quality drilling fluids. A small track mounted HDD rig is shown in Figure 2.5.

Figure 2.5 Horizontal directional drilling rig (Astec Industries, 2011).

Horizontal Directional Drilling utilizes water based drilling fluids or foam drill fluids. The fluids provide hydraulic power to cutting heads and jets, provide cooling and lubrication for the cutting tool and drill rod, transport cuttings, and stabilize the borehole. Similar to the directional drilling performed by oil field drillers, HDD makes use of instrumentation to monitor the progress of the borehole. Battery powered instrumentation, particularly inclinometers, are placed in the head of the drilling assembly. These tools transmit information concerning the inclination to a handheld device, which is carried overhead. By knowing the inclination of the device and the location of the device (marked by the person standing above it with the monitoring device), the borehole may be guided with relatively high accuracy.

Following the completion of a borehole, it may be necessary to widen the hole, or “back-ream” the hole. In these situations, the initial hole acts merely as a pilot hole, guiding the back reaming device. A back reaming device is shown in Figure 2.6.

Figure 2.6 Horizontal directional drilling back reaming device (Wuxi Drilling Tools Factory, 2011).

The back reaming tool is attached to the end of the drill rod, and pulled back through the initial borehole. This process widens the hole to the desired width. Additionally, the pipe, conduit, or wiring for which the borehole was created may be attached behind the back reamer, allowing the drillers to widen the hole and place materials in one pass.

2.2.3 Environmental and Water Well Drilling

Environmental and Water Well Drilling focus on the installation of water wells for monitoring water quality, and providing personal and municipal water supplies. This drilling application typically does not require directional drilling; rather, a relatively vertical borehole is created.

While drilling, drilling fluid is circulated through the drill rod and out the bit. The fluid will act to prevent contamination from surrounding subsurface formations, prevent the intrusion of groundwater into the borehole, stabilize the borehole, suspend and transport soil cuttings within the borehole, and provide lubrication to the cutting tool and drill rod while rotating. Drinking wells are usually stabilized by casing and not mineral or polymers that might contaminate the water. Further, mineral slurry products adversely affect the yield performance of well thereby sealing off the excavation instead of opening the formation to free flowing water.

2.2.4 Geotechnical Exploration

Exploratory and Geotechnical Drilling aim to gather qualitative and/or quantitative information pertaining to a region or soil strata of interest. Commonly a Standard Penetration Test (SPT) is performed in conjunction with the drilling process, gathering both soil samples and soil strength information. This type of drilling commonly makes use of drill rigs similar to that shown in Figure 2.7.

Figure 2.7 Truck-mounted drill rig

This type of drilling commonly makes use of mineral-based drilling fluids and does not require directional drilling. The drilling fluid acts to prevent sample contamination from surrounding formations, prevent intrusion of groundwater into the borehole, stabilize the borehole, suspend and transport cuttings, and provide lubrication to the cutting tool and drill rod while rotating.

2.2.5 Foundation Drilling

Foundation Drilling is typically concerned with the construction of deep foundation elements, particularly drilled shafts. These drill rigs may be truck, track or crane mounted, and may be used with a wide variety of drilling tools. Foundation construction makes use of multi-flight bits for removing relatively soft soils, and clean-out buckets, as shown in Figure 2.8, from right to left.

Figure 2.8 Foundation drilling tools.

Multi-flight bits are rarely found with more than three or four flights, since filling the flights becomes increasingly difficult as the bit is filled with cuttings. These bits carry the material back up the borehole, and are spun clean by the operator at the surface.

Drill buckets can feature cutting teeth in addition to a swiveling bottom. The bucket is placed in the shaft and spun in one direction, causing the bucket to fill. Once full, the operator will spin the bucket in the opposite direction, closing the bottom. A vent is provided in the drill bucket shown above, minimizing suction from forming beneath the bucket when the operator raises the bucket, helping to prevent the collapse of the side walls.

Cleanout buckets, similar to that shown to the left of Figure 2.8, are used to create a clean bottom in a shaft. The operator simply presses the bucket into the bottom of the shaft and spins it, scraping the bottom clean. Once full, the operator closes the bucket in the same fashion as the drill bucket previously described, and raises it. A vent is provided at the bottom of the cleanout bucket as well, to prevent suction from forming while raising the bucket. The operator must continue to clean the shaft bottom until the amount of sediment accumulation on the bottom is satisfactorily minimized.

Various types of drilled shaft construction are permitted, which make use of different materials and methods. These methods include the "Dry Method", the "Wet Method", and methods using temporary or permanent casings.

The dry method of shaft construction does not utilize any drilling fluids. Dry shafts are constructed when soil conditions facilitate this construction method. Rocky formations or cohesive formations which do not permit excessive intrusion of groundwater are ideal for constructing a dry shaft. Once the required depth or formation is reached, the hole is inspected, reinforcement is placed, and the hole is concreted.

The wet method of constructing a drilled shaft requires the use of drilling fluid and typically a portion of temporary casing, placed at the surface. The casing must be placed a specified distance into the ground (typically 1.5 times the shaft diameter) and extend to a specified elevation above ground. The casing is used to contain drill fluids at or above ground level, depending on the height of the groundwater table. As construction progresses, drilling fluid is placed in the hole from the surface as cuttings are removed. The operator must take care not to insert or remove the cutting tool too quickly, or disturbance to the excavation is likely. Once the desired depth or formation is reached, the hole is cleaned and inspected, reinforcement is placed, and the hole is concreted via tremie or similar. While concreting, the drilling fluid is displaced. Finally, the temporary casing is removed at the surface. An example of a shaft constructed utilizing the wet method is displayed in Figure 2.9.

Figure 2.9 Temporary surface casing (left) after extraction (right).

When sufficiently above ground, the casing allows for the development of a larger pressure head within the excavation, provided by the drilling fluid. The primary purpose of the drilling fluid, which is most commonly a water based mineral drilling fluid consisting of water and sodium bentonite, is to provide stability to the borehole by preventing the intrusion of groundwater and providing a net lateral pressure into the soil excavation walls.

Occasionally, shaft construction requires the placement of temporary or permanent casings along the full length of the shaft. The casing is vibrated, driven, or oscillated into the ground, until the desired depth or formation is reached. The drill operator then excavates the material within the casing, with or without the use of drilling fluid. Once complete, the hole is inspected, reinforcement is placed, the hole is concreted, and temporary casings are retrieved.

2.3 Types of Drilling Fluid

Drilling fluids vary widely, depending on the application and desired properties. Descriptions of the primary drilling fluid categories are presented in the following text.

2.3.1 Petroleum/ Oil Based Mud (OBM)

Petroleum based drilling fluids, such as a diesel based fluid, are commonly used in oil field drilling applications. The fluid is typically modified with mineral, chemical, and polymer additives to achieve desired fluid properties. The fluid is circulated through the drill string during drilling, and performs a variety of tasks while drilling. The fluid resists breakdown under high temperatures and pressures, provides hydraulic power to cutting heads on the bit, provides lubrication and cooling to the bit and drill string, provides a means for communicating with instrumentation within the drill string, provides a buoyant force which helps to support the drill string, and transports cuttings (Schlumberger, 2011). These fluids have good lubricating properties especially for horizontal drilling through hard rock formations.

2.3.2 Synthetic Petroleum Drilling Fluid/ Synthetic Based Mud (SBM)

Synthetic Based Muds, which have properties similar to OBM, may be desirable for oil field drilling applications. The fluid performs the same tasks as OBM while remaining safer for workers. One of the most notable safety features of SBM is the decreased chance of explosion while working in confined spaces (Schlumberger, 2011).

2.3.3 "Kill Fluid"

"Kill Fluid" is an extremely heavy fluid used to stabilize wells which encounter pressurized formations, used by oil field drillers. This fluid may be an OBM or a SBM which contains large quantities of minerals and polymers, increasing the density of the material. The primary purpose of this fluid is to develop massive hydrostatic pressure heads, preventing pressurized formations from overwhelming the borehole and causing a blow-out, ejecting the drill string, damaging drilling equipment, and potentially killing anyone within close proximity. This fluid should not be used while actively drilling due to large quantities of suspended solids. The fluid tends to set up if allowed to rest, making it extremely difficult to restart drilling operations without damaging equipment (Schlumberger, 2011).

2.3.4 Air

Air has been used as a drilling fluid in certain applications. To make use of this fluid, air is compressed and directed through the drill rod, exiting the cutting tool. The air then travels through the annular space between the drill rod and the borehole wall, carrying loose cuttings upward, exiting at the surface often times violently.

2.3.5 Foam

Foam drilling fluid, consisting of a mixture of air, water, and polymer, has been used as a drilling fluid. The foamy mixture is sent through the drill rod, exiting the drill bit. The mixture provides additional stability to the borehole in unstable zones, transports cuttings, reduces dust production during air drilling operations, and has a relatively low environmental impact (Wyo-Ben, 2011).

2.3.6 Water

Water may be utilized as a drilling fluid in a variety of drilling applications. Water circulated through the drill rod to the cutting tool, or simply placed in the hole from the surface. Upon entering the borehole, the water may mix with the soil and cuttings, producing “natural slurry”. Hydrostatic pressure developed by the water acts to stabilize the walls of the borehole, while helping to suspend fine cuttings. When used for drilled shaft applications, natural slurries tend not to suspend solids reliably, but should be treated / tested like any other slurry prior to concreting.

2.3.7 Water Based Mineral Fluid

Drilling fluids consisting of water premixed with a mineral product, frequently sodium montmorillonite (bentonite) or calcium montmorillonite (attapulgite), until the desired properties (viscosity and/or density) are attained. The product is then pressurized and sent down the borehole through the cutting tool to stabilize the borehole, lubricate and cool the cutting tools and the drill rod, to transport cuttings, to prevent groundwater intrusion, and to stabilize the borehole. It may also be placed directly into the hole from the surface, to stabilize the excavation walls (trenches or holes) and prevent groundwater intrusion.

2.3.8 Water Based Polymer Fluid

A premixed drilling fluid consisting of water and polymers may be useful in certain applications. Some polymers may be used as standalone drilling fluids or to modify other fluids, such as bentonite drilling fluid. Other products are manufactured solely to modify drilling fluids consisting of polymers, minerals, or a combination of the two. Drilling fluid modifications are as diverse as the product field itself. Products are available to increase the suspension and transportation capacities of drilling fluids, primarily useful in directional drilling applications. Densifying additives are available to increase the unit weight of drilling fluids as necessary. Filtrate control additives are manufactured to decrease the permeation of drilling fluid into the surrounding formations, and vary depending on the type of soil formation causing a significant loss of fluid. Surfactants are regularly used to prevent the wetting of clays and shales encountered while drilling, to control the weight of the drilling fluid. Products are even available to aide in the disposal of used drilling fluids (CETCO, 2011).

2.4 Tested Drilling Products

The drilling fluids available on the market are vast. These materials have been engineered for virtually every purpose imaginable. The products selected for testing in this project are but a few of those potentially available. These products were selected for testing only after consulting local product consumers and suppliers. The products include untreated bentonite, "High Yield" bentonite, attapulgite, and polymer additives. Untreated products typically yield 90 bbl per ton, where 1 bbl is equal to 42 gallons, whereas a polymer modified product, such as a "High Yield" bentonite, will yield upwards of 200 bbl/ton. Most products are manufactured by five different major companies including: Baroid Industrial Drilling Products (Baroid IDP, a division of Haliburton), CETCO, Floridan (Active Minerals International), KB International, and Wyo-Ben. The products tested in this study are shown in Figure 2.10. A discussion of the products tested is presented in this section.

Figure 2.10 Products tested.

2.4.1 Baroid Products Tested

Baroid IDP is a worldwide producer of drilling and construction products and services. One product, No-Sag, was selected for testing from the Baroid product line. No-Sag is a “biopolymer”, acting to enhance the suspension capabilities of either mineral or polymer drilling fluids without significantly impacting the viscosity (Baroid IDP, 2011). This product is not advertised to be used as a standalone drilling product.

2.4.2 CETCO Products Tested

CETCO is a major producer of a wide range of drilling products, supplying both mineral and polymer products. Two products were selected for testing from the CETCO line. These products included an untreated bentonite, PureGold Gel, and a high yield bentonite, Super Gel-X. PureGold Gel produces a minimum of yield 80 to 90 bbl/ton, and Super Gel-X typically produces 217 bbl/ton (CETCO, 2011). These products perform several functions, including but not limited to, cooling and lubricating the drill bit, suspending and transporting cuttings, and stabilizing the borehole.

2.4.3 Floridan (Active Minerals International) Products Tested

A single product was selected for testing from Active Minerals International. Florigel, a mineral drilling fluid consisting of attapulgite, was prepared for testing. Attapulgite is recommended for use primarily in saltwater drilling conditions over Sodium Bentonite (Active Minerals International, 2011).

2.4.4 KB International Products Tested

One product from KB International was selected for testing. SlurryPro CDP, a pure polymer drilling product, is designed to stabilize boreholes during excavation (KB International, 2011). Very small quantities of the product are necessary to produce a desired density and viscosity, with yields ranging from 2800 bbl/ton to 5700 bbl/ton, based on manufacturer recommended addition rates.

2.4.5 Wyo-Ben Products Tested

Three products from the Wyo-Ben product list were selected for testing. Wyo-Ben NaturalGel, an untreated Sodium Bentonite product, Wyo-Ben Extra High Yield Bentonite, a polymer modified drilling product, and Wyo-Vis “DP”, a polymer material were chosen. NaturalGel is designed to improve filtrate loss (migration of fluid out of excavation and into surrounding formations) and provide stabilization to excavations, while providing a yield of approximately 80-90 bbl/ton. Extra High Yield Bentonite is modified to provide the same fluid characteristics as NaturalGel while yielding 220-235 bbl/ton. Wyo-Vis “DP” is a dry granular polymer additive. This product may be used to modify drilling fluids, to increase viscosity and improve filtrate properties, or it may be used as a standalone drilling product (Wyo-Ben, 2011).

2.5 State Specifications

Drill slurry has almost the same density as water (mineral – heavier; polymer – lighter) and therefore its surface elevations must always be maintained sufficiently higher than the groundwater to affect a net positive pressure against the excavation walls. Although no steadfast value for the differential head are generally specified, it is understood that this level is performance driven. Generally, mineral slurry should be at least 4ft above ground water, polymer slurries slightly higher (e.g. 6 ft). The health of the slurry is best measured by the pH which indicates whether or not an excavation has encountered organics (low pH) or other materials that compromise the integrity of the slurry. Required values of density, viscosity, pH, and sand content are provided in the FDOT 455-Standard Specifications for Road and Bridge Construction and are shown in Tables 2.1 and 2.2 (FDOT, 2010). Tabular information from each state is provided in Appendix B for both mineral and polymer slurries.

Table 2.1 Mineral slurry specifications (FDOT, 2010).

Slurry Property	Required Range	Test Method
Density	64 – 73 pcf (fresh water) 66 – 75 pcf (salt water)	Mud density balance: FM 8-RP13B-1
Viscosity	28-40 sec	Marsh Cone Method: FM 8-RP13B-2
pH	8-11	Electric pH meter or pH indicator paper strips: FM 8-RP13B-4
Sand Content	4% or less	FM 8-RP13B-3

Table 2.2 Polymer slurry specifications (FDOT, 2010).

Slurry Property	Required Range	Test Method
Density	62 – 64 pcf (fresh water) 64 – 66 pcf (salt water)	Mud density balance: FM 8-RP13B-1
Viscosity	Viscosity Range Published By The Manufacturer for Materials Excavated	Marsh Cone Method: FM 8-RP13B-2
pH	pH Range Published By The Manufacturer for Materials Excavated	Electric pH meter or pH indicator paper strips: FM 8-RP13B-4
Sand Content	0.5% or less	FM 8-RP13B-3

The specifications for slurry properties are necessarily different for mineral and polymer slurry products based on the varied stabilization mechanism. Both slurries are given a performance-based requirement such that sufficient head should be provided to prevent caving of the excavation. In the case of mineral slurries, an additional stipulation is imposed to maintain a 4 ft head differential with the existing ground water table. A similar head differential is not provided for polymer slurry, but it is generally accepted that this value should be at least 2 to 4 ft higher than mineral slurry to assure the same differential pressure on the excavation wall. The present polymer specification (455-15.8.2) permits the slurry to be of lesser density than water. Table 2.3 shows the near surface pressure differences with different slurry densities and differential heads. Using a 6 ft minimum head the lateral pressures near the surface are higher than mineral slurry; even at great depths a lighter than water slurry density does not become critical (net lateral pressure = zero) until a depth of over 900 ft (Figure 2.11).

Table 2.3 Pressure differentials for slurry type

Slurry Type	Head Differential (ft)	Min. Pressure Differential z = 0 (psf)	Max Pressure Differential z = 0 (psf)
Mineral	4	(64pcf)(4ft) + (64-62.4)z = 256	(68.5)(4) + (68.5-62.4)z = 274
Polymer	6-8	(62pcf)(6) + (62–62.4)z = 372	(64)(6) + (64-62.4)z = 384

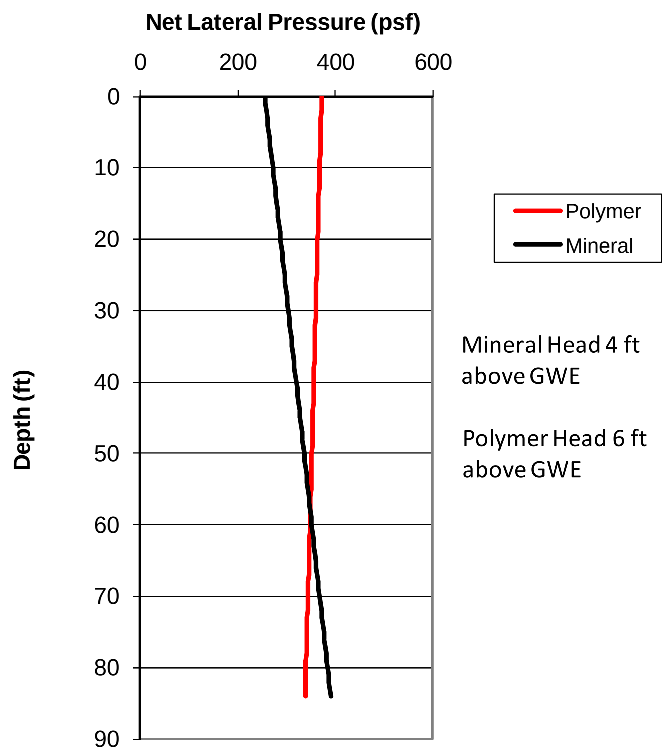

Figure 2.11 Net lateral pressure on excavation walls from mineral and polymer slurry.

2.6 Testing of Drilling Fluids

As previously mentioned, specific slurry properties may be desired, depending on the drilling conditions. Numerous tests and equipment have been developed for use in the field, and are discussed in the following text.

2.6.1 Density

The density of the drilling fluid represents not only the amount of material in the drilling fluid prior to being introduced to the hole, but also the quality of the fluid after introduction. The presence of large amounts of suspended solids, collected while drilling, may increase the density of the fluid over time. This is of particular concern in drilled shaft applications, where the slurry must be displaced during concreting. If the slurry is too dense at the time of concreting, the slurry is not easily displaced, and mixing of the concrete and slurry may occur, lowering the strength of the concrete.

To measure the density of the drilling fluid while in use, "any instrument that will permit accurate measurement within $^{1}/_{10}$ lb or ½ pcf" may be used (Wyo-Ben, 2011). A balance type scale, referred to as a "mud balance" is typically used, and is available from most major drilling fluid manufacturers. A mud balance is shown Figure 2.12.

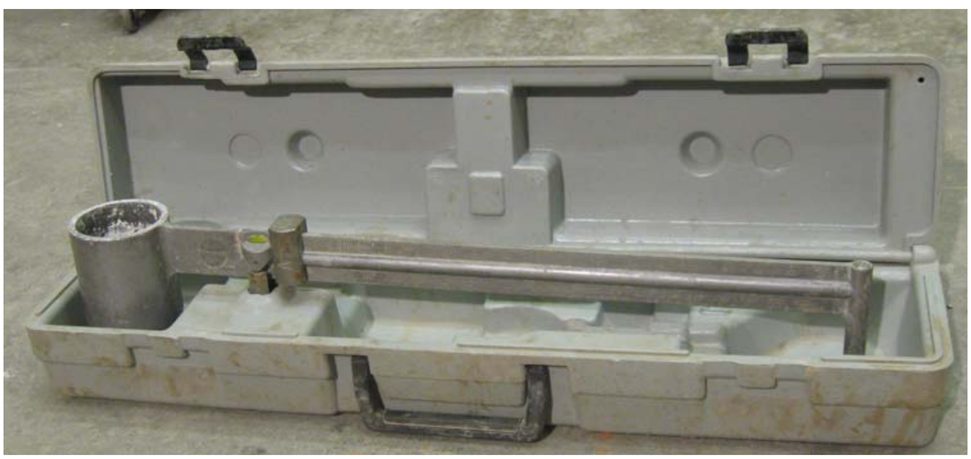

Figure 2.12 Mud balance with case

The proper procedure must be followed to determine the density of drilling fluids with a mud balance. The proper procedures are as follows:

1. Fill the cup with the mud to be weighed.
2. Place the lid on the cup and seat it firmly but slowly with a twisting motion. Be sure some mud runs out of the hole in the cap.
3. With the hole in the cap covered with a finger, wash or wipe all mud from the outside of the cup and arm.
4. Set the knife on the fulcrum and move the sliding weight along the graduated arm until the cup and arm are balanced.

5. Read the density of the mud at the left-hand edge of the sliding weight.
6. Report the result to the nearest scale division in $^{lb}/_{gal}$, $^{lb}/_{cu.\ ft}$, S.G., or $^{psi}/_{1000\ ft}$ of depth.
7. Wash the mud from the cup immediately after each use. It is absolutely essential that all parts of the mud balance be kept clean if accurate results are to be obtained.
8. Refer to [Mud Weight Conversion Table (Table 2.4)] for conversion data if not available on the balance.

Table 2.4 Mud weight conversion table (Wyo-Ben, 2011)

Mud Weight Conversion Table			
Lb per Gal	Lb per Cu Ft	Specific Gravity	Gradient, psi per 1000 Ft of Depth
6.5	48.6	0.78	338
7	52.4	0.84	364
7.5	56.1	0.9	390
8	59.8	0.96	416
8.3	62.4	1	433
8.5	63.6	1.02	442
9	67.3	1.08	468
9.5	71.1	1.14	494
10	74.8	1.2	519
10.5	78.5	1.26	545
11	82.3	1.32	571
11.5	86	1.38	597
12	89.8	1.44	623
12.5	93.5	1.5	649
13	97.2	1.56	675
13.5	101	1.62	701
14	104.7	1.68	727
14.5	108.5	1.74	753
15	112.2	1.8	779
15.5	115.9	1.86	805
16	119.7	1.92	831
16.5	123.4	1.98	857
17	127.2	2.04	883
17.5	130.9	2.1	909
18	134.6	2.16	935
18.5	138.4	2.22	961
19	142.1	2.28	987
19.5	145.9	2.34	1013
20	149.6	2.4	1039
20.5	153.3	2.46	1065
21	157.1	2.52	1091
21.5	160.8	2.58	1117
22	164.6	2.64	1143
22.5	168.3	2.7	1169
23	172.1	2.76	1195
23.5	175.8	2.82	1221
24	179.5	2.88	1247

2.6.2 Viscosity

The viscosity of the drilling fluid is a measure of the flow-ability of the material; the higher the viscosity, the more the fluid resists flow. To simplify viscosity measurements in the field, the Marsh Funnel was developed. The Marsh Funnel is a plastic funnel which features a screen mesh at the top, for filtering out large solids prior to viscosity measurements, and a small plastic measuring cup. The maximum capacity of the funnel for testing purposes is 1500 ml, and the accompanying measuring cup can handle little more than one quart. A Marsh funnel and measuring cup are exhibited in Figure 2.13.

Figure 2.13 Marsh funnel and cup.

To properly measure the Marsh viscosity of a drilling fluid, the following procedures must be followed:

1. Hold funnel in upright position with index finger over outlet.
2. Pour the test sample through the screen in top of the funnel until the mud level just reaches the underside of the screen.
3. Remove finger from outlet and measure the number of seconds required for a quart of fluid to run out (Wyo-Ben, 2011).

Additionally, prior to the test, the funnel opening should be checked for any obstructions. Any obstruction in the funnel will directly affect the viscosity reading. The Marsh funnel and screen should also be washed and dried after each use.

2.6.3 pH Measurement

The quickest and simplest test necessary to monitor drilling fluid is a pH test. Manufacturers of drilling fluids and additives typically provide a working pH range for their products, which may range from 8 to upwards of 10, depending on the product and the manufacturer. pH tests can be used to monitor the quality of the mix water prior to introduction of drilling products. Potable water sources may provide mixing water with a pH of approximately 7, however, this pH may be too low to fully utilize some drilling fluids, particularly polymers. If a potable water source is not available, water sources on site may be used, but might exhibit even lower pH values. The pH of the drilling fluid in use must be monitored as well, since soil conditions could affect the pH of the drilling fluid. Drilling fluids previously treated to the proper pH could encounter organic soils, causing a pH drop.

To monitor pH, two tools may be used: pH strips (litmus paper) or a pH meter. pH strips feature several reactive plates which change color when dipped into the drilling fluid. The colors are then matched up to a color key provided by the test strip manufacturer. pH meters provide even greater ease of use; after placing the pH probe in the drill fluid, the pH is output to a digital screen on the device. Both pH strips and a pH meter are shown in Figure 2.14.

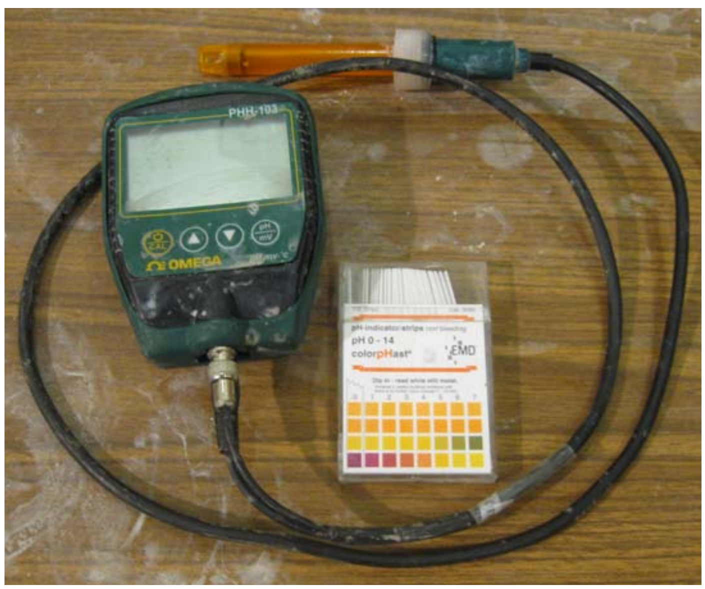

Figure 2.14 pH meter and strips.

2.6.4 Sand Content

As previously mentioned, the sand content of a drilling fluid directly affects the density of the material. An increased density may bring about problems when concreting a shaft, but the sand content of a drilling fluid plays other roles as well. A sand content test kit consists of a vial with measured volume markings, a #200 sieve, and a funnel. When filled to the "Mud to Here" line, 25 ml of drilling fluid is in the vial. The percent volume markings are based on this indication, with 1% of the volume corresponding to 0.25 ml. A sand content test kit is shown in Figure 2.15.

Figure 2.15 Sand content testing kit.

To properly measure the sand content of a particular drilling fluid, the following procedures must be followed:

1. Fill the sand content tube to the indicated mark with mud [“Mud to here” line]. Add water to the next mark [“Water to here” line]. Close the mouth of the tube and shake vigorously.
2. Pour the mixture onto the clean, wet screen. Discard the liquid passing through the screen. Add more water to the tube, shake, and again pour onto the screen. Repeat until the wash water passes through clear. Wash the sand retained on the screen to free it of any remaining mud.
3. Fit the funnel upside down over the top of the screen. Slowly invert the assembly and insert the tip of the funnel into the mouth of the tube. Wash the sand into the tube by spraying a fine spray of water through the screen (Tapping on the side of the screen with a spatula handle may facilitate this process). Allow the sand to settle, from the graduations on the tube, read the volume percent of the sand.
4. Report the sand content of the mud in volume percent. Report the source of the mud sample. Coarse solids other than sand will be retained on the screen (e.g., lost circulation material, coarse barite, coarse lignite, etc.) and the presence of such solids should be noted. (Wyo-Ben, 2011).

When performing directional drilling, the accumulation of solids is of much greater concern than in vertical drilling situations. The suspended cuttings have very little room to accumulate, and no tool will pass by to remove this accumulated material. In these situations, it becomes necessary to increase the suspension capabilities of the drilling fluid, allowing the cuttings to be carried out of the borehole efficiently. However, upon exiting the hole, the drill fluid will have an elevated sand content. Desanding equipment must be provided to remove suspended sands from the slurry before recirculation. This not only improves the suspension capabilities of the recirculated drilling fluid, but it also reduces wear and tear on pumps and equipment. A desanding cone is displayed in Figure 2.16.

Figure 2.16 Desanding cone (Revata Engineering, 2011).

In a desanding cone, slurry enters the apparatus along the circumference of the cone, which corresponds to the horizontal fitting in Figure 2.16. The slurry spins rapidly inside, forcing the solids to the walls of the cone. Once the sand has migrated to the edge of the cone, the lighter slurry exits through a pick-up in the middle of the cone, ready for further refinement or reuse. The sand and a small amount of drilling fluid exit the bottom and are discarded (Schlumberger, 2011).

2.6.5 Filtrate Control

The ability of a drilling fluid to seal the borehole from the surrounding formations, to prevent the intrusion of groundwater or to minimize the amount of slurry lost to the formation is the filtrate control. Drilling fluids partially penetrate the surrounding formations, depositing suspended drilling materials along the wall, with clean water migrating away from the borehole. This process builds a “filter cake” or a “mud cake”. The thickness of the mud cake is directly related to the filtrate efficiency of the drilling fluid. The thinner the filter cake, the more efficient the filtrate control. A thin filter cake is highly beneficial in directional drilling applications. Since directional drilling relies on the ability to transport cuttings out of the hole in the space between the drill string and the borehole walls, the buildup of a thick filter cake is detrimental. Thin mud cakes are beneficial in drilled shaft construction as well. The formation of a thick mud cake will necessitate over-reaming of the excavation, increasing both labor and material costs to produce a slightly larger hole.

To measure the filtrate efficiency of a drilling fluid, a filter press test is utilized. A filter press apparatus is shown in Figure 2.17.

Figure 2.17 Bench top filter press

A filter press is a designed to supply (or be provided) constant pressure to a vessel containing drilling fluid and filter paper over a 30 minute period. A graduated cylinder is placed below the apparatus, and the volume of water which passes through is collected and measured. To properly perform a filter press test with the apparatus shown above, the following procedures must be followed:

1. Before beginning a test, make sure each part of the cell is clean and dry, particularly the screen. Examine the gaskets for distortion and wear. Make sure the screen is free of sharp edges, burrs, or tears.
2. Measure the initial temperature of the mud sample and record it for later analysis.
3. To assemble the test cell, begin by turning the base cap upside down and placing a rubber gasket inside it. Then, place the screen, one sheet of filter paper, and another gasket. Finally, place the cell body into the base cap and turn it to lock it in place. (See Figure 2.18)

Figure 2.18 Filter press test cell

4. Pour the freshly stirred sample fluid into the cell, leaving 0.5 in (13 mm) of empty space at the top.
5. Place a rubber gasket inside the top cap. Make sure it is seated all the way around the cap. Then place the top cap onto the cell body and place the entire cell into the frame. Secure the cell with the T-screw.
6. Place a clean, dry graduated cylinder under the filtrate tube.
7. Attached the hose from the dead-weight hydraulic pressure source to the inlet valve on the top cap.
8. Fill the reservoir on the dead-weight hydraulic assembly with clean, fresh water.
9. Make sure the bleeder valve is closed before pressurizing the cell.
10. Raise the dead weight about a foot and allow it to settle. In about two thirds of a stroke, the pressure gauge will indicate 100 psi (689.5 kPa).
11. Lift the dead-weight back to the top of the stroke. Timing of the test should begin now. One stroke of the piston allows a maximum filtration loss of approximately 30 mL.
12. After 30 minutes, measure the volume of filtrate collected. Shut off the flow from the pressure source.
13. Record the volume of filtrate collected in cubic centimeters to the nearest 0.1 cm^3. Label this value "API Filtrate". Record the time interval and the initial mud temperature. Save the filtrate for chemical analysis.
14. At the end of the test, open the bleed-off valve, which releases the pressure on the filter press cell.
15. Make sure all pressure has been released from the cell. Remove the cell from the frame and disassemble it. Discard any remaining mud.
16. Carefully save the filter paper and deposited cake. Wash the excess filter cake on the paper with a gentle stream of water. If you are testing oil mud, use diesel oil to clean the filter cake instead of water.
17. Measure and record the thickness of the filter cake to the nearest 1/32 in (0.8 mm). A cake thickness less than 2/32 in is usually considered acceptable. Observe and record the quality of the cake: hardness, softness, toughness, slickness, rubberiness, firmness, flexibility, sponginess, etc.
18. After each test, disassemble the test cell and thoroughly clean all surfaces with soap and water. Make sure all parts are clean and dry before storing the unit (Ofite, 2011).

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Chapter Three: API Filter Press Testing

This chapter provides an overview of the API Filter Press testing performed on the pure mineral, polymer modified (high yield), and polymer enhanced (hybrid) mineral slurries. This testing was a primary focus of this study as the resistance of slurry to flow into a drilled shaft excavation walls is a direct indication of the slurry performance. Slower flow rates imply greater lateral pressure against the surround soil and increased side wall stability.

3.1 API Filter Press Setup

The API Filter Press test involves applying a constant pressure to a confined volume of slurry from which the slurry can only escape through a fine porous stone. The porous stone is lines with a filter paper placed at the bottom to prevent contaminating the stone. The pressure being applied forces water through the filter, but leaves behind a paste-like residue of slurry products (filter cake). The volume of water that is filtered through is collected in a graduated cylinder and measured after 30 minutes or the time is noted when 25 ml is obtained, whichever occurs first. Two results are made from this testing (1) the API flow rate and (2) the filter cake thickness. The test apparatus is shown in Figure 3.1.

Figure 3.1 Components of the API filter press with dead-weight system (Ofite, 2011).

Many of the first tests performed using the equipment as shown did not achieve a constant pressure as designed; whereby, the plunger / dead weight system is intended to function similar to an automotive master cylinder (braking system). In this case, the target 100 psi constant pressure was never achieved; further the actual pressure was inconsistent. Therefore, in lieu of the dead weight approach, a constant pressure sources was obtained using compressed air which could be regulated to a reliable 80 psi. Figure 3.2 shows the modified filter press with an airline attached to provide consistent pressure during testing.

Figure 3.2 API filter press test in progress using a constant air pressure source.

3.2 Product Preparation

The slurry was mixed using a drill press with a mixing paddle attachment. Batches of 3000 ml (0.792 gal) were prepared for each slurry product. Water was placed into a 6" diameter and 12" high cylinder and placed under the drill press. An angle bracket was attached to the cylinder to cause additional agitation from the mixing process (and stop swirling). The dry slurry product was slowly added to the mixing water and mixed for 30 minutes. Figure 3.3 shows the slurry being mixed.

The initial testing matrix involved 6 existing products (Figure 3.4) mixed at ratios of 0.1 to 0.5 lb/gal (dry powder to water volume) for a pH of mix water of 7.1. Subsequent tests were performed with a mix water pH of 8.2 and 10.0. The latter series of pH varied testing was only conducted at mix ratios of 0.1, 0.3, and 0.5 lb/gal.

Figure 3.3 Slurry Mixing Setup

Figure 3.4 Materials chosen for baseline testing using the API filter test.

3.3 Verification Testing

Marsh funnel testing and slurry density testing were also performed on each product tested with the filter press. This provided a correlation for the filter press tests to field testing. However, additional refinements to field slurry testing protocols were also applied to the Marsh funnel test and slurry density. Figure 3.5 shows the Marsh funnel filling a taller, smaller cross-section container which provided a more defined point for the determination of the one quart fixed volume of flow. A reduction in test variation was noted between researchers when timing the Marsh funnel results using this system.

Figure 3.5 Viscosity measurements using a 1000 ml beaker marked precisely at the one quart volume.

Likewise, the field balance typically used to measure slurry density is fraught with reproducibility and accuracy issues. As a result, all slurry densities were determined using a 1000 ml volumetric flask weighed with a digital scale (Figure 3.6).

Figure 3.6 Density measurements with a digital scale and a volumetric flask.

3.4 Filter Press Testing of Existing Products

The initial filter press testing was performed on the existing products shown in Figure 3.2. Figures 3.7 through 3.12 show the relationship of density to mix ratio, viscosity to mix ratio, and flow rate to viscosity for the different slurry products at varying pH values. Figures 3.13 through 3.18 show the results of varying the product type and mix ratio.

The density results are not surprising as all materials have roughly the same specific gravity and the mix ratios are all the same ranging from 0.1 to 0.5 lb of powder slurry per 1 gallon of fresh water added.

The viscosity versus mix ratio trends clearly define the three distinctly different materials: the attapulgite which has far less gel strength than bentonite, the “pure” bentonite products, and the high yield polymer fortified bentonite product. The “pure” bentonite products actually had one Section 9 and one Section 10 product but both had virtually the same viscosity response.

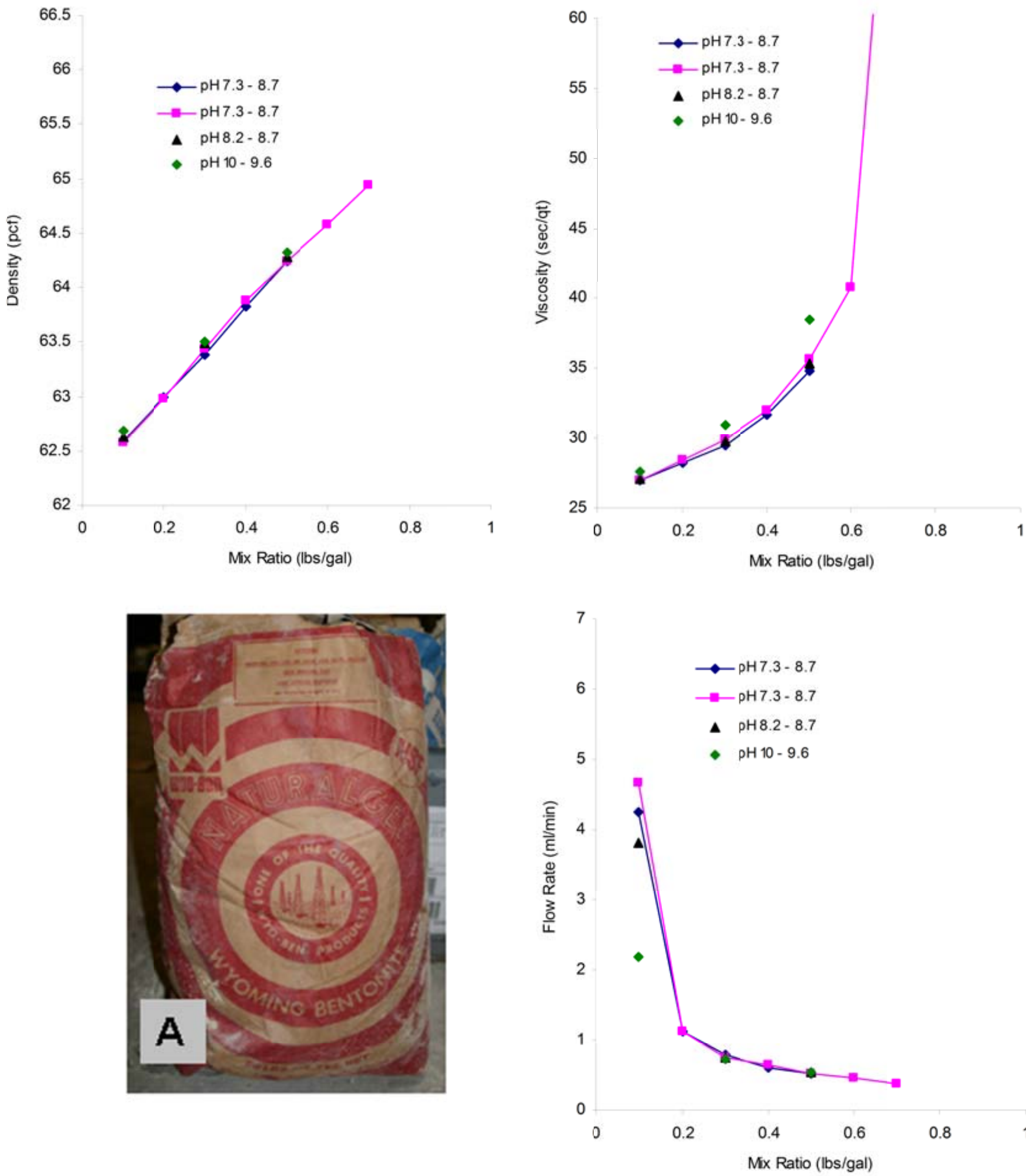

Figure 3.7 Wyo-Ben Natural slurry testing results.

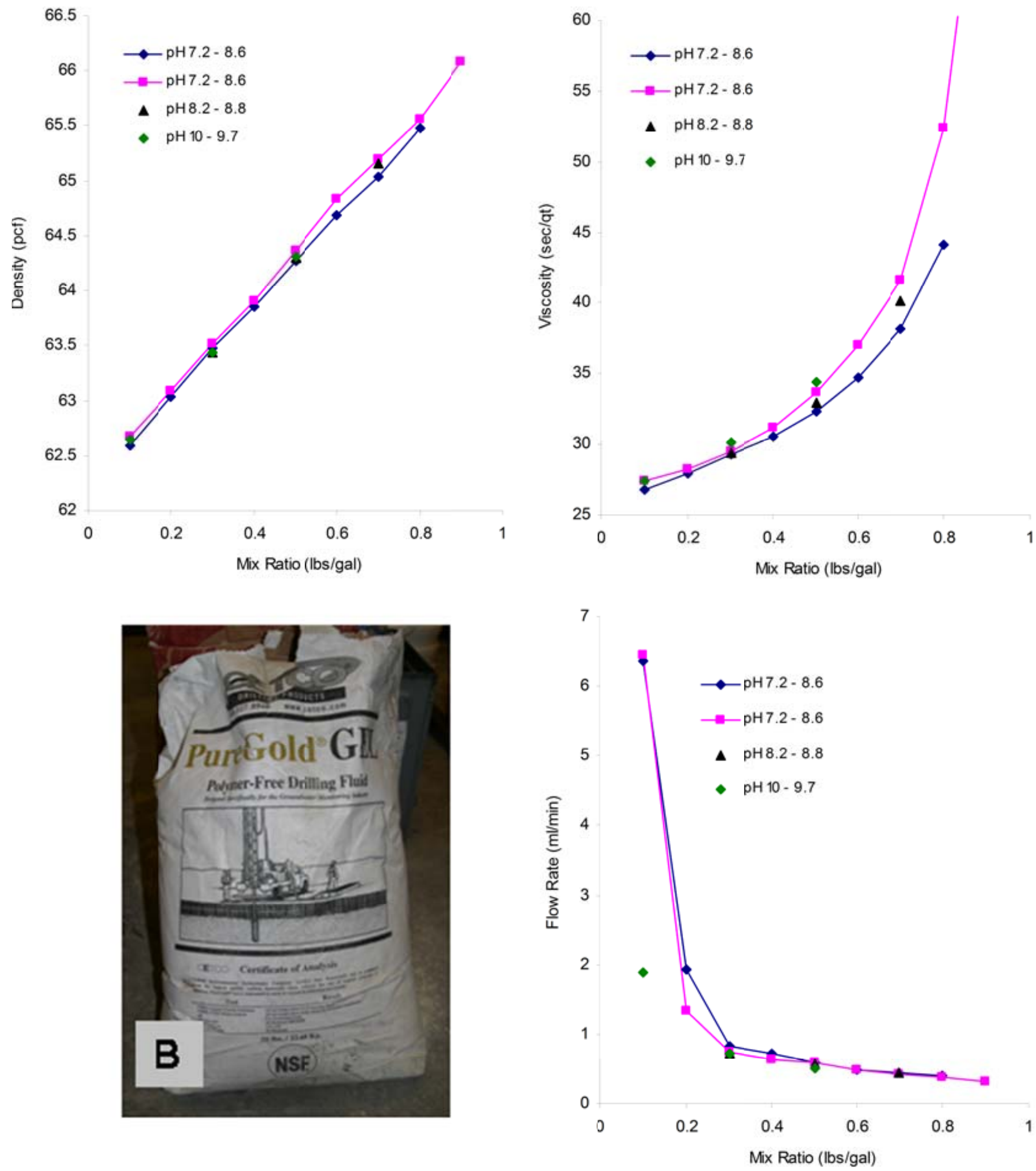

Figure 3.8 Pure Gold slurry testing results.

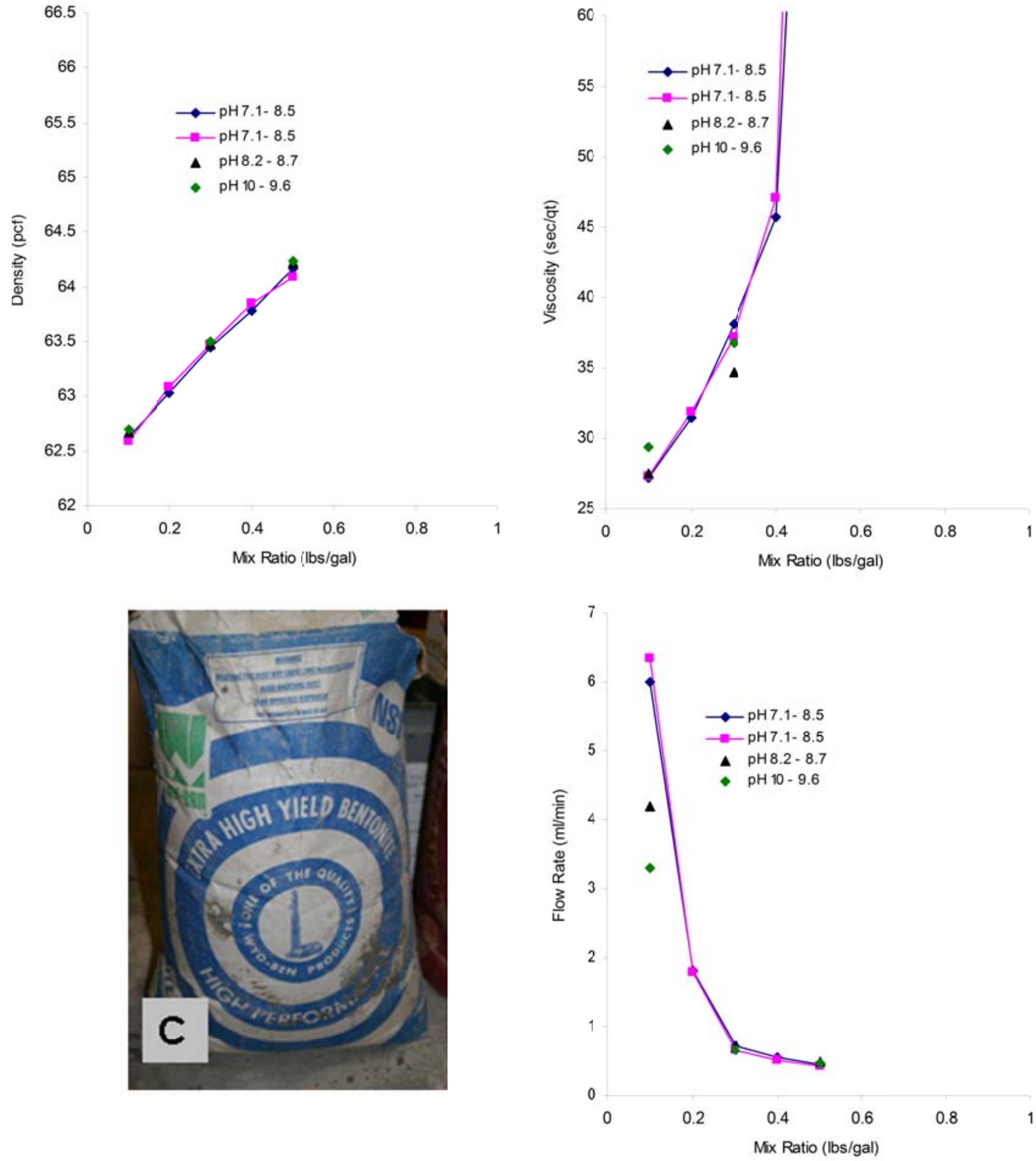

Figure 3.9 Wyo-Ben Extra High Yield slurry testing results.

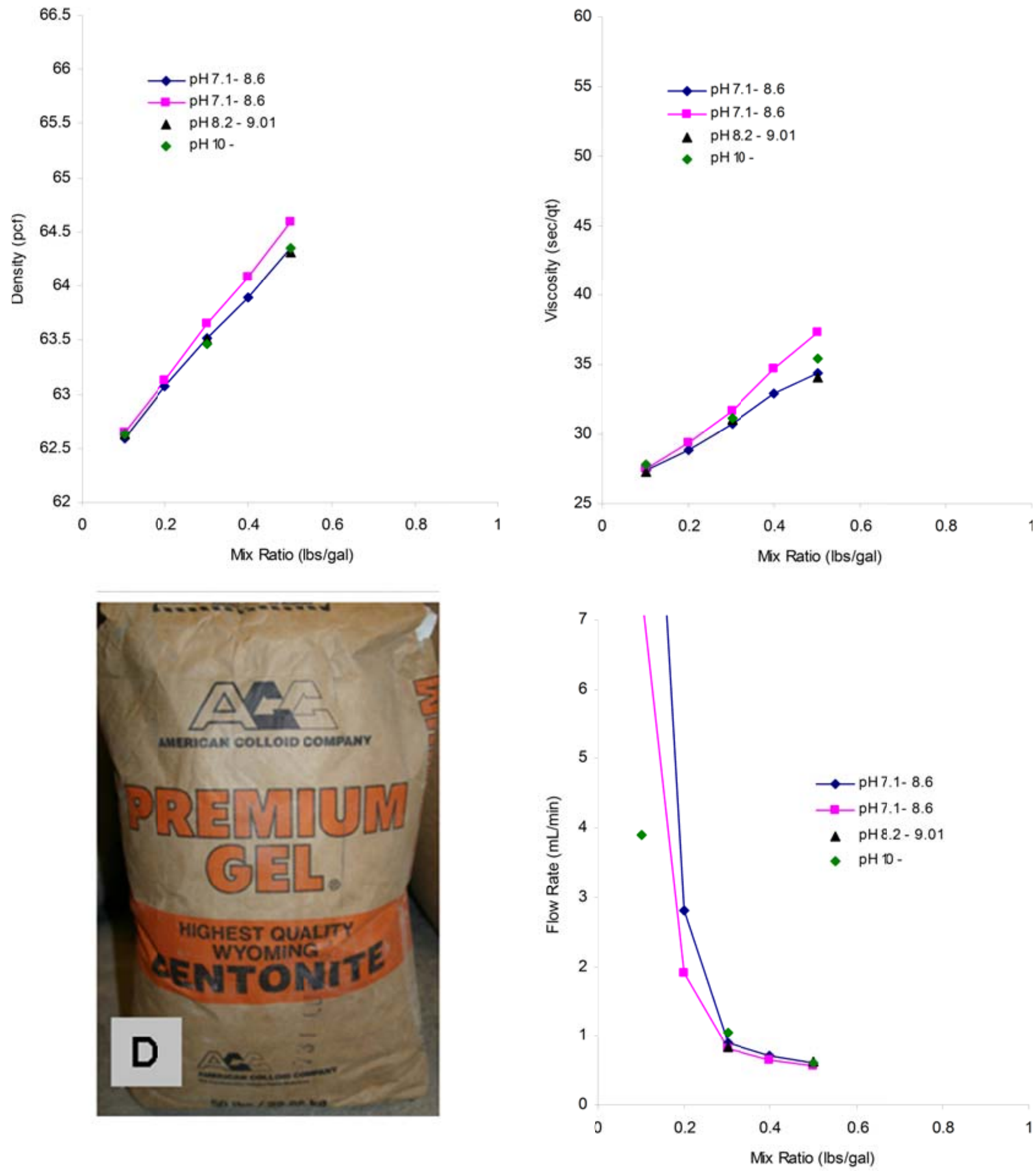

Figure 3.10 Premium Gel slurry testing results.

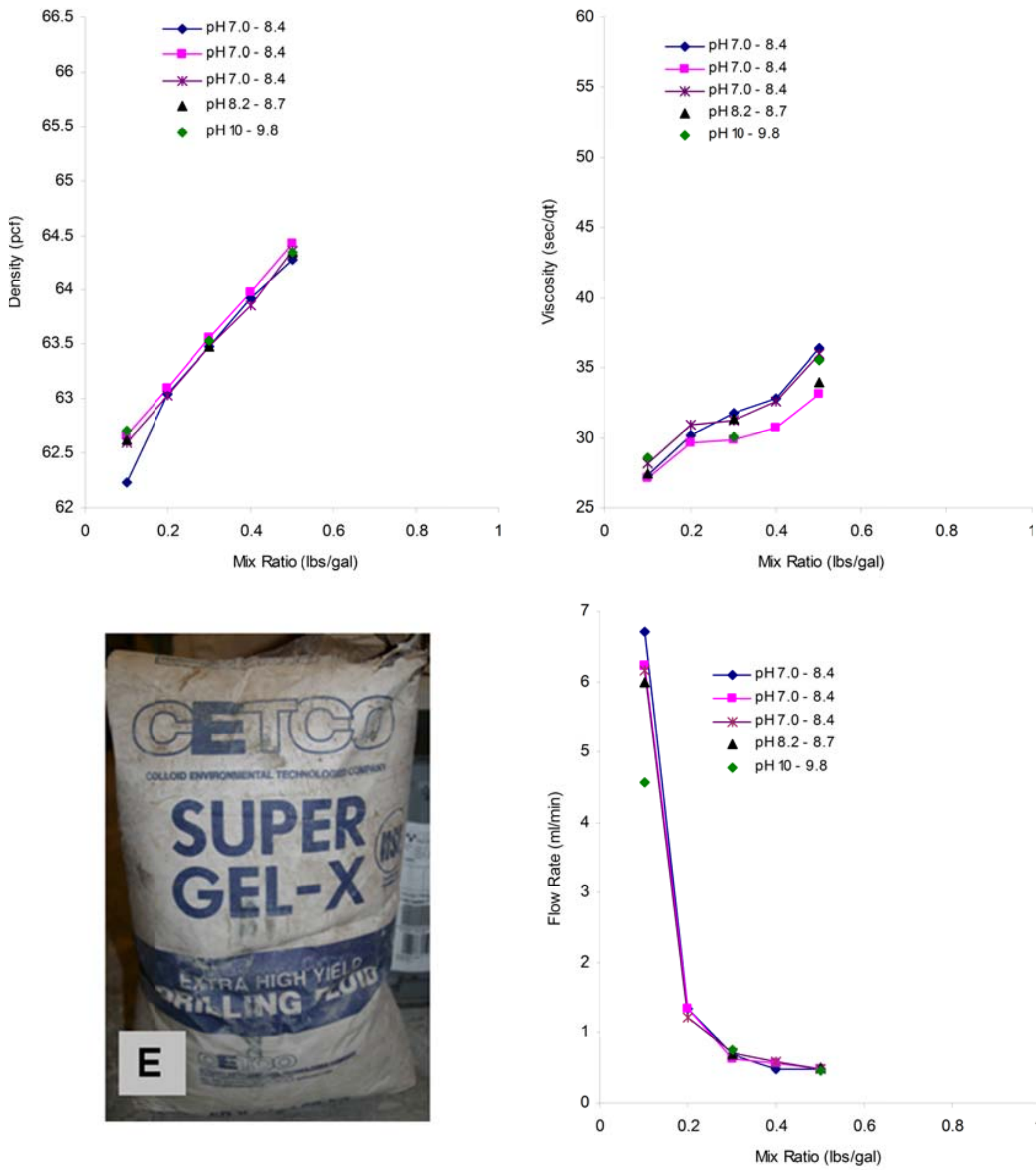

Figure 3.11 Super Gel-X slurry testing results.

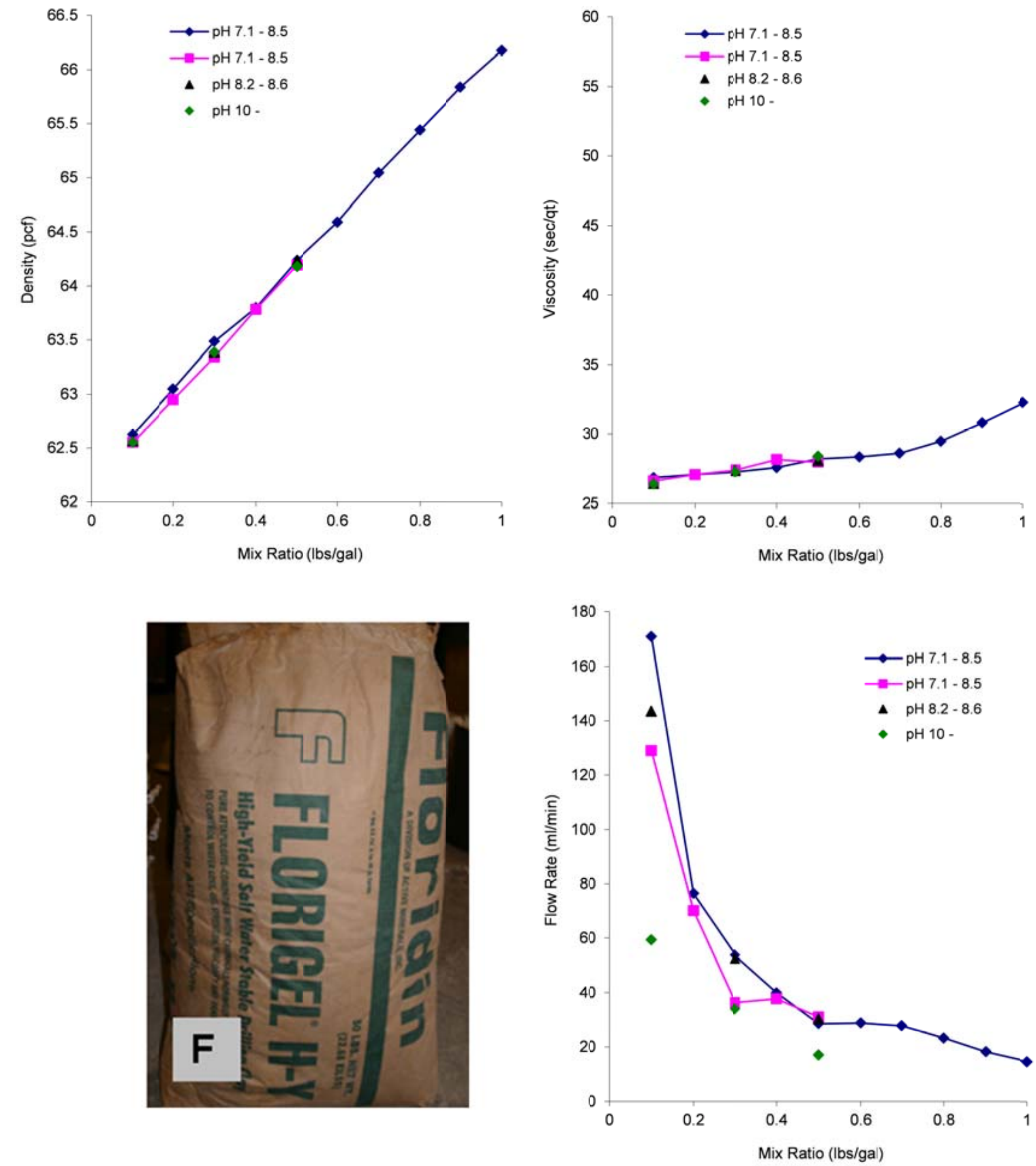

Figure 3.12 Florigel High Yield slurry testing results.

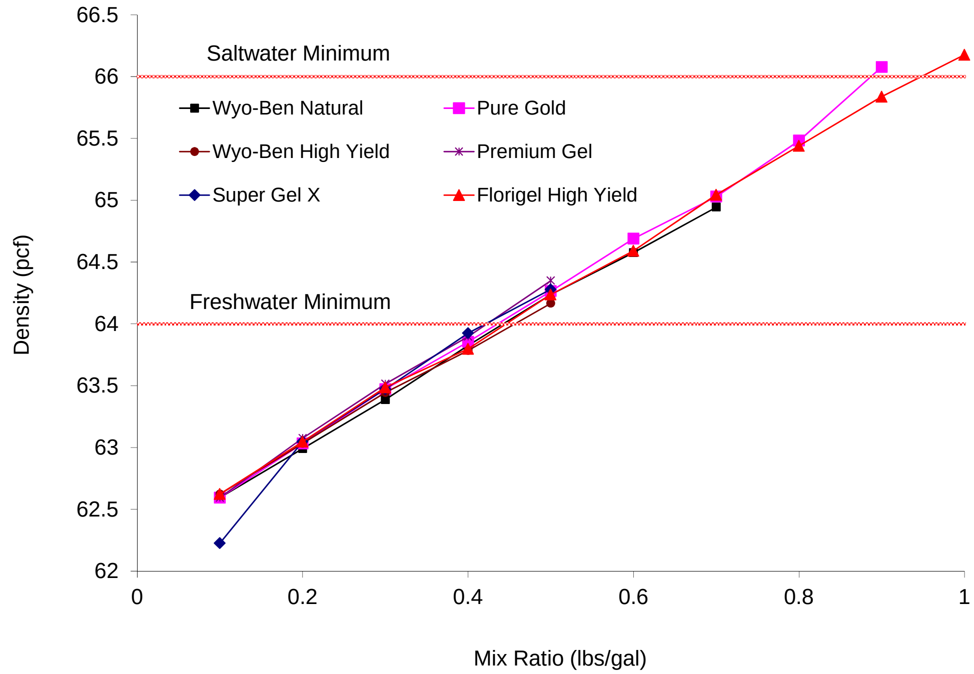

Figure 3.13 Density versus mix ratio comparison of each product.

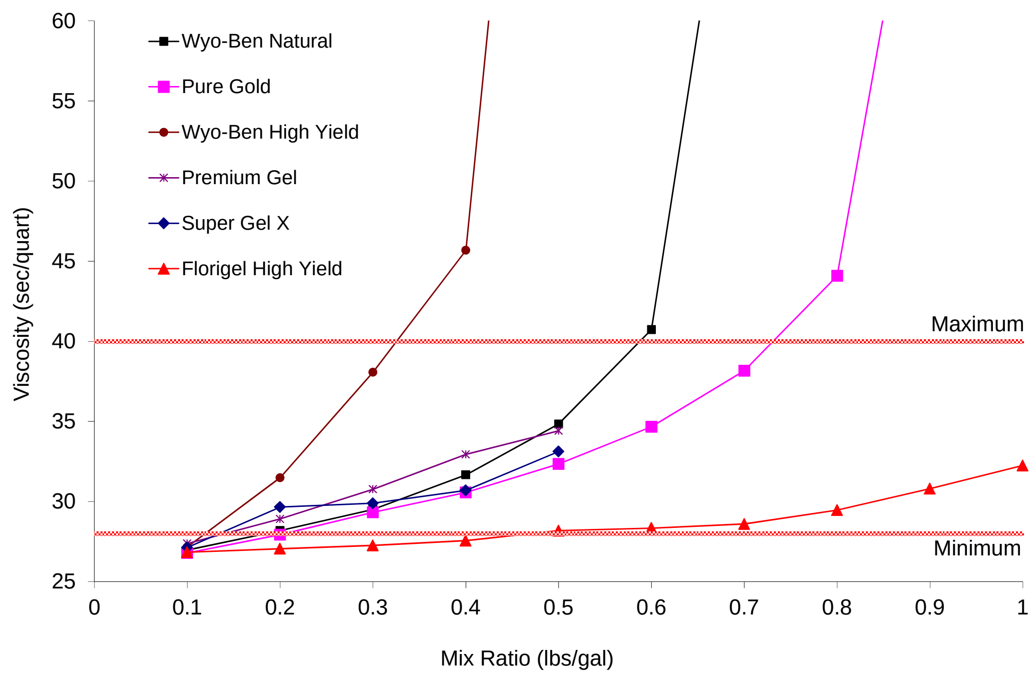

Figure 3.14 Viscosity versus mix ratio comparison of each product.

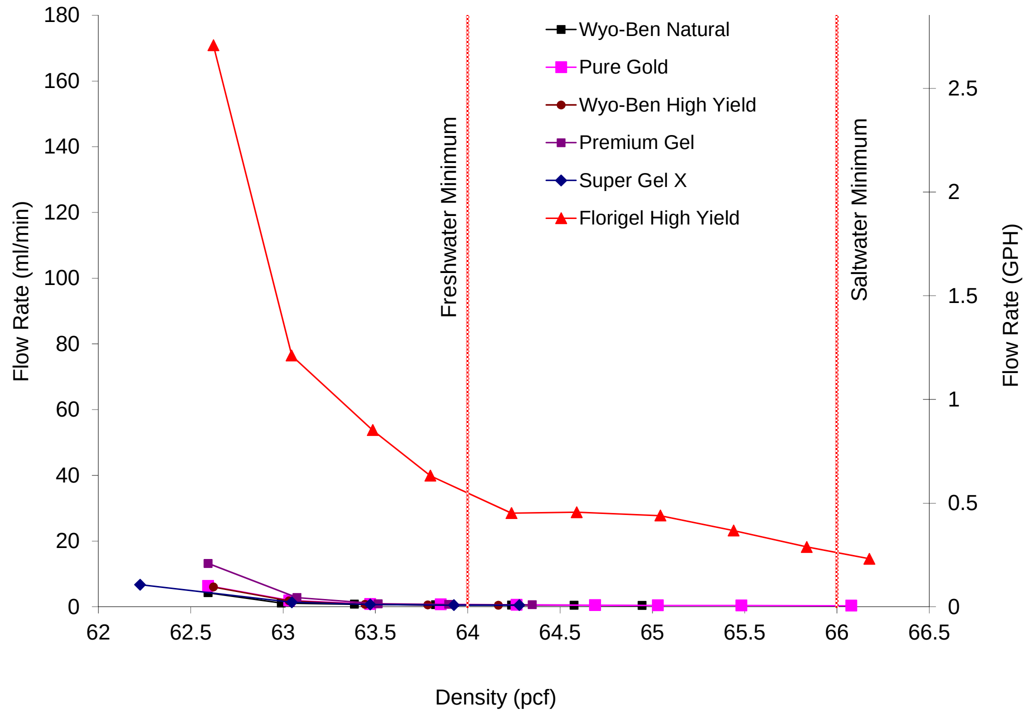

Figure 3.15 Flow rate versus density comparison of each product.

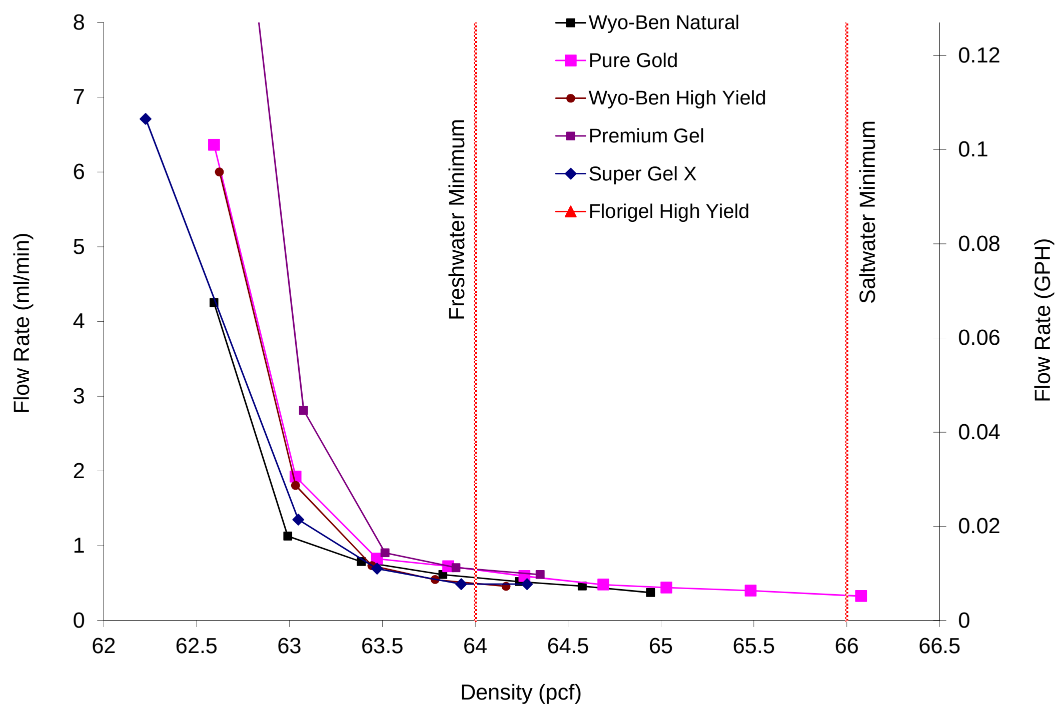

Figure 3.16 Flow rate versus density comparison of each product (excluding attapulgite).

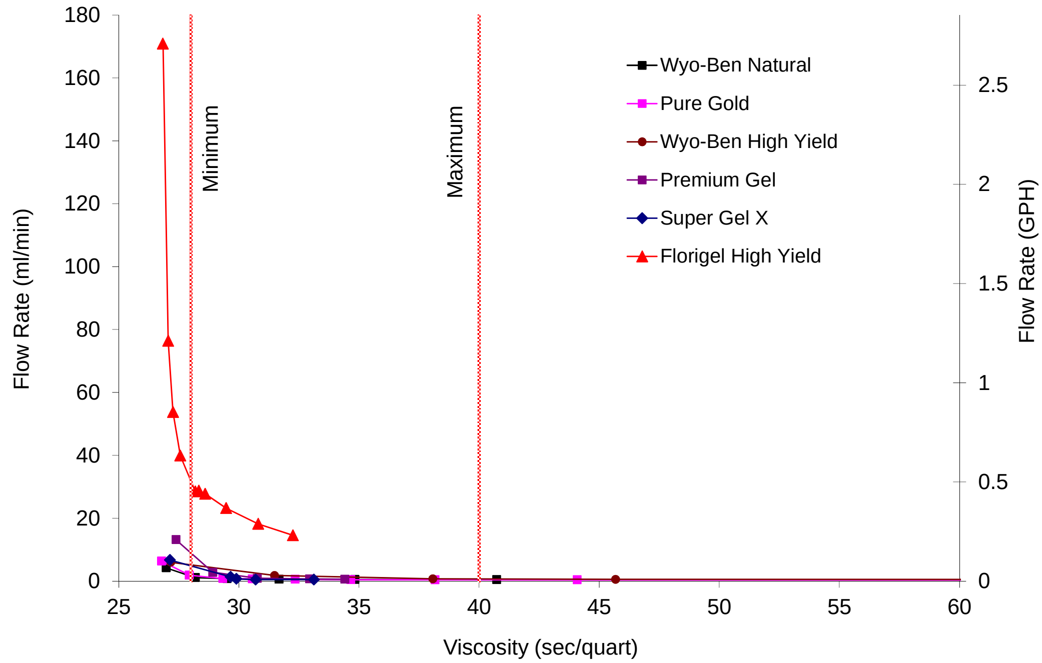

Figure 3.17 Flow rate versus viscosity comparison of each product.

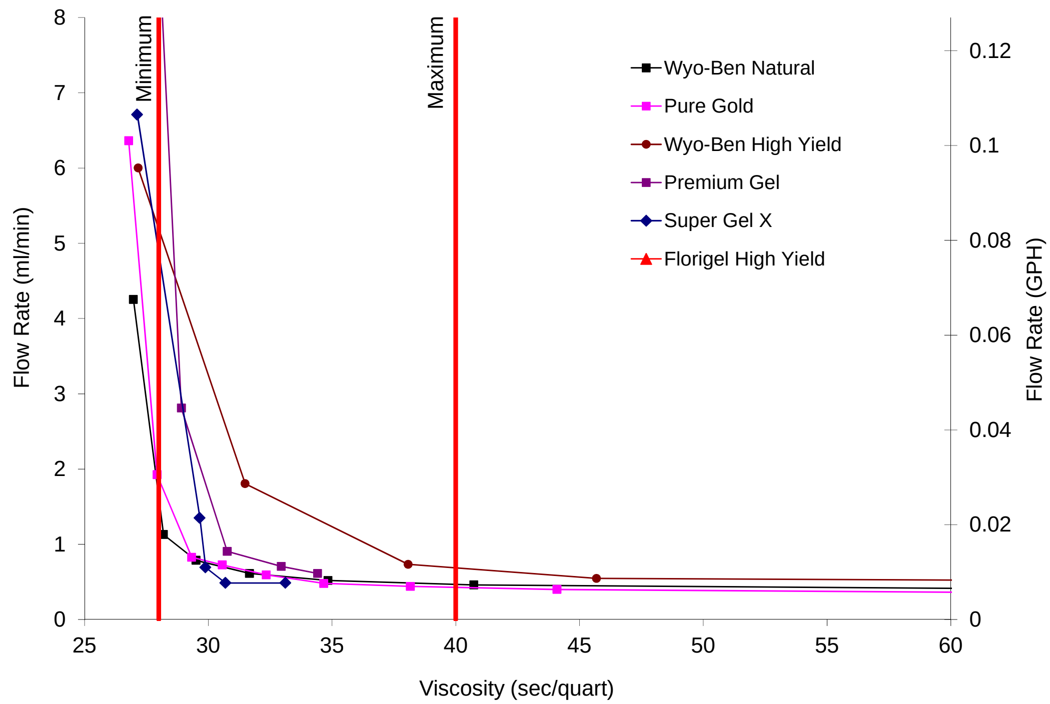

Figure 3.18 Flow rate versus viscosity comparison of each product (excluding attapulgite).

3.5 Filter Press Applied Pressure Evaluation

The original tests conducted used an 80 psi pressure source for the filter press. The standard testing procedures require a constant pressure of 100 psi. This pressure was not available at the time of testing, therefore 80 psi was used. Testing was conducted to determine the effects f varying pressures on the API flow rate. Figures 3.19 through 3.21 show the results from tests performed with varying cell pressures to the API filter press on pure bentonite, high yield, and attapulgite, respectively. Each slurry tested mix ratios of 0.1, 0.2, 0.3, 0.4, and 0.5 lb/gal with water at a pH of 7.1.

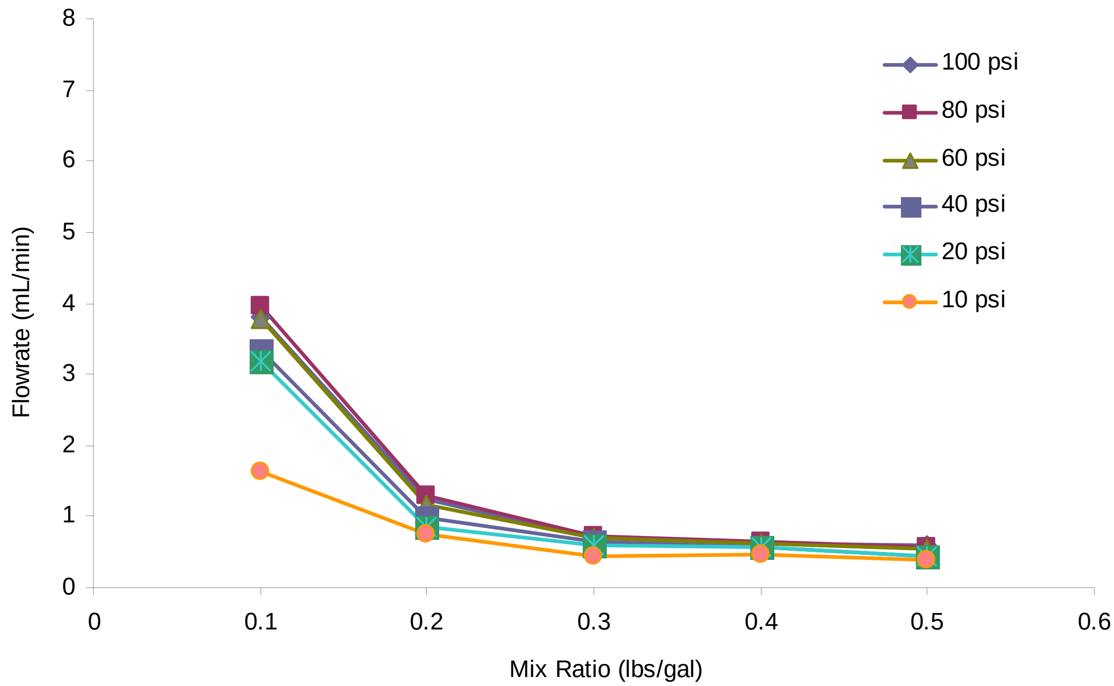

Figure 3.19 API filter press flow rate versus mix ratio at various pressure for pure bentonite slurry.

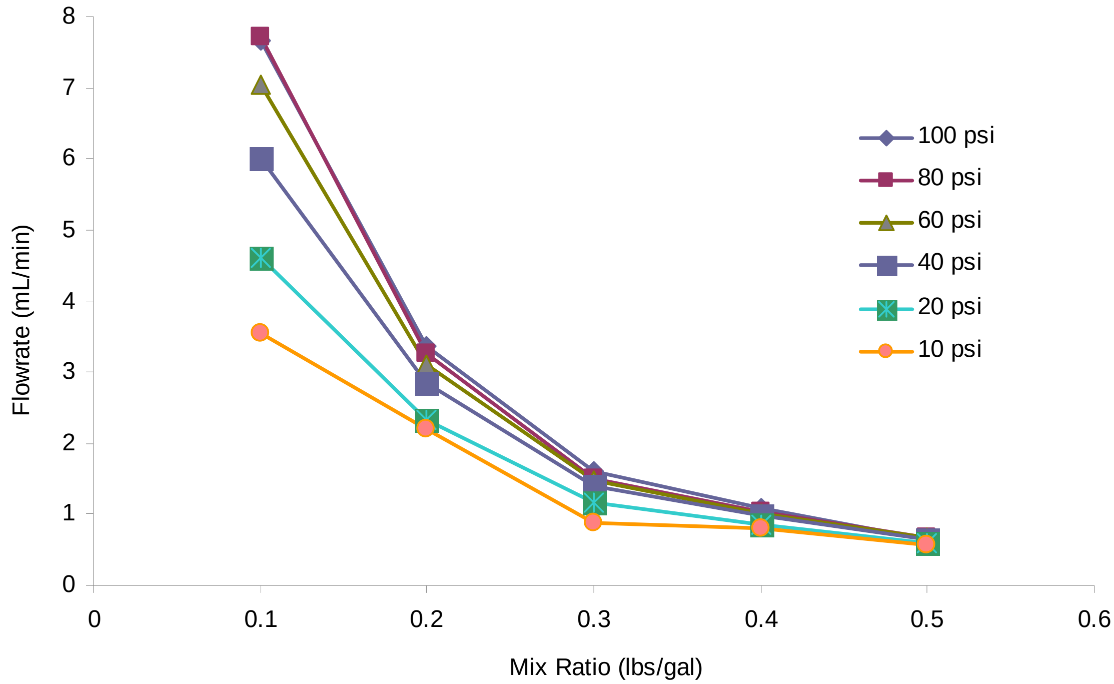

Figure 3.20 API filter press flow rate versus mix ratio at various pressure for high yield slurry.

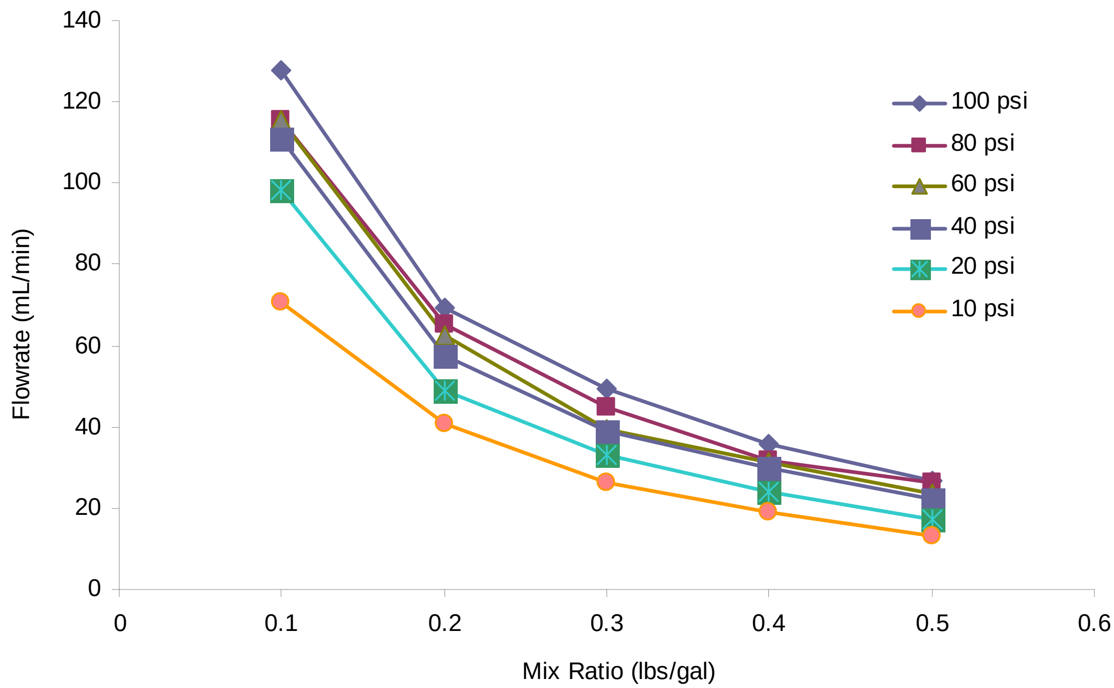

Figure 3.21 API filter press flow rate versus mix ratio at various pressure for attapulgite slurry.

3.6 Filter Press Testing with Slurry Additives

The effect of two additives on slurry viscosity, density, and API filter test flow rate were tested. These products were Wyo-Vis “DP” and NO-SAG suspension enhancer (Figure 3.22). In general, additive concentrations were varied along with the initial bentonite mix ratio such that no more than a 40 sec/qt Marsh funnel viscosity was achieved. Thicker slurries, although often encountered in the field, are usually the product of increased sand content or the effect of natural clay added to slurry. New slurry, prior to introduction into the drilling process, should be comfortably between the standard specification values (28-40 sec/qt) to assure conformance.

Figure 3.22 Polymer additives used for API filter tests.

3.5.1 Wyo-Vis “DP”

Wyo-Vis “DP” is a viscosifier dry powder polymer that is used in water based drilling fluids. When added to a pure bentonite product, the Wyo-Vis “DP” will increase the viscosity of the mixture. It can also be used as a standalone drilling product, although this application was not been investigated.

The manufacturer recommends different mix ratios of Wyo-Vis “DP” based on the pure bentonite mix ratio as well as the application or soil type:

- Fine and medium sands, it is recommended that a mix ratio of 0.2 lb/gal of pure bentonite be used with a additive mix ratio of 0.25 lb of the dry powder polymer per 100 gal of slurry.
- Coarse sand to fine gravel, 0.3 lb/gal of pure bentonite and 0.5 lb of dry powder polymer per 100 gal of slurry.
- Gravel and cobble, 0.4 lb/gal of pure bentonite and 1 lb of dry powder polymer per 100 gal of slurry.

Figure 3.23 shows the effects of Wyo-Vis "DP" on density for a pure bentonite. As expected, the addition of the additive has little to no effect on the density. The deviations in the graphs likely stem from normal laboratory variability and do not exceed 0.2 pcf. This effect on the density was to be expected, as the amount of dry powder added relative to the amount of pure bentonite added was extremely small. Other additives designed to increase density due exist but these are not the focus of this study and were not tested.

Figure 3.24 shows the effect of the Wyo-Vis "DP" on viscosity for a pure bentonite product. Even with an extremely small amount of the polymer being added the viscosity exhibited a significant increase.

Figures 3.25 and 3.26 show there was a significant change in the API filter test flow rate for mix ratios of 0.1 and 0.2 lb/gal, but not a very noticeable effect for the 0.3 and 0.4 lb/gal mix ratios. In Figure 3.25, each data set has four data points that correspond to the varied concentrations of additive where the left most point represents the lowest concentration and the right most point represents the highest. The concentration for each point and each data set can be obtained from Figure 3.26.

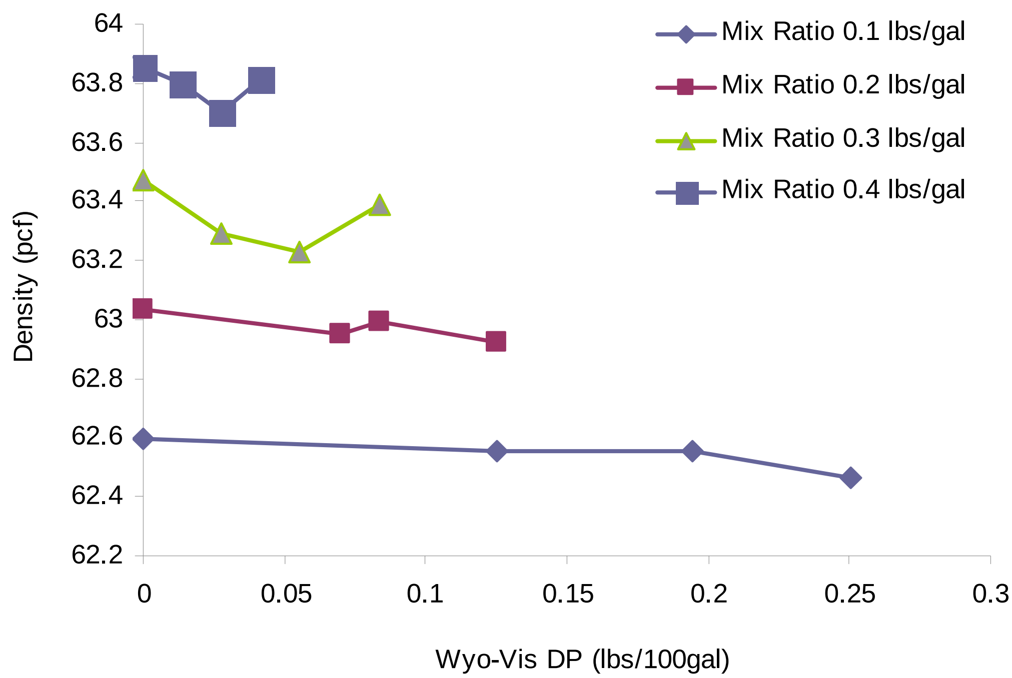

Figure 3.23 Effect of Wyo-Vis “DP” on density for a pure bentonite product.

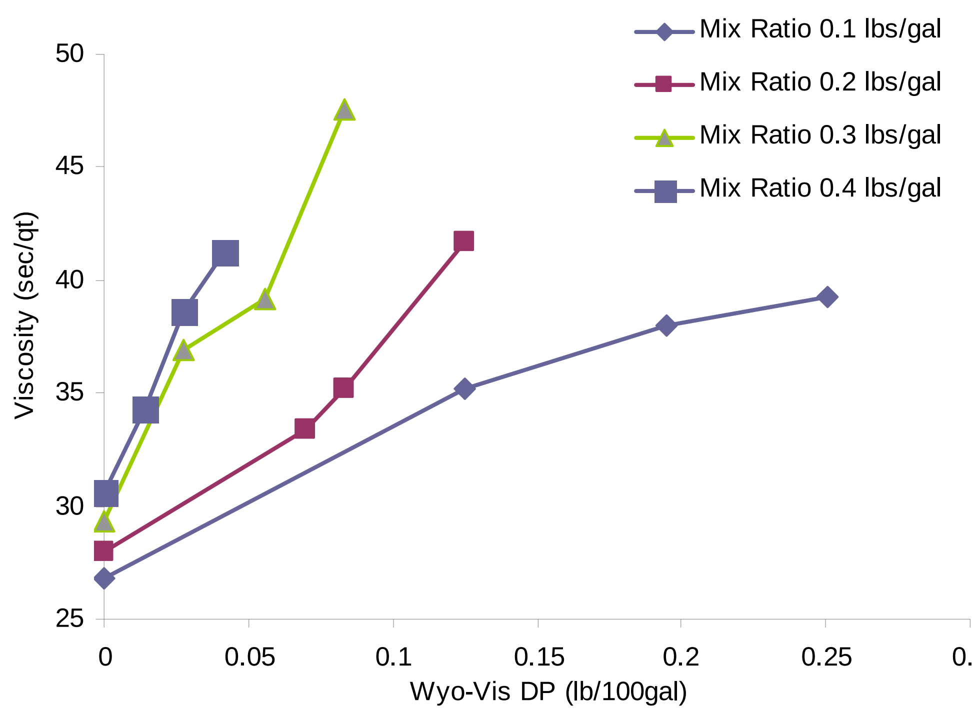

Figure 3.24 Effect of Wyo-Vis “DP” on viscosity for a pure bentonite product.

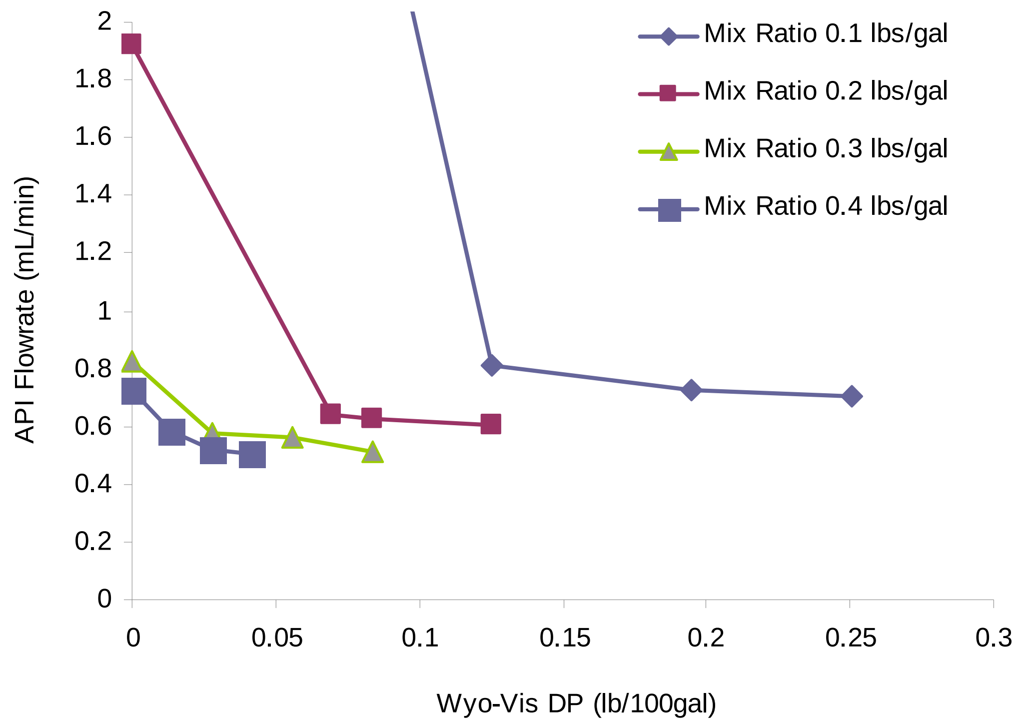

Figure 3.25 Effect of Wyo-Vis “DP” on API Filter test flow rate for a pure bentonite product.

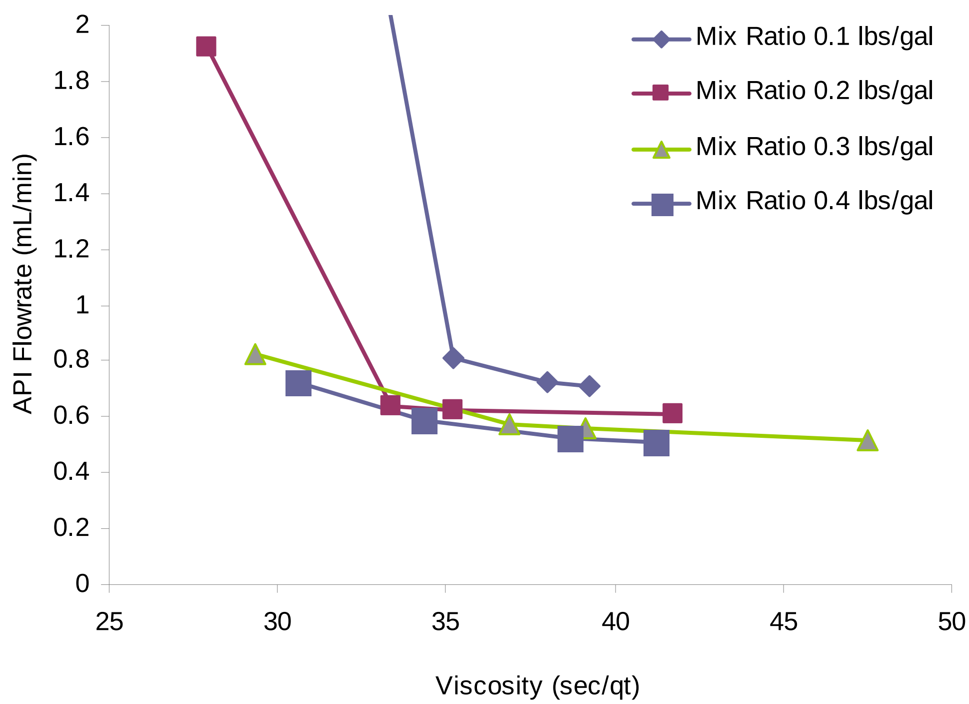

Figure 3.26 Viscosity versus API Filter test flow rate for a pure bentonite product modified with Wyo-Vis “DP”.

3.5.2 NO-SAG Suspension Enhancer

Another additive product tested was the NO-SAG suspension enhancer. The purpose of this additive is to increase the carrying capacity of the bentonite products while not having a large increase to the viscosity. The manufacturer recommends mix ratios for a bentonite product to range from 0.5 lb/100 gal to 1.5 lbs/100 gal.

Figure 3.27 shows the effects of the suspension enhancer on the density of a pure bentonite product. The addition of the additive has little to no effect on the density. This is to be expected, as the amount of suspension enhancer added relative to the amount of bentonite added is extremely small and is similar to the findings of the other additive tested.

Figure 3.28 shows the effects of the suspension enhancer on the viscosity of a pure bentonite product. The effects are apparent that the suspension enhancer provides a measureable increase in viscosity, despite the manufacturer's description. A range of 27 sec/qt viscosity without any suspension enhancer versus 38 sec/qt when 1.75 lbs/100 gal of additive was added (mix ratio 0.1 lb/gal). This could prove problematic if the viscosity is already approaching specified upper limits (40 sec). For a mix ratio of 0.3 lb/gal an 18 sec/qt increase was observed.

Figures 3.29 and 3.30 show a significant reduction in the API filter test flow rate resulted with even the smallest amount of additive. In fact, almost no significant reduction in flow rate was observed for the two higher concentrations of suspension enhancer. In Figure 3.30, the left most data point in each data set represents the lowest mix ratio and increases to the right.

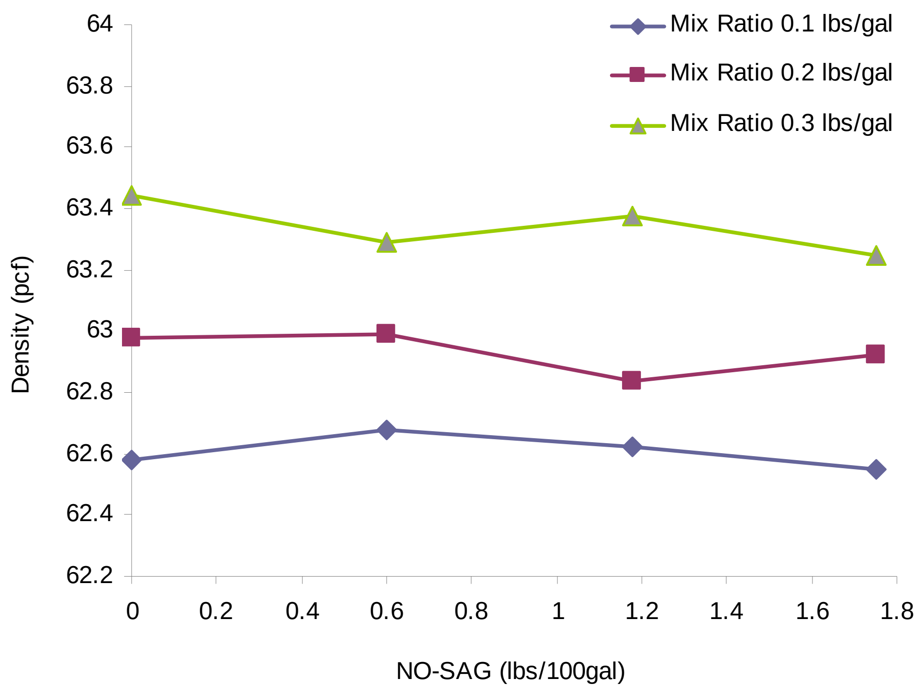

Figure 3.27 Effect of NO-SAG on density for a pure bentonite product.

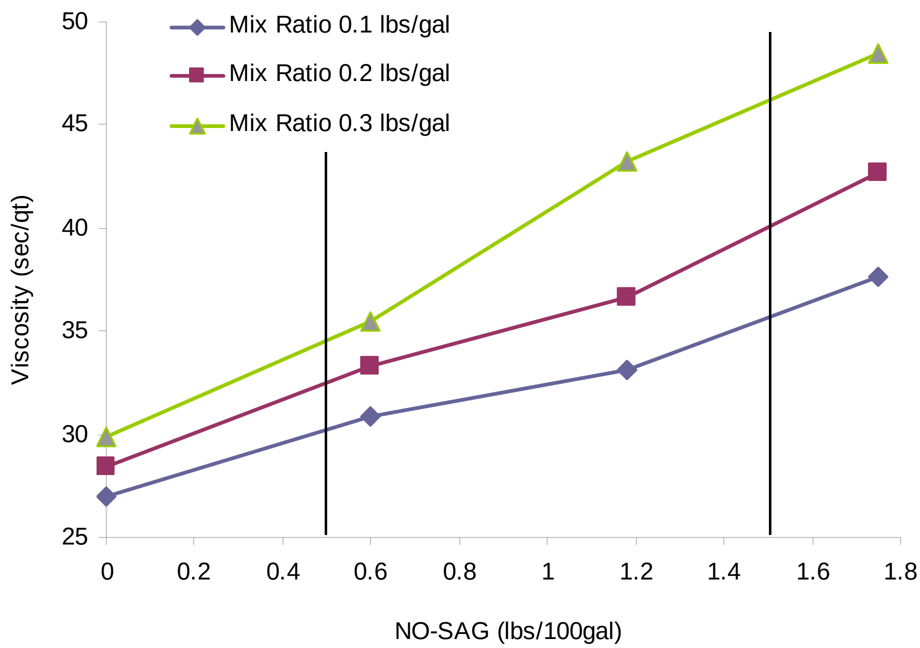

Figure 3.28 Effect of NO-SAG on viscosity for a pure bentonite product.

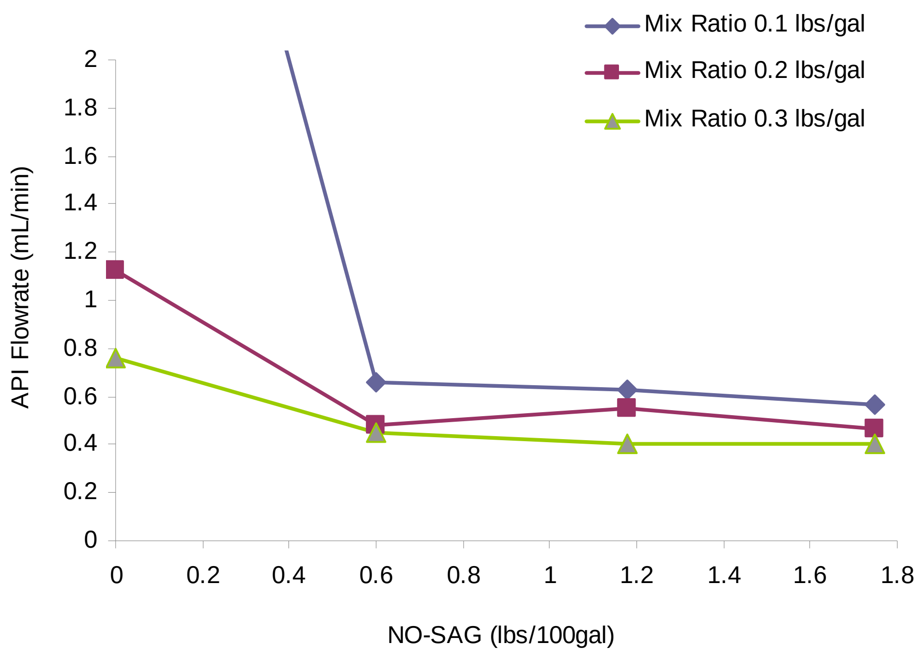

Figure 3.29 Effect of NO-SAG on API Filter test flow rate for a pure bentonite product.

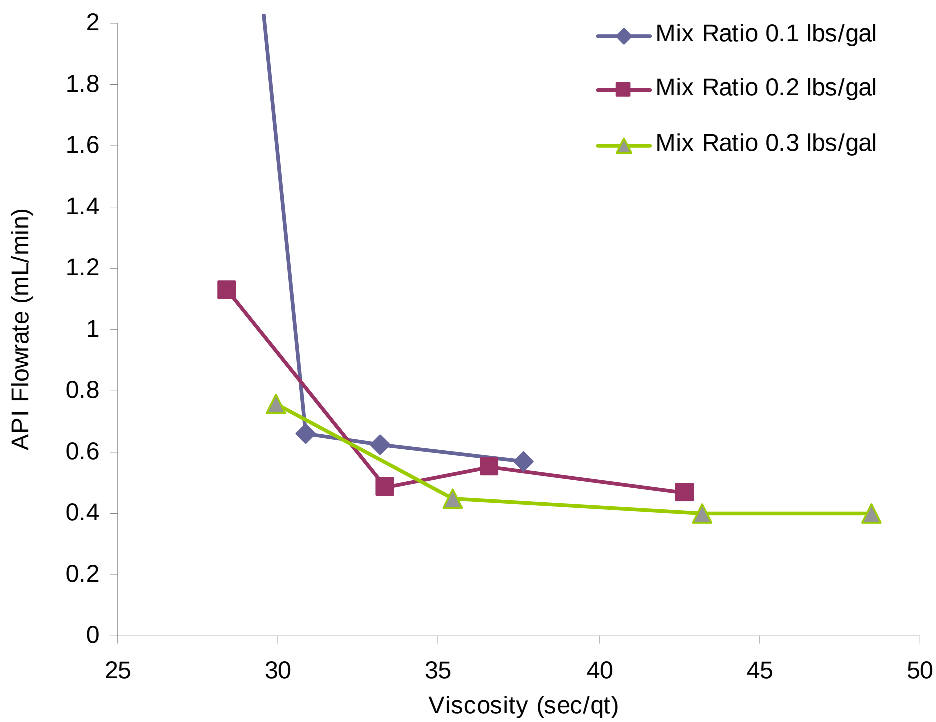

Figure 3.30 API Filter test flow rate versus viscosity for pure bentonite modified with NO-SAG.

Chapter Four: Sand Fallout Testing

This chapter provides an overview of the sand fallout testing performed on the pure bentonite, polymer modified (high yield) and polymer enhanced mineral (hybrid) slurries.

4.1 Large-scale Sand Fallout Testing

4.1.1 Test Setup

A test apparatus was constructed to measure the depth of sand accumulation on the bottom of a column of slurry after given periods of time. The apparatus consisted of a 200 gallon overflow tank, a centrifugal pump, a 13 ft tall 12 in PVC column, and several access ports along the length of the column. Figure 4.1 shows the test apparatus.

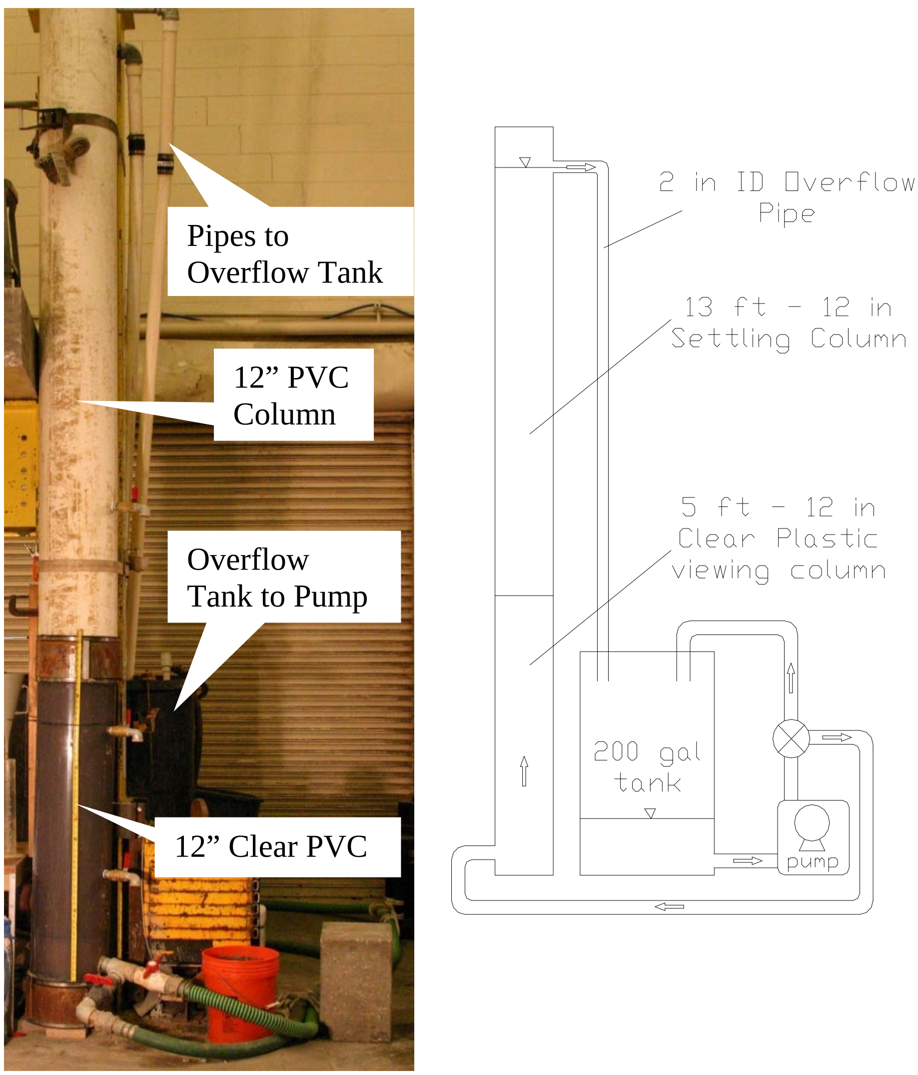

Figure 4.1 Sand settling column.

4.1.2 Product Preparation

A test matrix of readily available mineral slurry products involved five products mixed at ratios ranging from 0.2 to 0.7 lb/gal. Each test involved 150 gallon slurry batches prepared from potable water and dry powder mineral slurry. Slurry mixing was accomplished by re-circulating the fixed volume (150 gallons) of water through a single mixing eductor until the target amount of dry powder (30 – 105 lb) was introduced into solution. Once fully mixed, the valve on the pump was opened, allowing the slurry to circulate from the mixing / overflow tank into the bottom of the PVC column, which filled and overflowed back into the tank. Figure 4.2 shows the products tested.

Figure 4.2 Slurry products tested.

The Marsh funnel viscosity and density of the material were tested for each product similar to the API filter testing procedures. Additional testing included sand content for each test. Figure 4.3 shows the standard API equipment used to determine the sand content of the slurry.

Sand was added to the system incrementally, starting with low sand contents and stepping up throughout the tests to higher sand contents. Initially, sand content was increased by approximately 1% (by volume) per test. Sand was poured into the overflow tank until sand content testing verified the suspended sand content. Figure 4.4 shows the grain size distribution chart for the sand used within the testing. Coarse sand (SP) was selected due to the difficulty associated with suspending such materials.

Figure 4.3 API Sand content testing equipment.

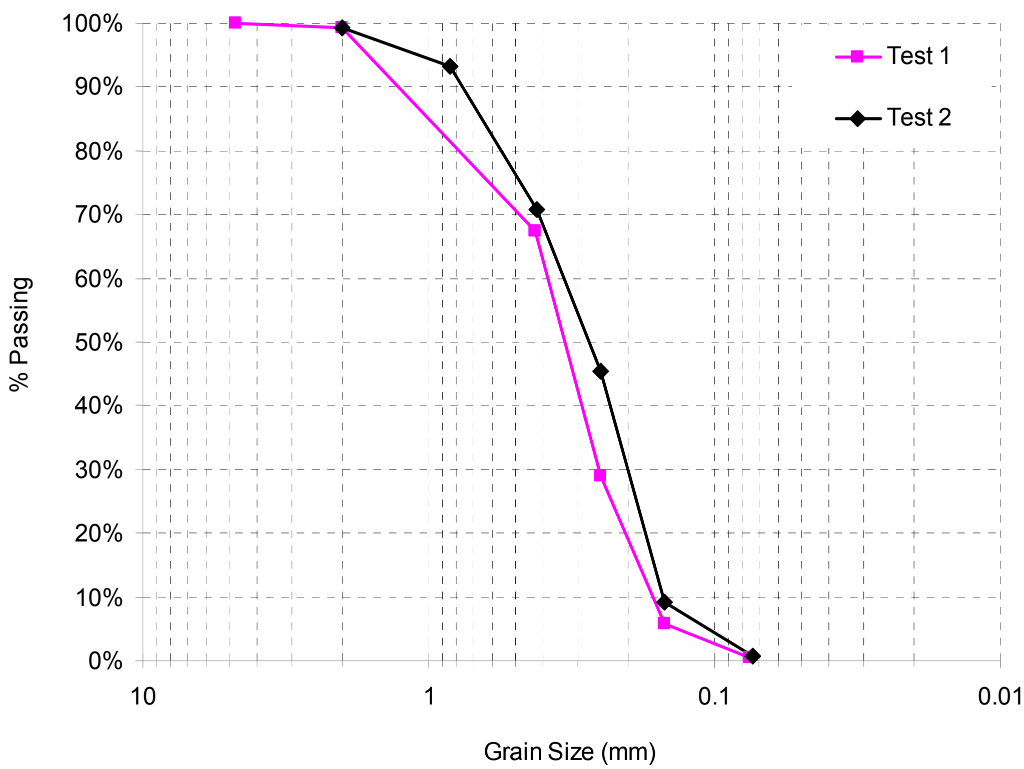

Figure 4.4 Grain size distribution for the sand used in the testing.

4.1.3 Sand Content Testing of Existing Products

Initially, the depth of sand accumulated at the base of the settling column was measured at 1, 2, 5, 10, 30, and 60 minutes after slurry circulation was stopped. The depth of the sand was determined visually by observing the accumulation in the clear portion of the settling column. Figures 4.5 and 4.6 summarize the viscosity, density, and average sand content of the materials tested. The results of the accumulation testing are shown in Figures 4.7 through 4.10.

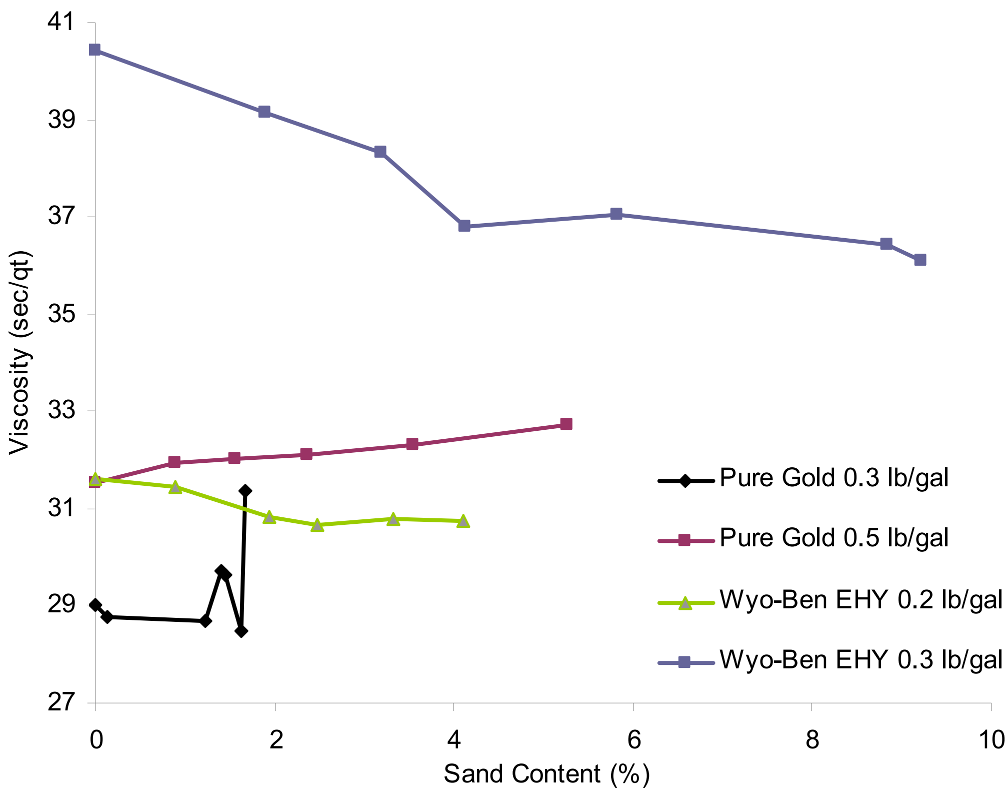

Figure 4.5 Measured sand content versus viscosity.

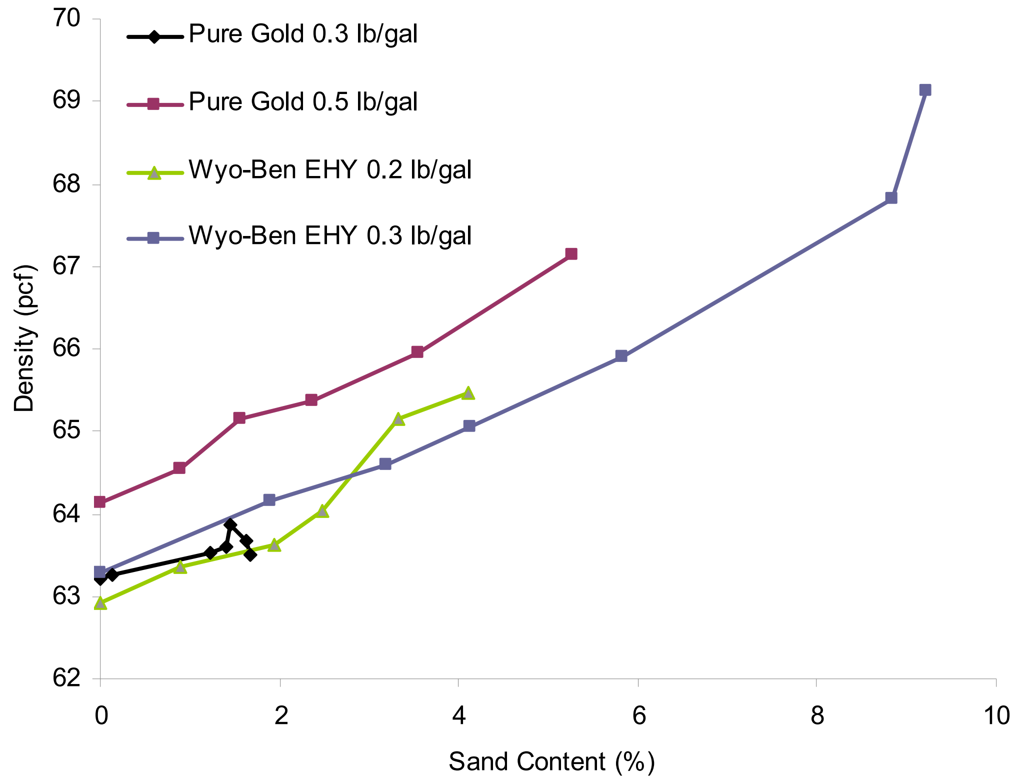

Figure 4.6 Measured sand content versus density.

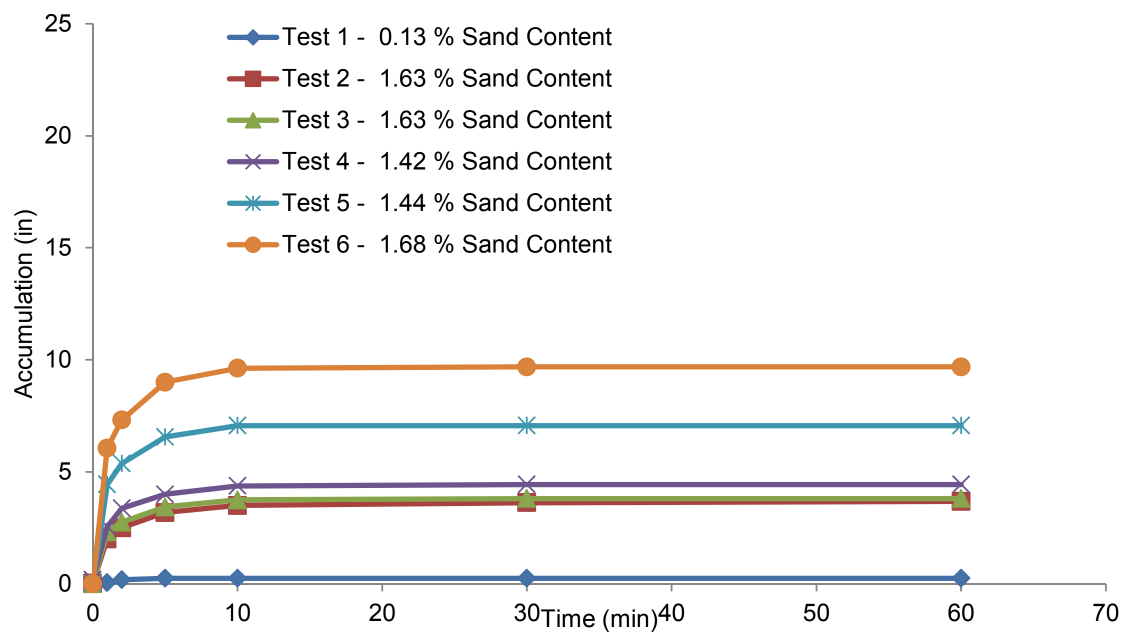

Figure 4.7 Measured accumulation for 0.3 lb/gal PureGold.

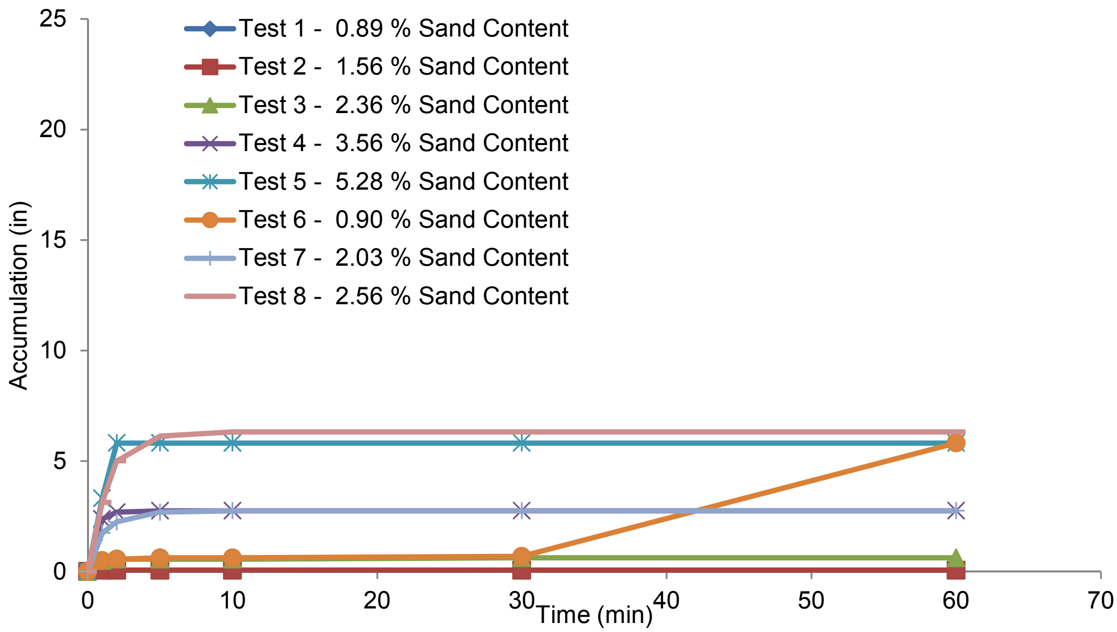

Figure 4.8 Measured accumulation for 0.5 lb/gal PureGold.

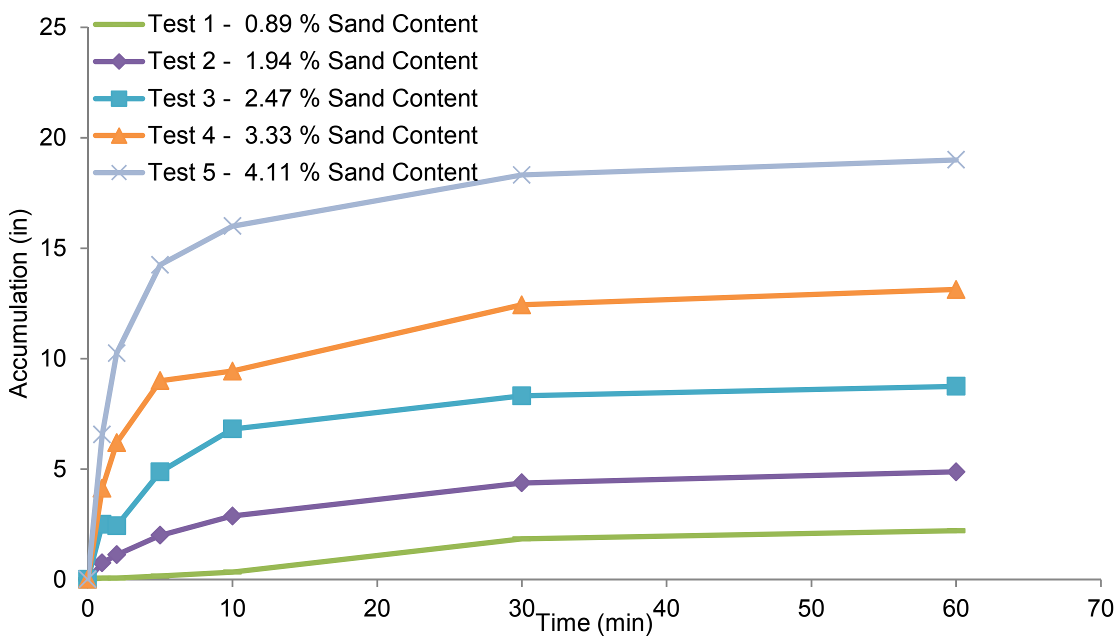

Figure 4.9 Measured accumulation for 0.2 lb/gal Wyo-Ben High Yield.

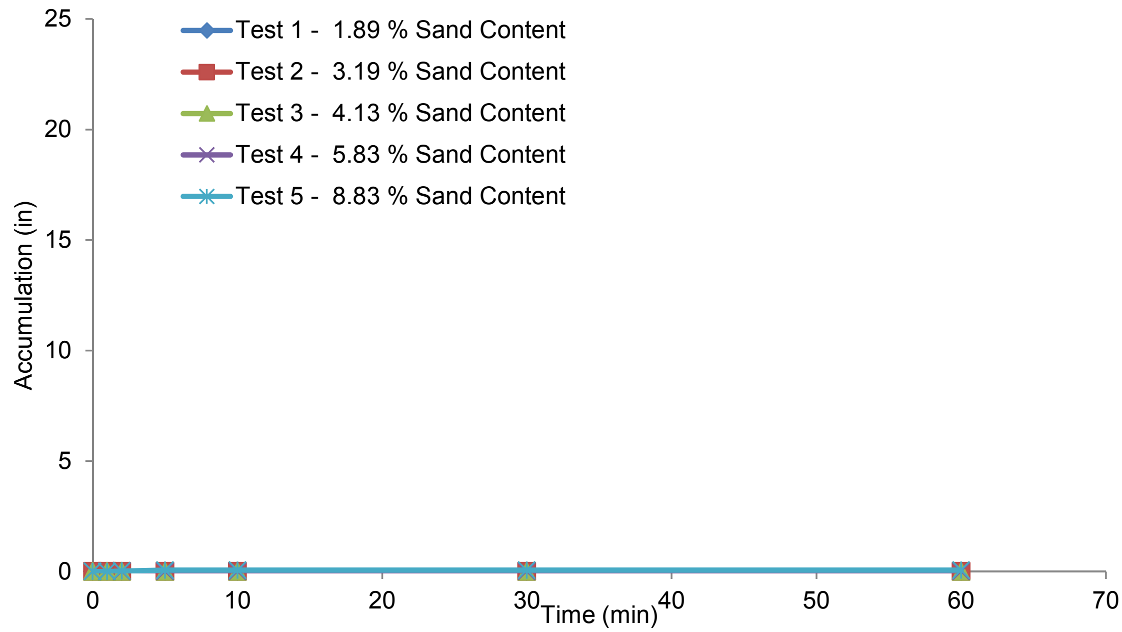

Figure 4.10 Measured accumulation for 0.3 lb/gal Wyo-Ben High Yield.

A polymer drilling slurry product, SlurryPro CDP, was also tested. The manufacturer's recommended mixing ratio for SlurryPro CDP is 0.75 – 1.5 kg/m^3 of mixing water (0.006 – 0.013 lb/gal). The manufacturer's minimum recommended mix ratio was prepared for testing. The pH of the mixing water was adjusted to approximately 10 through the addition of soda ash.

To incorporate approximately 1 lb of polymer drilling powder into 150 gallons of water, a high shear pump and a single eductor was used. The high shear pump and energetic mixing methods cut the polymer strands, and the viscosity of the material varied over time after mixing was terminated. The viscosity and density were monitored for two hours following mixing, and the results of the testing are shown in Figures 4.11 and 4.12.

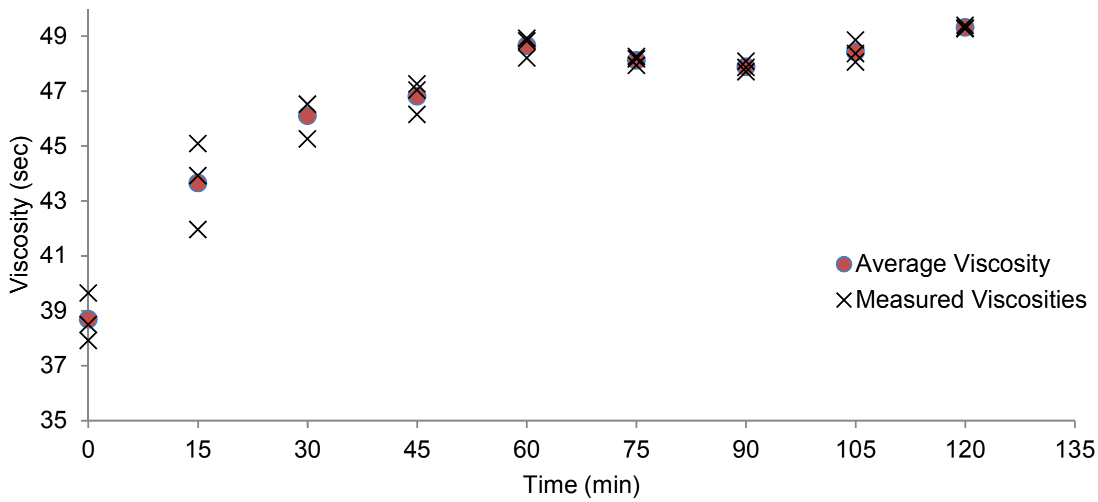

Figure 4.11 Polymer viscosity recovery following high shear mixing.

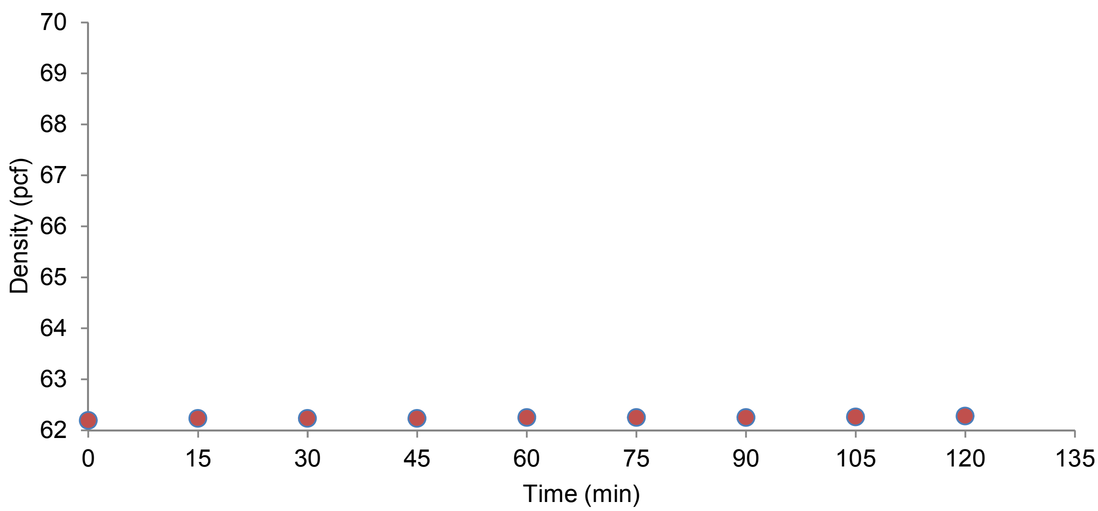

Figure 4.12 Polymer density recovery following high shear mixing.

4.2 Sand Content Testing Versus Depth

Following the accumulation testing of low viscosity slurries, higher viscosity slurries were tested. However, with the increased amount of slurry powder incorporated into the water, determining the accumulation accurately over time proved extremely difficult. To continue to describe the sand suspension properties, several ports were placed along the height of the column. The ports were placed at the bottom of the column, ¾ the distance from the top of slurry, and ½ the distance from the top of slurry. Figures 4.13 and 4.14 show the ports drilled and tapped into the clear portion of the settling column.

Figure 4.13 Sand content port.

Figure 4.14 Sand content ports on transparent PVC column.

Mixing of slurry was accomplished through the use of a high shear pump, in the same manner as with lower viscosity mineral drill slurries. Once mixing was completed and the desired amount of sand had been incorporated, the mixing was stopped, and the sand content was measured at each port as well as the top of slurry.

4.2.1 Existing Product Testing

A high viscosity pure bentonite product (0.7 lb/gal mix ratio) was tested which started with a viscosity of 38.5 sec/qt with no sand. Slurry samples were taken from each port along the height of the column and sand contents were determined over various time periods. The results generated while testing this material are presented in Figures 4.15 through 4.20.

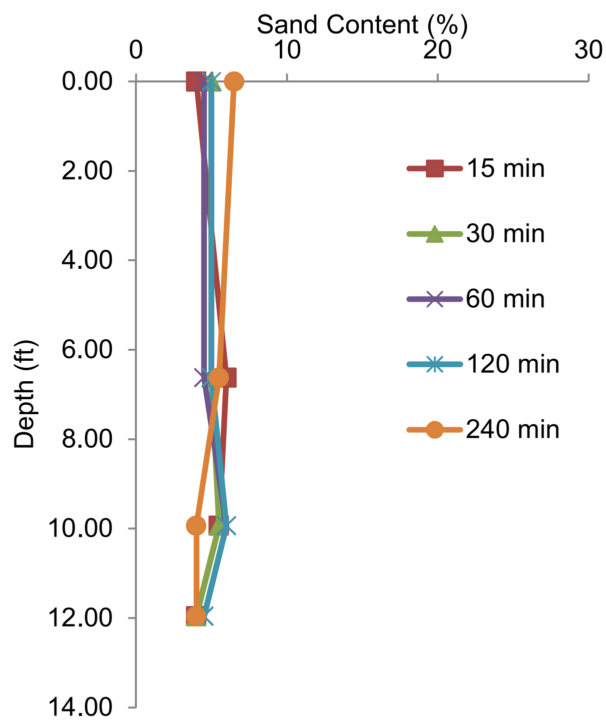

Figure 4.15 Measured sand content versus depth (4.9% overall starting sand content).

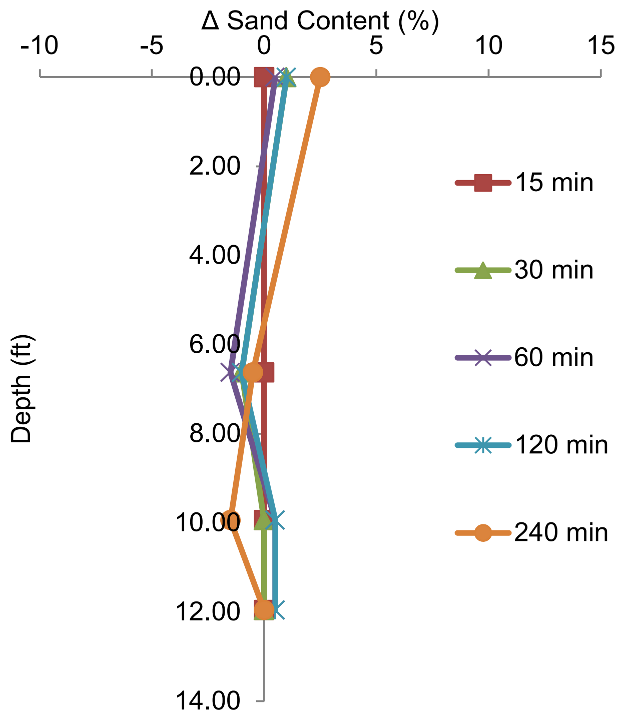

Figure 4.16 Change in sand content versus depth (4.9% overall starting sand content).

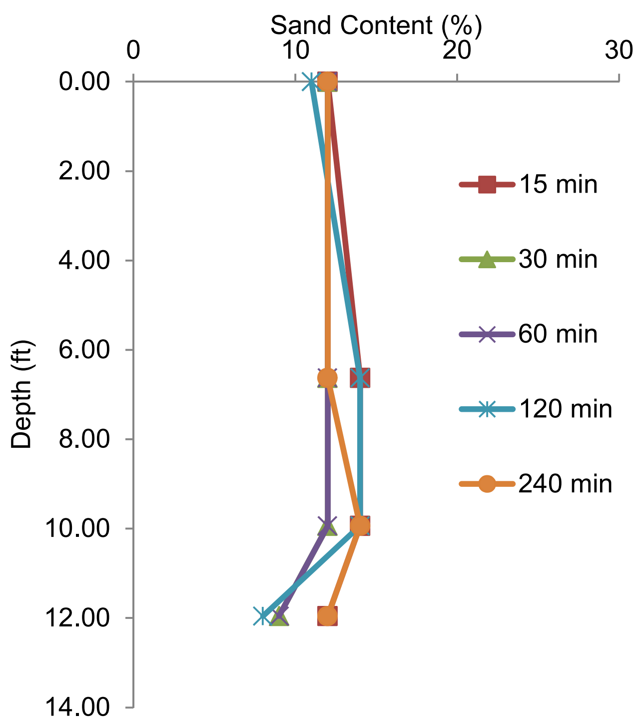

Figure 4.17 Measured sand content versus depth (13% overall starting sand content).

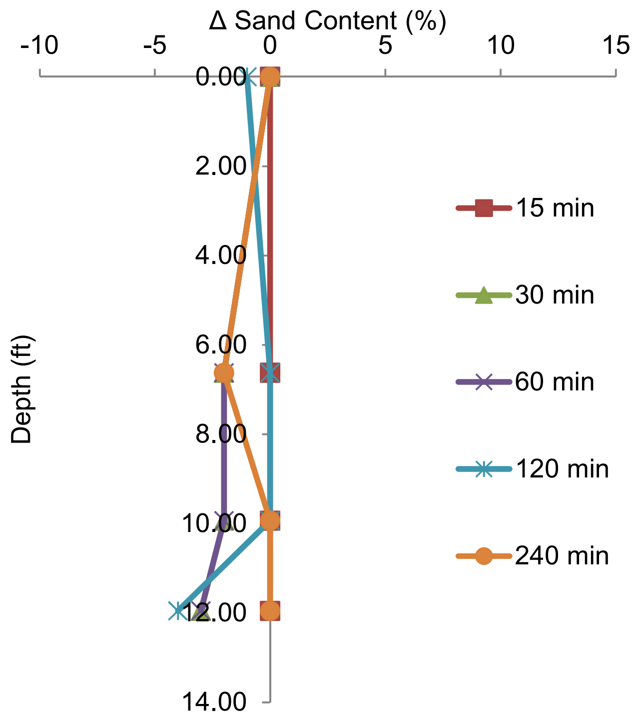

Figure 4.18 Change in sand content versus depth (13% overall starting sand content).

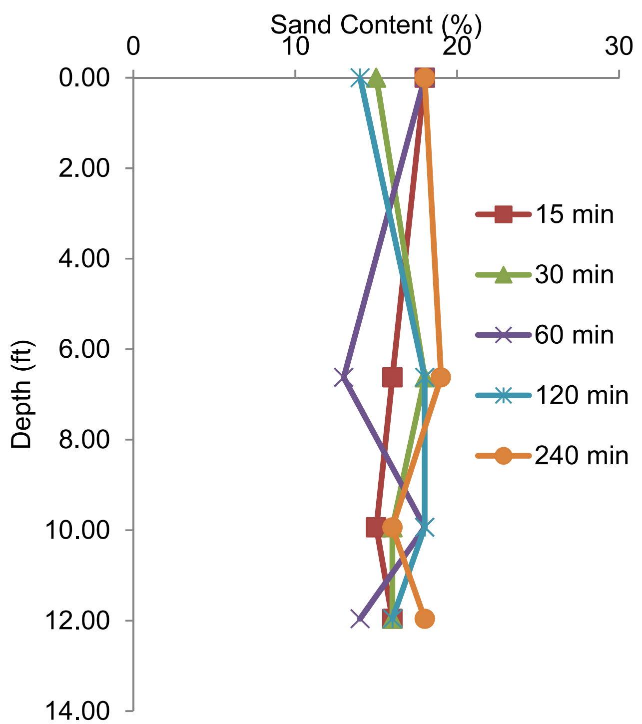

Figure 4.19 Measured sand content versus depth (16.25% overall starting sand content).

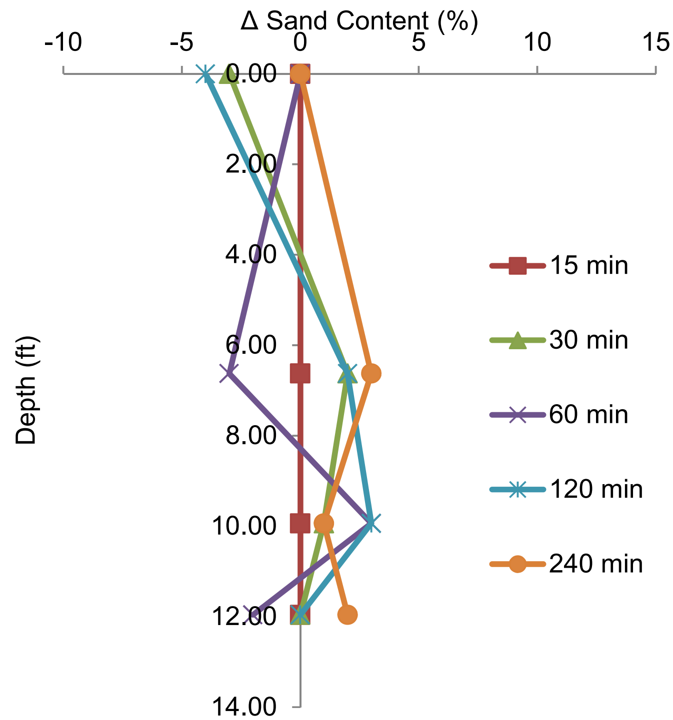

Figure 4.20 Change in sand content (16.25% overall starting sand content).

The change in sand content over time at each location varied only slightly indicating sufficient suspension strength (gel strength). Variations in the results are in keeping with the level of sophistication associated with the test method. However, the test procedure was slightly altered to reduce the amount of material drawn during each test, as well as the frequency of testing to minimize the effects of over sampling and causing needless disturbance to the settling process.

A new batch of slurry mixed at 0.6 lb/gal was produced wherein the decreased frequency testing program was instituted. Prior to testing, the viscosity and density of the slurry was tested over time at each of the sand content ports, as well as the top. The viscosity and density of the material at each location over time proved to be roughly constant. The test results are shown in Figures 4.21 and 4.22.

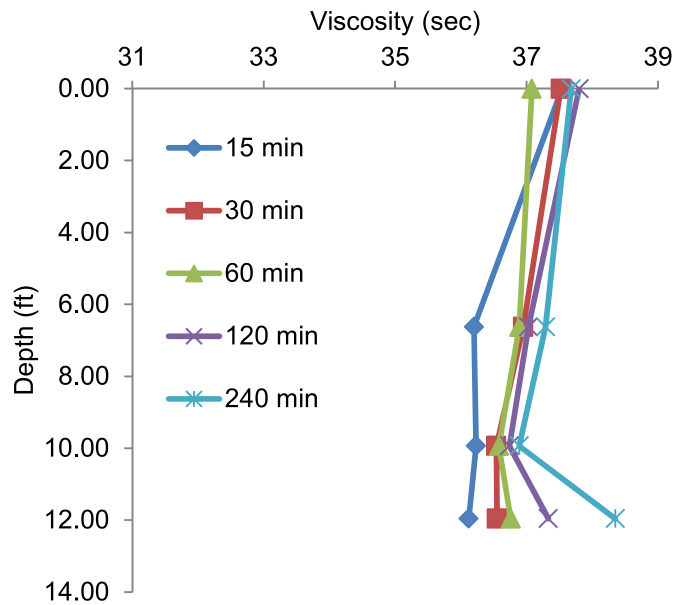

Figure 4.21 Initial viscosity measurements for 0.6 lb/gal

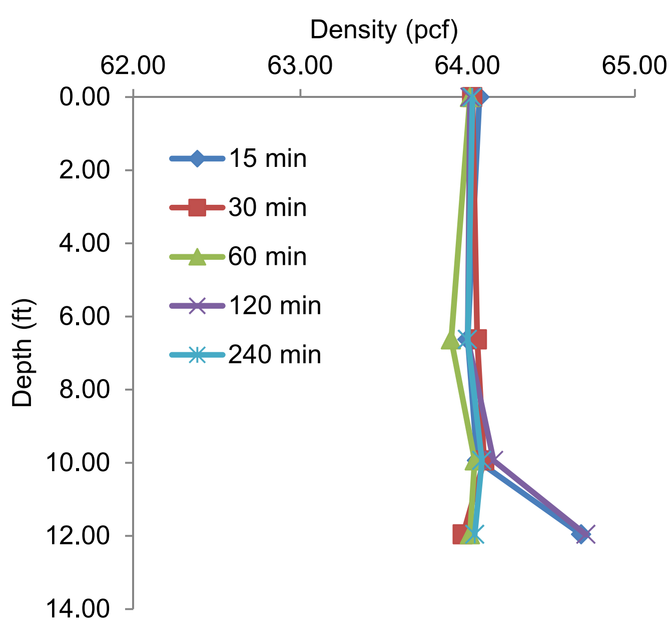

Figure 4.22 Initial density measurements for 0.6 lb/gal

Knowing the viscosity and density are roughly constant over time at each depth of interest, the decreased frequency sand content testing commenced. These tests produced similar results to those shown above wherein only subtle changes in sand content were observed. Figures 4.23 through 4.30 show the results at various sand contents tested.

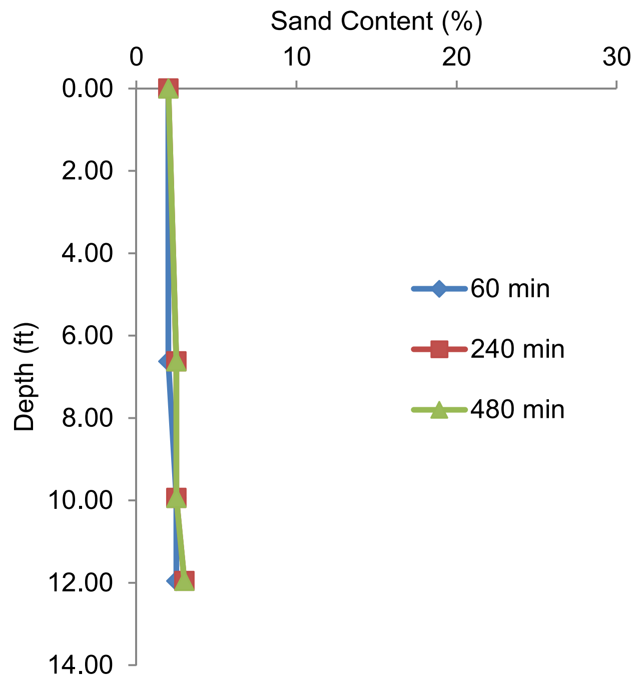

Figure 4.23 Measured sand content (2.25% overall starting sand content).

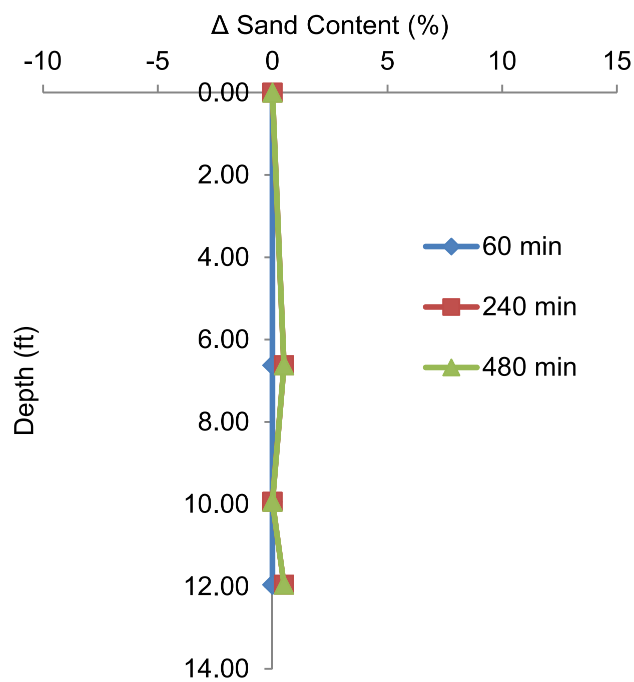

Figure 4.24 Change in sand content (2.25% overall starting sand content).

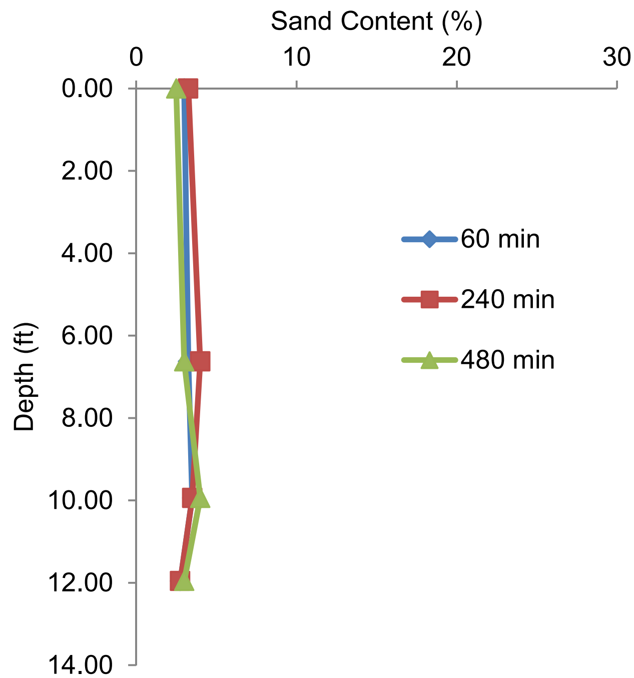

Figure 4.25 Measured sand content (3.1% overall starting sand content).

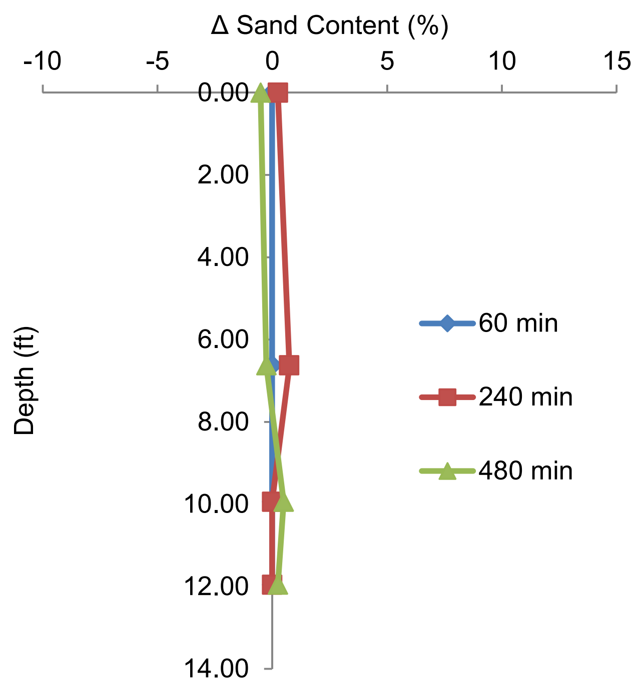

Figure 4.26 Change in sand content (3.1% overall starting sand content).

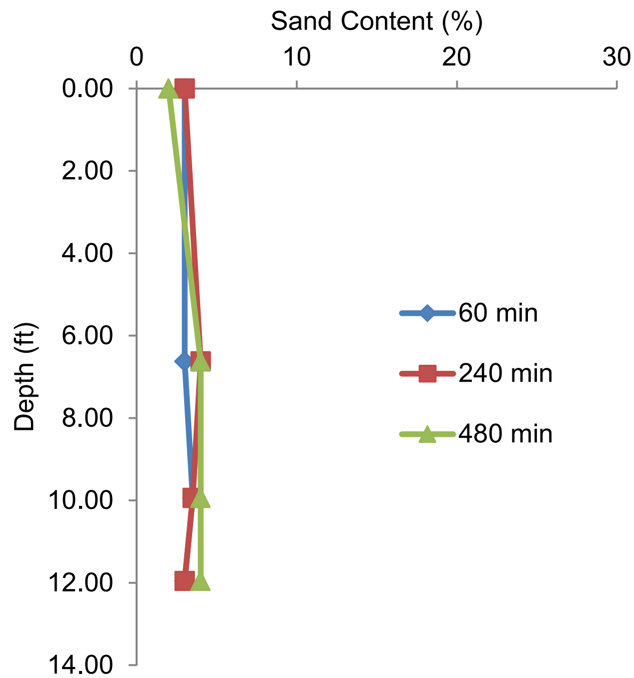

Figure 4.27 Repeated measured sand content (3.1% overall starting sand content).

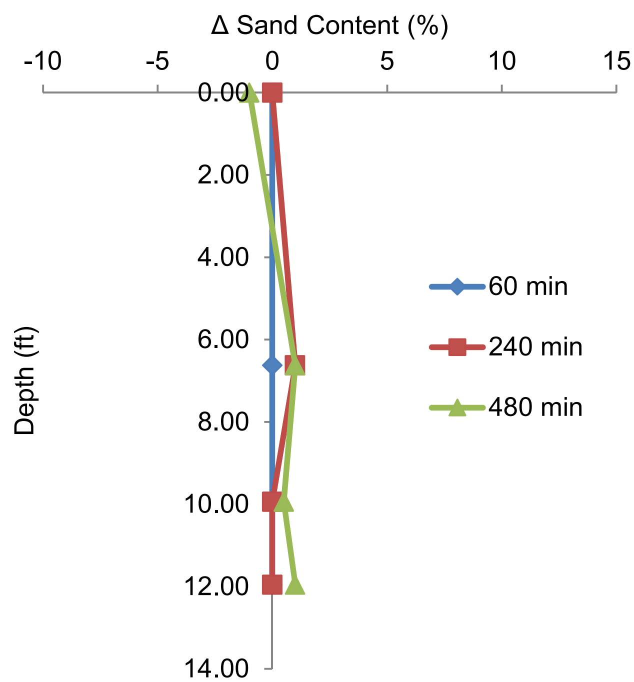

Figure 4.28 Repeated change in sand content (3.1% overall starting sand content).

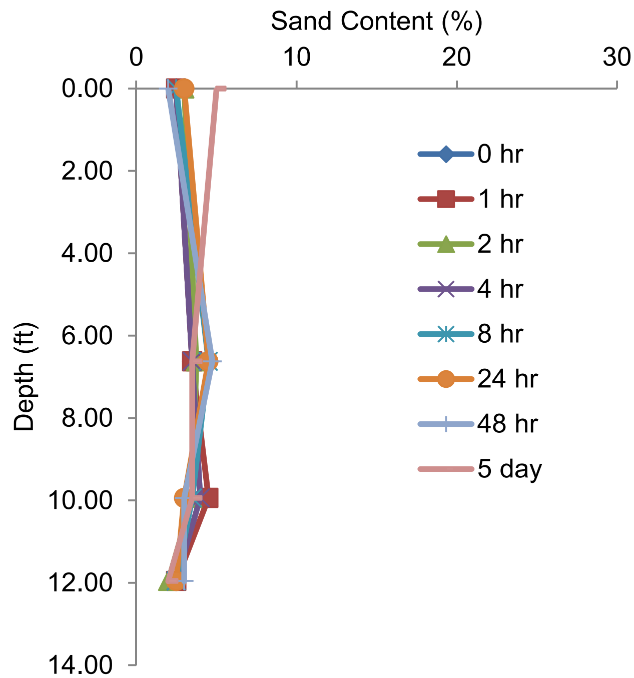

Figure 4.29 Repeated measured sand content (3.1% overall starting sand content).

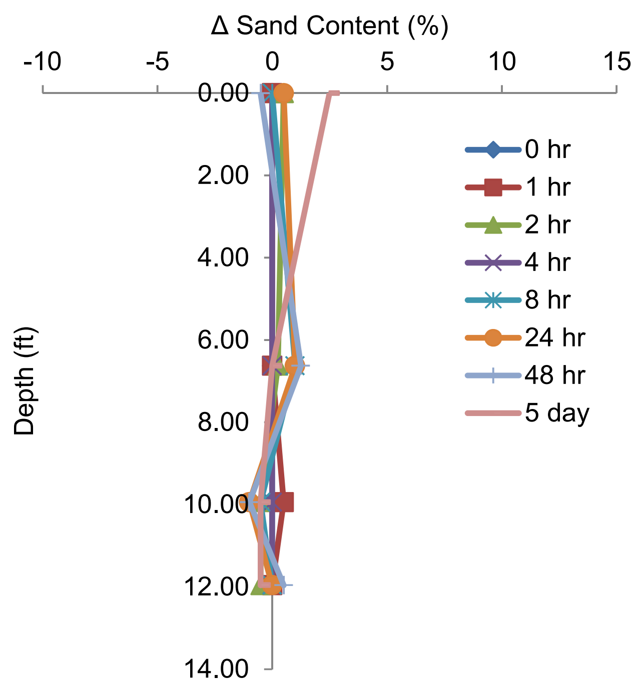

Figure 4.30 Repeated change in sand content (3.1% overall starting sand content).

Continued testing with the large-scale settling column was performed but with a polymer fortified bentonite material. This material, Wyo-Ben Extra High Yield Bentonite, was tested at a mix ratio of 0.3 lb/gal. This material had an initial average viscosity of 40 sec. The measured sand content and the change in sand content for varying initial average sand content are shown in Figures 4.31 through 4.34.

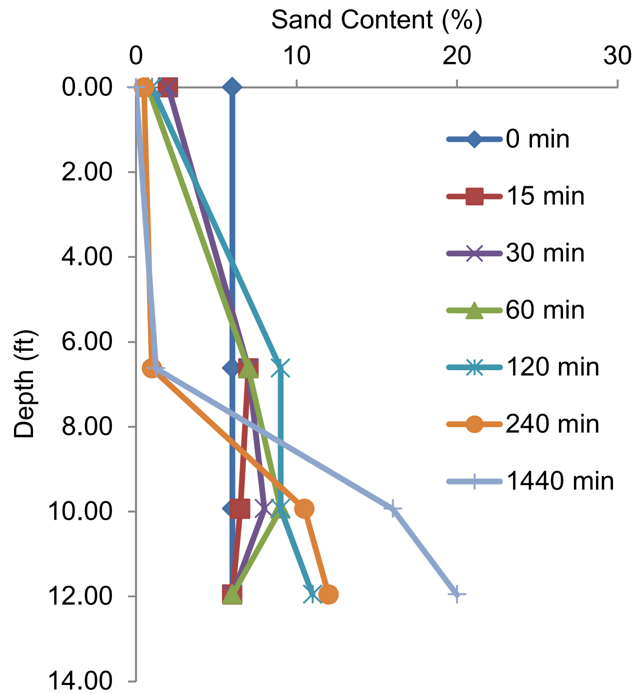

Figure 4.31 Measured sand content (6% overall starting sand content).

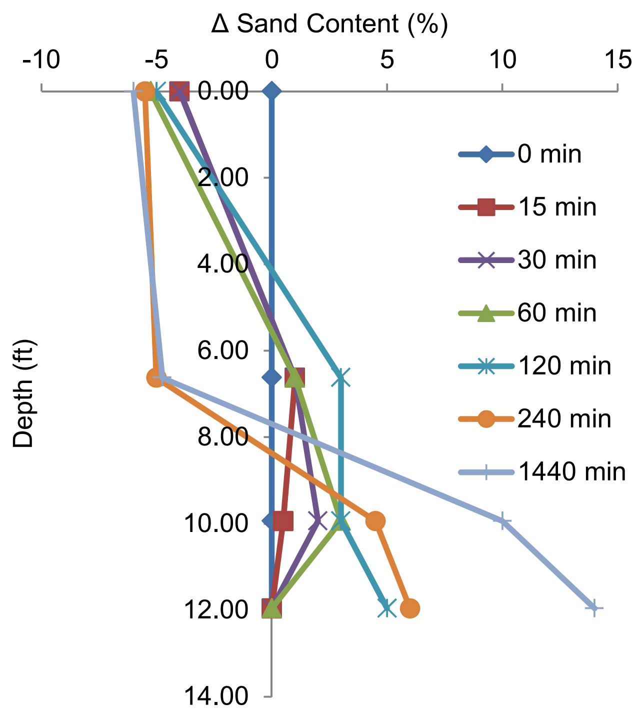

Figure 4.32 Change in sand content (6% overall starting sand content).

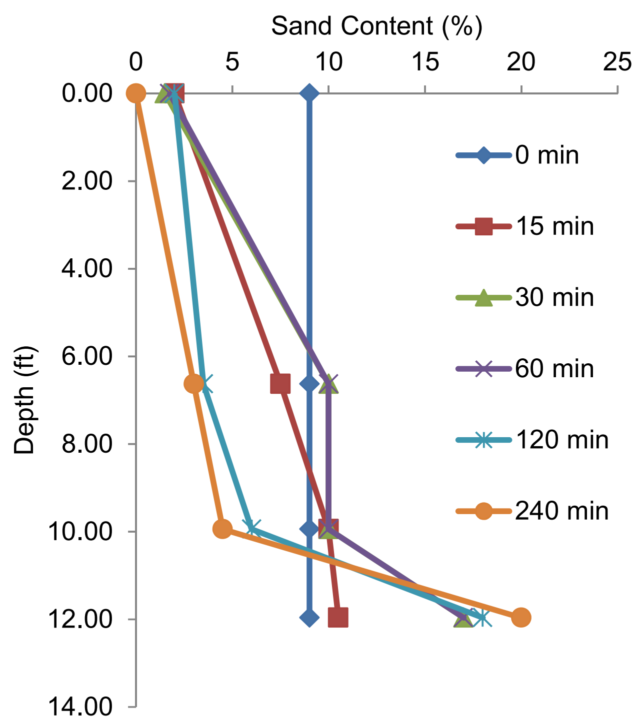

Figure 4.33 Measured sand content (9% overall starting sand content).

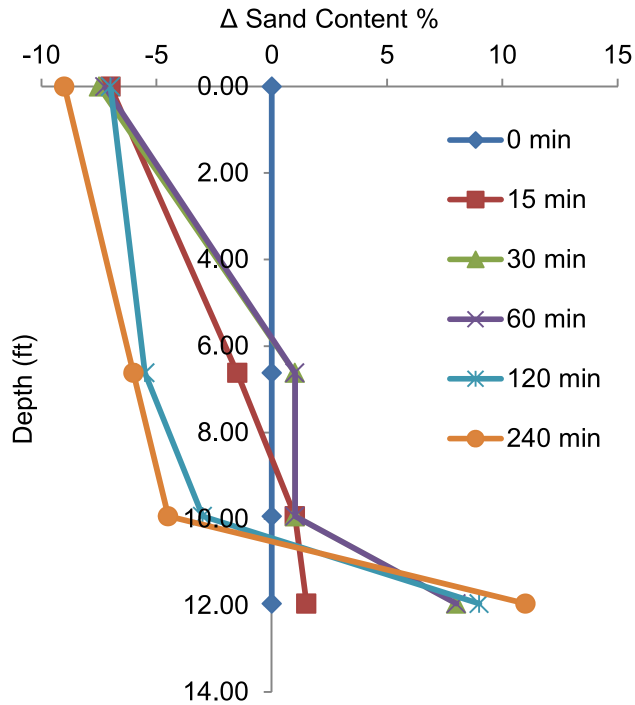

Figure 4.34 Change in sand content (9% overall starting sand content).

Although this material had a high initial viscosity (40 sec/qt), the ability to suspend sand was not comparable to the pure bentonite for the same viscosity.

4.2.2 Slurry Additive Testing

The effect on sand fallout (or suspension) was tested with polymer additives incorporated into pure bentonite. Although numerous mix ratios and additive concentrations could be entertained, the mixes selected were based on the minimum amount of bentonite that could be used with this additive without exceeding the 35 sec/qt viscosity value (Figure 3.23). Using Figure 3.23, a 40 sec/qt viscosity could have been achieved using the following combinations:

- 0.4 lb/gal bentonite; 0.025 lb/100 gal Wyo-Vis "DP"; 40 sec/qt
- 0.3 lb/gal bentonite; 0.04 lb/100 gal Wyo-Vis "DP"; 40 sec/qt
- 0.2 lb/gal bentonite; 0.12 lb/100 gal Wyo-Vis "DP"; 40 sec/qt, or
- 0.1 lb/gal bentonite; 0.3 lb/100 gal Wyo-Vis "DP"; 40 sec/qt.

As the 0.3 and 0.4 lb/gal mix ratios already met minimum viscosity specifications without additives, the 0.2 lb/gal option was selected. The mix had an average initial viscosity of 33 seconds. The initial viscosity and density findings are shown in Figure 4.35 and 4.36. The results of the sand content testing are shown in Figures 4.37 through 4.42. Despite numerous attempts, this hybrid mix ratio would not retain more than 2 percent sand long enough to perform even the shortest duration tests.

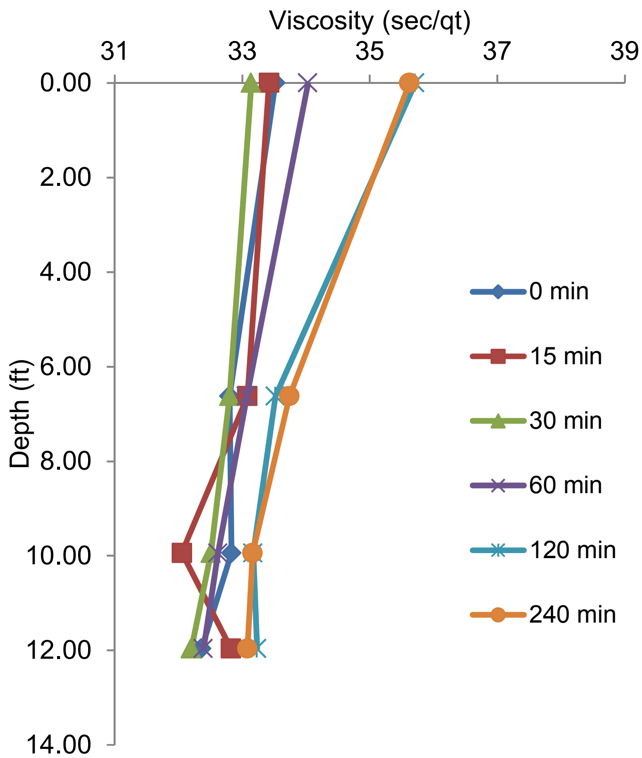

Figure 4.35 Initial hybrid slurry viscosity testing (bentonite 0.2 lb/gal; Wyo-Vis “DP” 0.12 lb/100 gal).

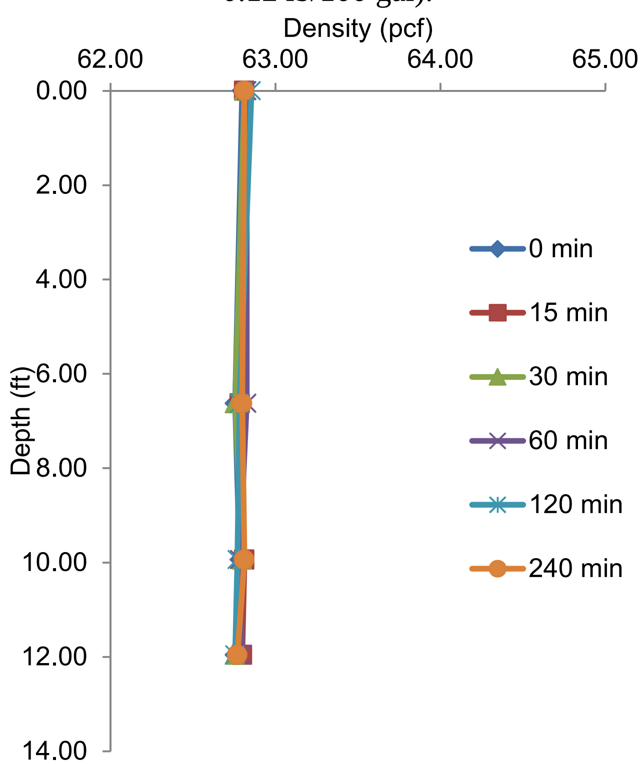

Figure 4.36 Initial hybrid slurry density testing (bentonite 0.2 lb/gal; Wyo-Vis “DP” 0.12 lb/100 gal).

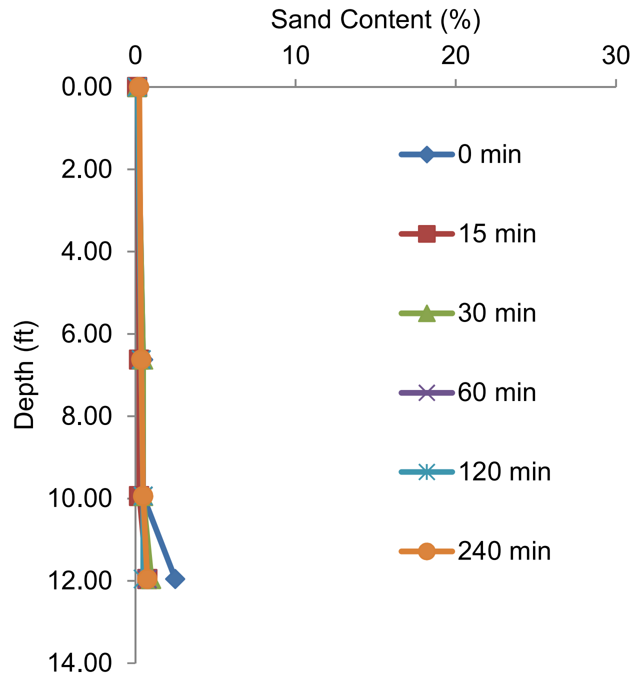

Figure 4.37 Measured sand content (0.9% initial sand content; 0.2 lb/gal; 0.12 lb/100 gal).

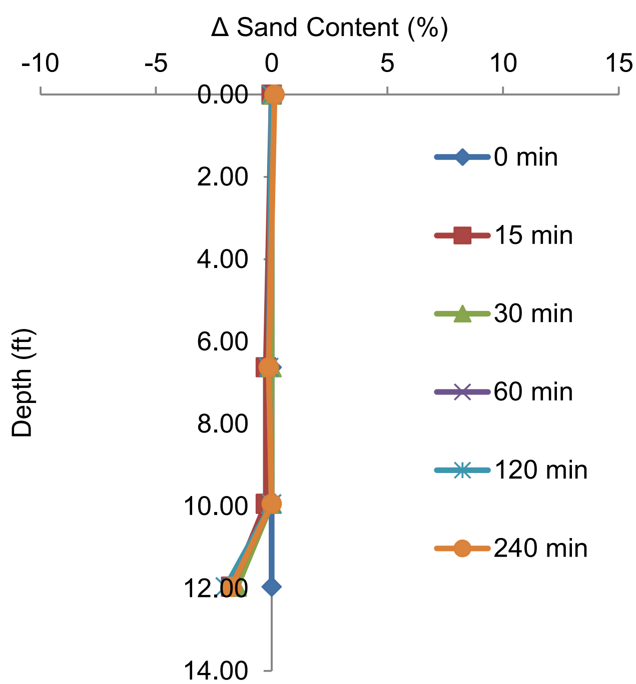

Figure 4.38 Change in sand content (0.9% initial sand content; 0.2 lb/gal; 0.12 lb/100 gal).

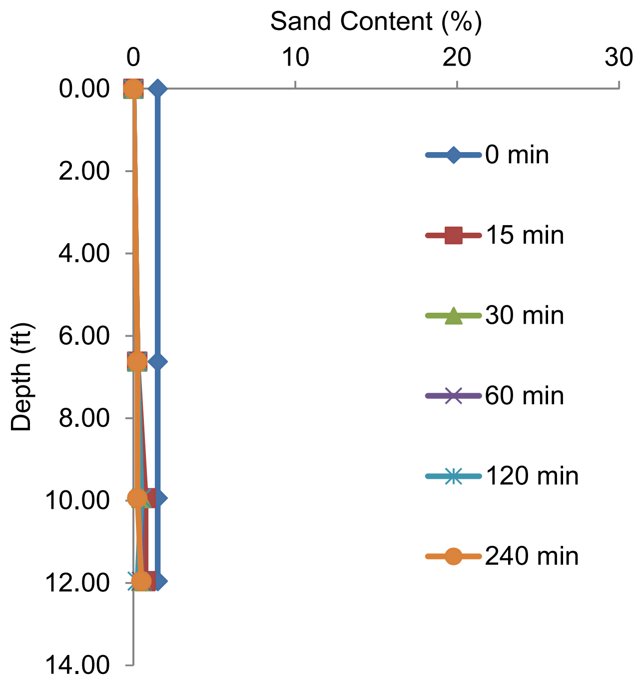

Figure 4.39 Measured sand content (1.5% initial sand content; 0.2 lb/gal; 0.12 lb/100 gal).

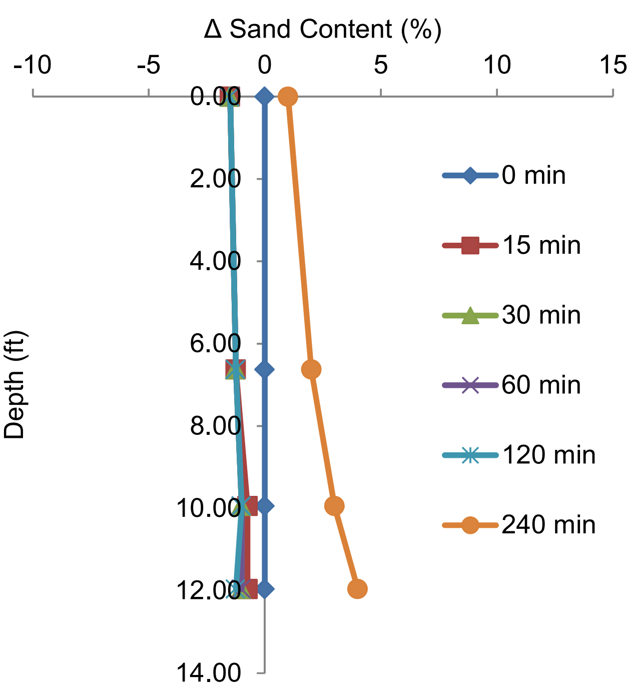

Figure 4.40 Change in sand content (1.5% initial sand content; 0.2 lb/gal; 0.12 lb/100 gal).

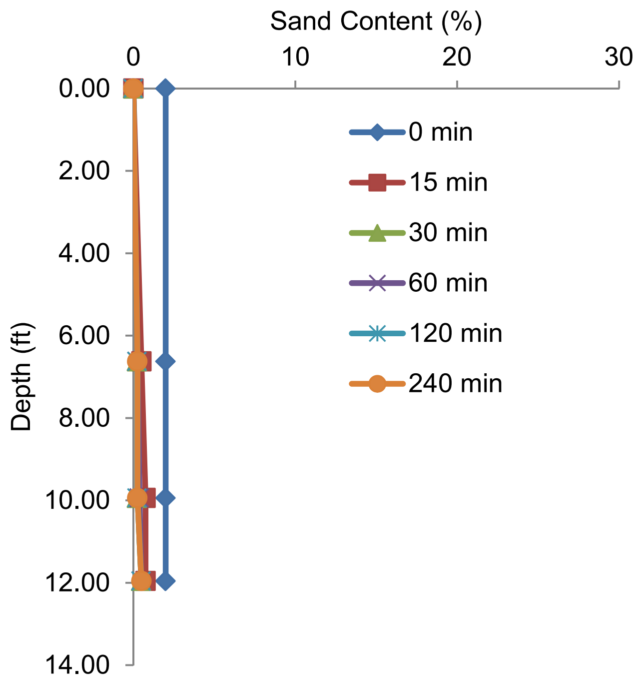

Figure 4.41 Measured sand content (2% initial sand content; 0.2 lb/gal; 0.12 lb/100 gal).

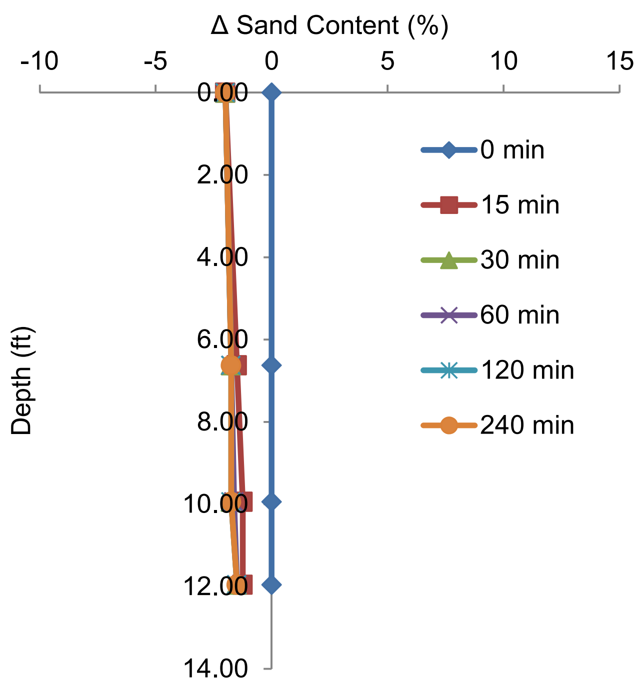

Figure 4.42 Change in sand content at (2% initial sand content; 0.2 lb/gal; 0.12 lb/100 gal).

4.3 Sand Fallout Verification

As very little sand could be detected through the “clear” portion of the sand settling column, a different approach to evaluating the accumulation at the bottom of the column was developed. This stemmed largely from the poor transparency of the bottom portion of the settling column. Further, even if better clarity had been availed, the color of the slurry in many cases was too similar to that of the sand that was intended to be measured externally (as shown by the measuring tape aside the column in Figures 4.1 and 4.14). Therefore, a sample bucket with a false bottom was fabricated, and was lowered to the bottom of the slurry column once mixing ceased. The bucket was left on the bottom for the duration of the accumulation time period, and was retrieved at the appropriate time. The depth of the sand accumulation on the false bottom was measured, and the results recorded. The accumulation bucket and false bottom are pictured in Figures 4.43 and 4.44.

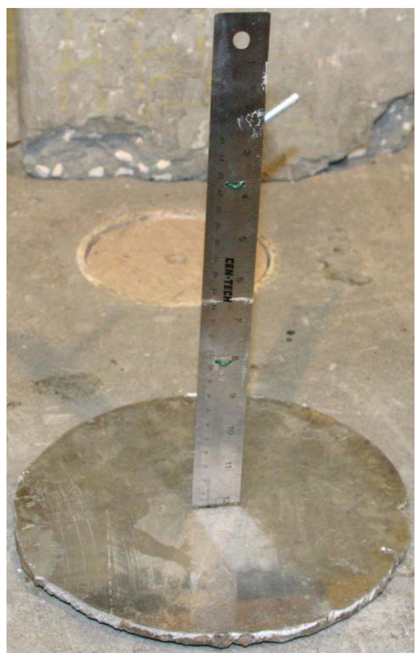

Figure 4.43 Bucket sampler false bottom with accumulation ruler.

Figure 4.44 Bucket sampler with removable false bottom.

To measure the accumulation on the false bottom of the sampler, slurry within the bucket had to be dumped out, and the false bottom had to be raised. By dumping slurry and raising the false bottom, it was unclear if accumulated sand was being removed from the false bottom. With these doubts, a second sampler was fabricated. This sampler featured an extremely clear Lexan bottom and tube, with stainless steel hardware. The improved sampler is shown in Figure 4.45.

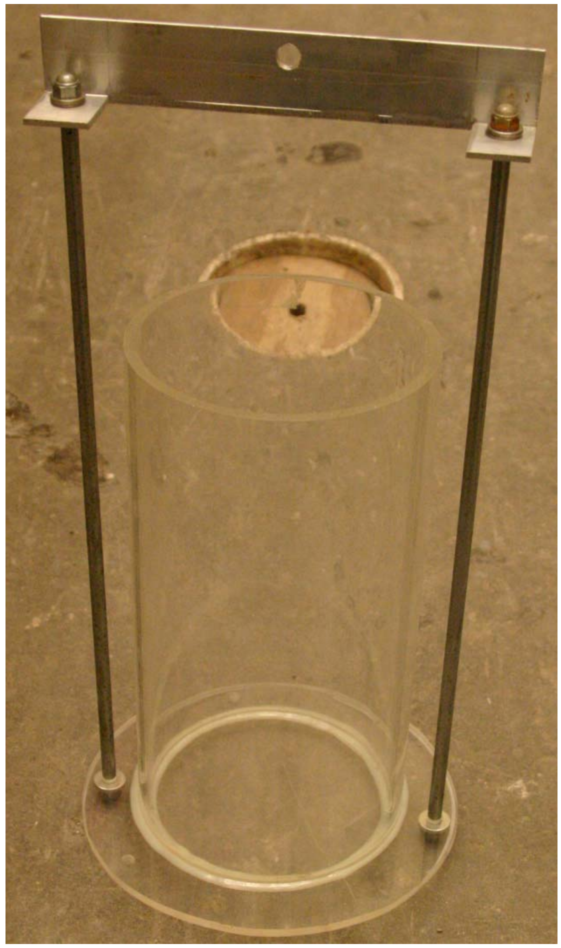

Figure 4.45 Lexan accumulation sampler

Accumulation collected within the sampler was compared to the accumulation measured through the "clear" PVC portion of the settling column, to determine the accuracy and reliability of the sampler. In reality, in prior tests the materials were not clearly visible through the PVC column. A comparison of the Lexan sampler versus the clear PVC column showed a slight difference between the two methods (< 1/8 inch).

Although the improved sampler provided easier to read values, it was extremely delicate, and fell apart while being retrieved from the column after several applications. Given the cumbersome nature of testing in the large-scale settling column and with the knowledge gathered from the previous testing, a small-scale test matrix was developed to rapidly gather accumulation data on multiple slurry products and mix ratios using hydrometer jars.

4.4 Small-scale Sand Fallout Testing

Based on the trends seen in the tests done in the PVC column, the majority of the sand accumulation occurs within the first 15 minutes of testing, and is complete within 60 minutes. Therefore, small batches of slurry were produced and sediment accumulation was measured in graduated cylinders. Eight products were prepared for testing, at various mix ratios. Figure 4.46 shows the line of slurry products used for small-scale accumulation testing.

Figure 4.46 Mineral and polymer drilling products.

4.4.1 Test Setup

Slurry was mixed using the mixing paddle drill press, the same procedure as was used for API filter press .testing. Batches of 4500 ml of slurry were produced for accumulation testing. The pH of the water was measured prior to the addition of any products. Soda ash was placed in the mix water prior to the addition of any slurry material (Figure 4.47) to counteract the presence of calcium ions within the water thus reducing the hardness of the mixing water. The pH of the water was raised to approximately 10.40 with the addition of soda ash. Once the full amount of powder was placed in the mixing water, the slurry was left to mix for approximately 15 minutes.

Figure 4.47 Introduction of soda ash into mixing water.

The slurry was then added to 1000 ml graduated cylinders in preparation for accumulation testing, as shown in Figure 4.48. The cylinders contained sand amounts corresponding to 2%, 4% and 8% sand content by volume. An additional cylinder was provided during testing which contained no additional sand. This sample served as a control, which was used to note any additional effects that may arise within the slurry due to the presence of sediment or high sand content within the bentonite powder itself.

Figure 4.48 Graduated cylinders with additional sand.

The cylinders were turned end-over-end for approximately 1 minute to thoroughly agitate the sand within the drilling fluid (Figure 4.49). Immediately following the agitation of the sample, the accumulation of sand was measured at 1, 2, 5, 10, 15, 30, and 60 minutes. The accumulation was carefully measured at three locations around the cylinder and averaged without disturbing the sample.

Figure 4.49 Agitation of sand and slurry solution.

4.4.2 Existing Product Testing

Pure bentonite products were tested, starting with Wyo-Ben NaturalGel. Mix ratios of 0.3 lb/gal and 0.6 lb/gal were prepared for testing. The initial properties of these mixes are summarized in Table 4.1. In both batches, the accumulation of sediment occurred rapidly and ceased in less than 10 minutes, regardless of the initial sand content. The results of the accumulation testing are shown below in Figures 4.50 and 4.51.

Table 4.1 Wyo-Ben NaturalGel initial properties

Mix Ratio (lb/gal)	Density (pcf)	Viscosity (sec/qt)	Initial Sand Content (%)	pH
0.3	63.81	30.23	<0.25	10.30
0.6	65.11	37.11	0.25	10.32

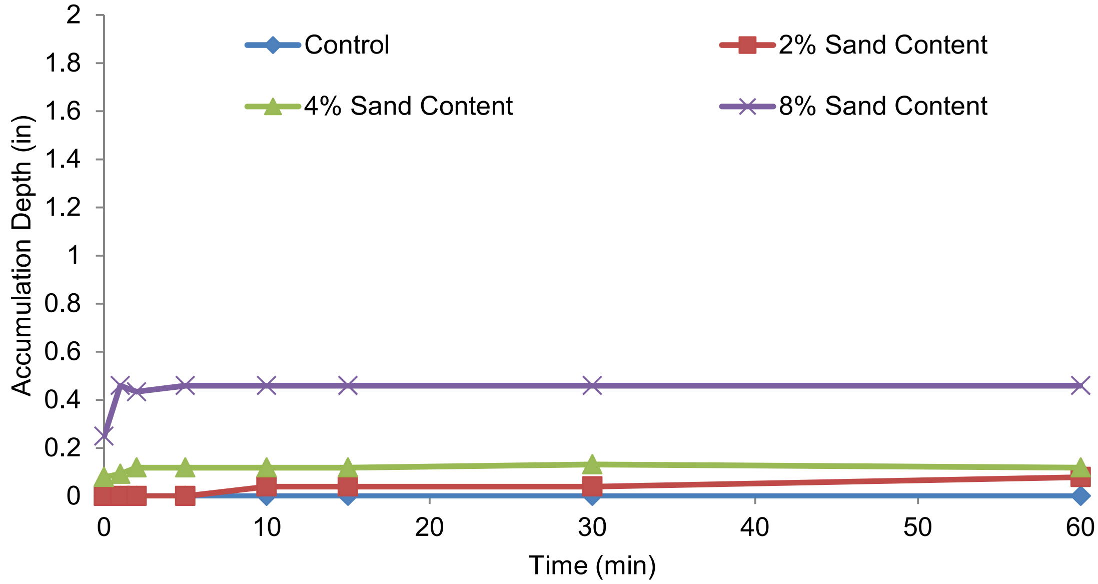

Figure 4.50 Sediment accumulation in 0.3 lb/gal Wyo-Ben NaturalGel.

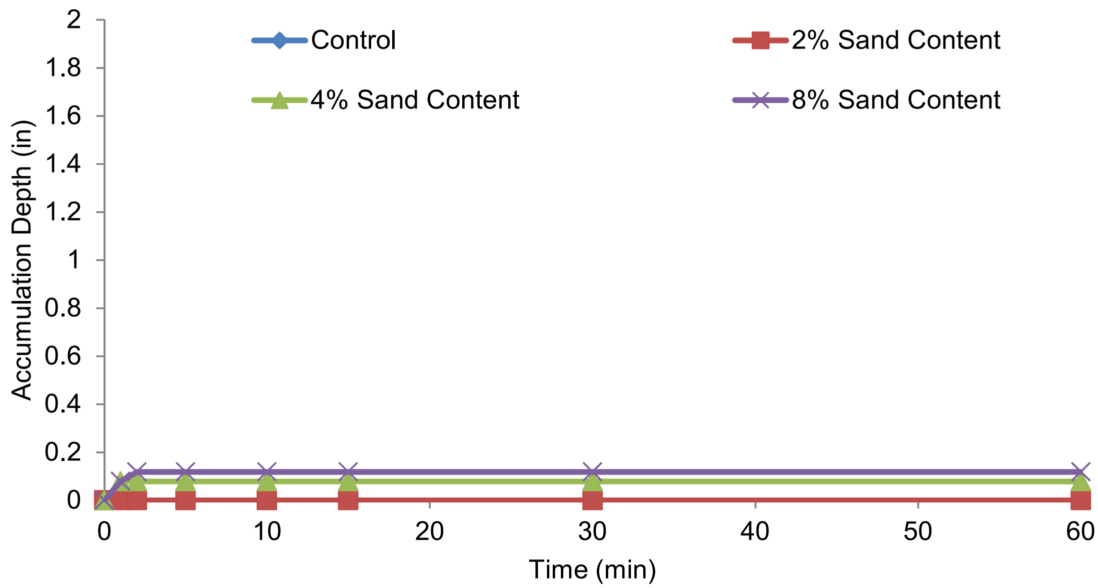

Figure 4.51 Sediment accumulation in 0.6 lb/gal Wyo-Ben NaturalGel.

PureGold was also tested at mix ratios of 0.3 lb/gal and 0.6 lb/gal. The initial properties of these mixes are summarized in Table 4.2. Once again, the accumulation of settlement occurred rapidly in both batches, regardless of the sand content of the sample. The settlement of sediment ceased within 10 minutes. The results of the accumulation testing are shown in Figures 4.52 and 4.53.

Table 4.2 PureGold initial properties

Mix Ratio (lb/gal)	Density (pcf)	Viscosity (sec/qt)	Initial Sand Content (%)	pH
0.3	63.77	29.85	<0.25	10.35
0.6	65.07	34.44	0.25	10.35

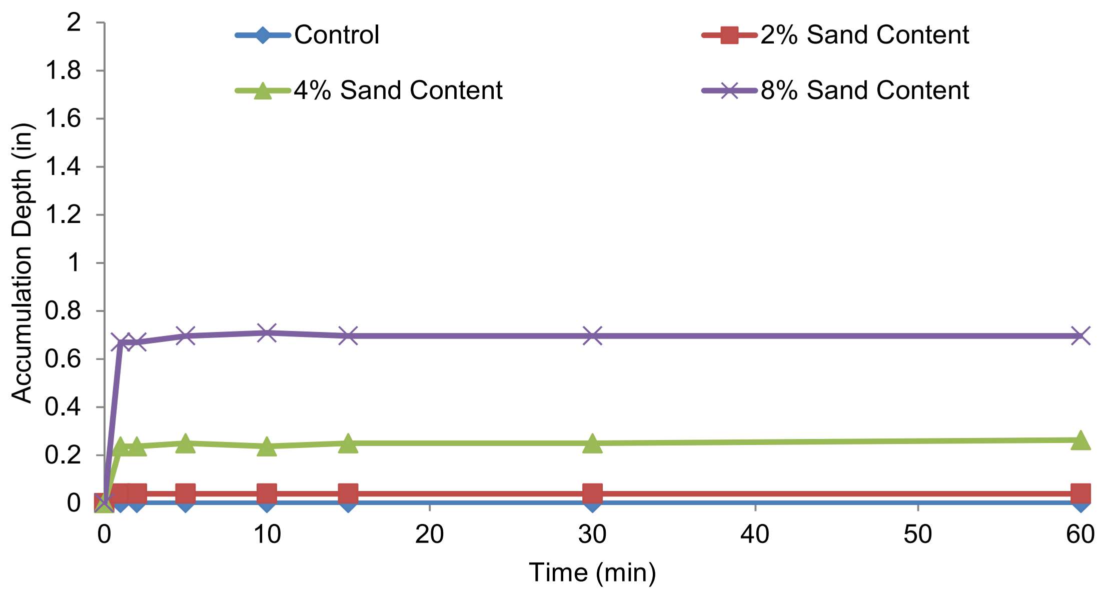

Figure 4.52 Sediment accumulation in 0.3 lb/gal PureGold.

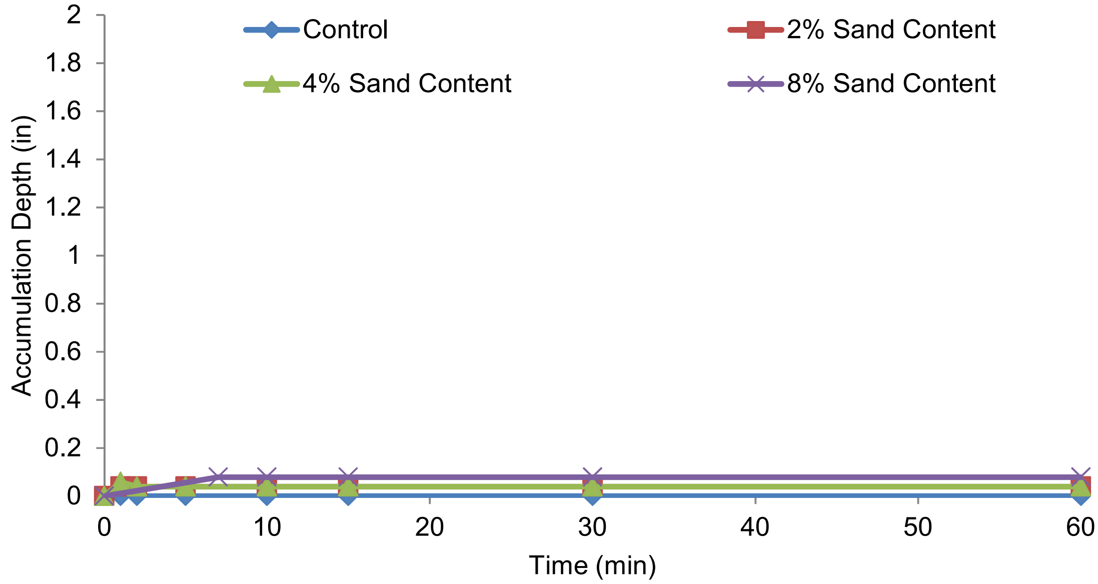

Figure 4.53 Sediment accumulation in 0.6 lb/gal PureGold

Wyo-Ben Extra High Yield bentonite was tested at mix ratios of 0.2 and 0.3 lb/gal. Table 4.3 contains the initial properties of these two mixes. As with the previous tests, the sediment accumulation stabilized within approximately 10 minutes in the 0.2 lb/gal mix in the 2% and 8% sand content cylinders. Sediment continued to accumulate in the cylinder containing 4% sand content. No accumulation occurred in the 0.3 lb/gal mix, regardless of the sand content. The results of these tests are shown in Figures 4.54 and 4.55.

Table 4.3 Wyo-Ben Extra High Yield Bentonite initial properties

Mix Ratio (lb/gal)	Density (pcf)	Viscosity (sec/qt)	Initial Sand Content (%)	pH
0.2	63.37	38.03	0.25	10.38
0.3	63.51	37.57	0.5	10.30

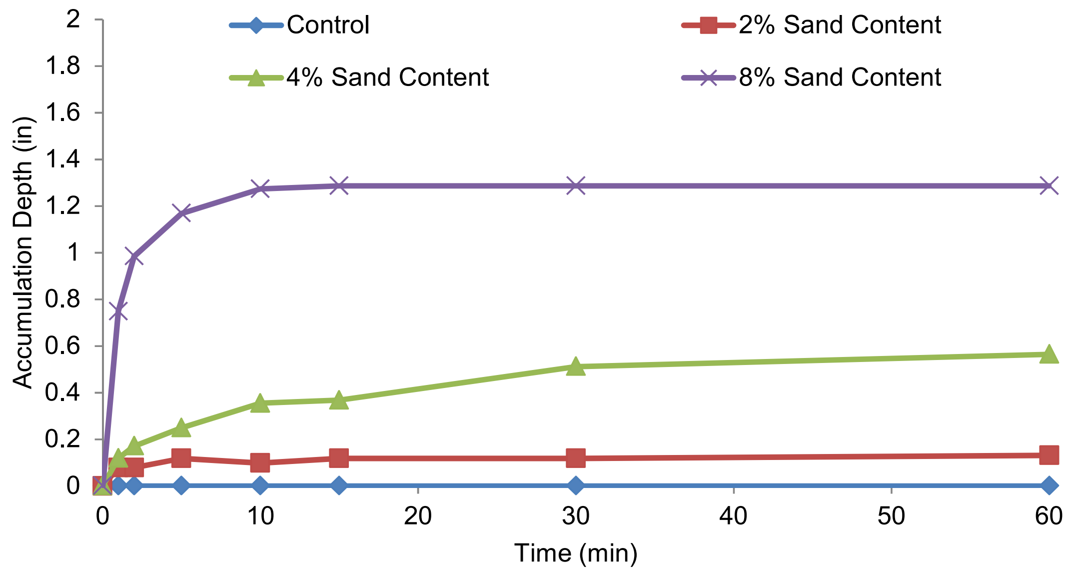

Figure 4.54 Sediment accumulation in 0.2 lb/gal Wyo-Ben Extra High Yield.

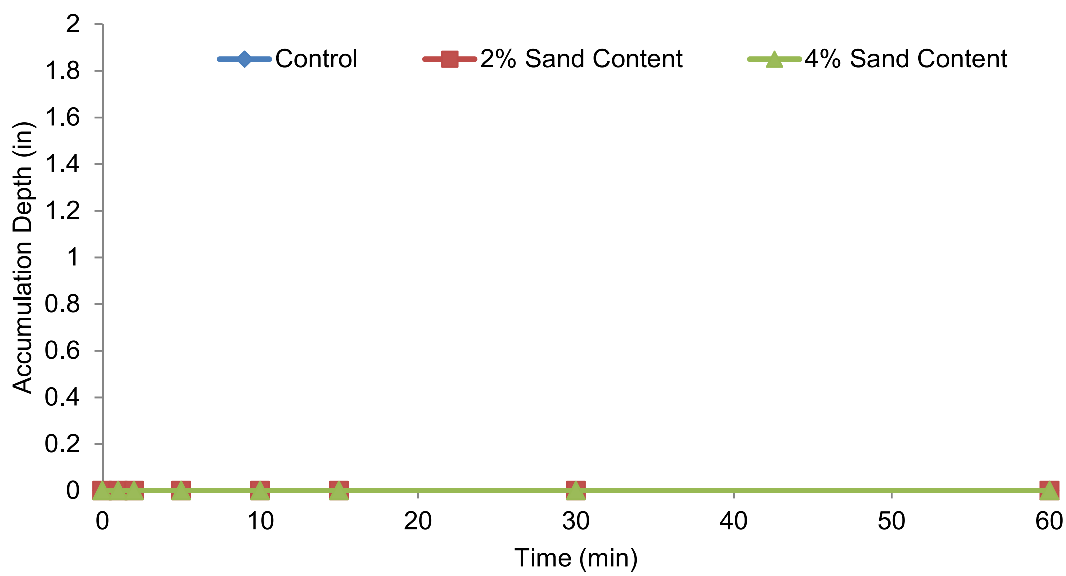

Figure 4.55 Sediment accumulation in 0.3 lb/gal Wyo-Ben Extra High Yield.

The accumulation could not be accurately determined in the 0.3 lb/gal mix ratio with 8% sand content, since the mixture was extremely thick. It was also noted that the slurry began to separate from the water within two minutes of standing, and samples containing sand experienced greater separation (Figures 4.56 and 4.57).

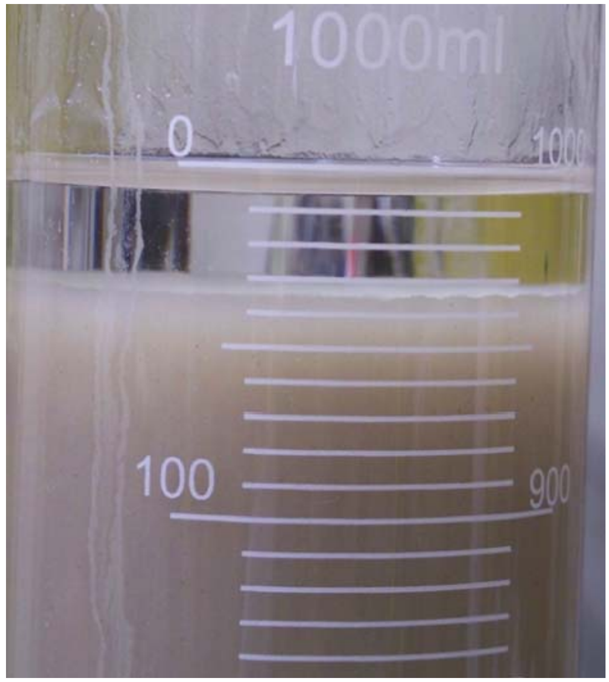

Figure 4.56 Separation of slurry and water in control sample.

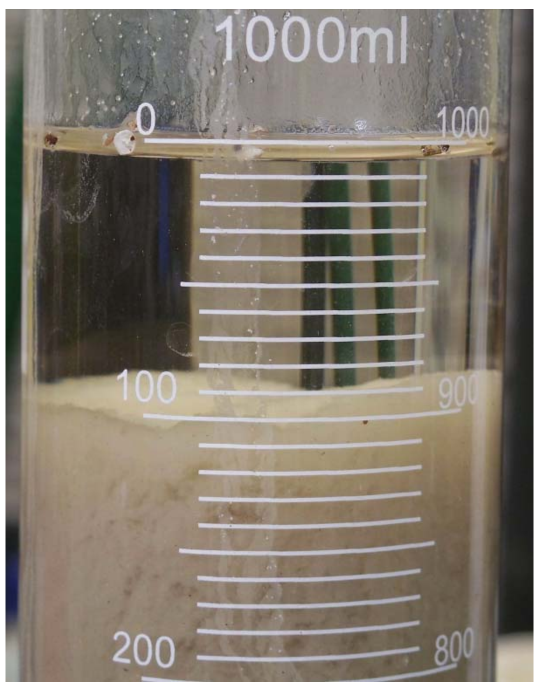

Figure 4.57 Separation of slurry and water with 4% sand content.

Super Gel-X was tested at mix ratios of 0.2 and 0.4 lb/gal. Table 4.4 contains the initial properties of the two mix ratios tested. As with the other products tested, sediment accumulation ended after approximately 10 minutes in both mixes prepared for all sand content cases. The results are shown below in Figures 4.58 and 4.59.

Table 4.4 Super Gel-X initial properties

Mix Ratio (lb/gal)	Density (pcf)	Viscosity (sec/qt)	Initial Sand Content (%)	pH
0.2	63.3	30.78	<0.25	10.44
0.4	62.78	31.97	0.25	10.43

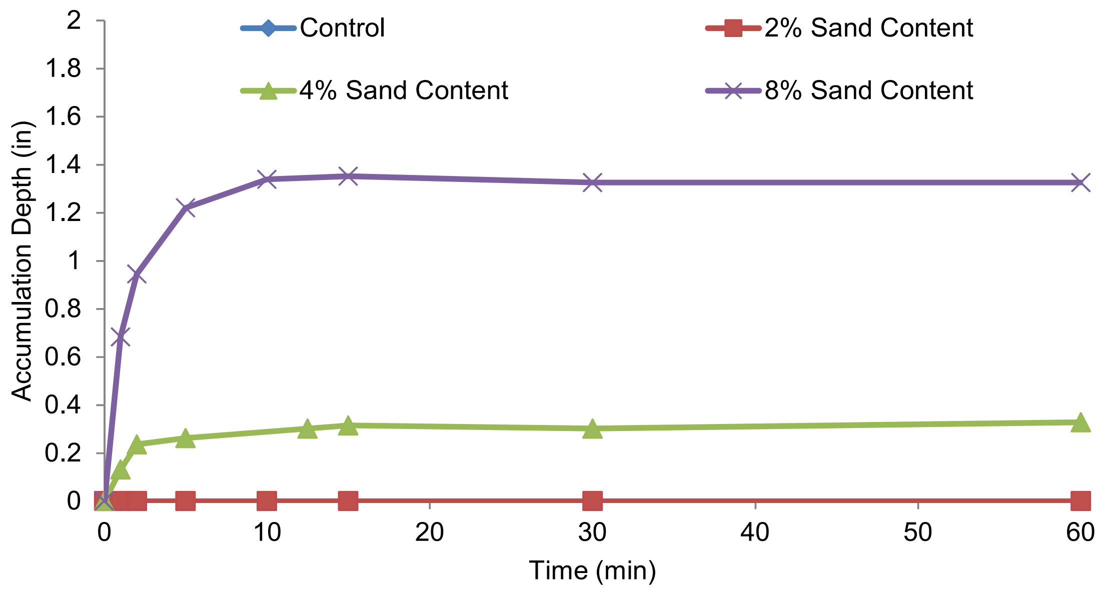

Figure 4.58 Sediment accumulation in 0.3 lb/gal Super Gel-X.

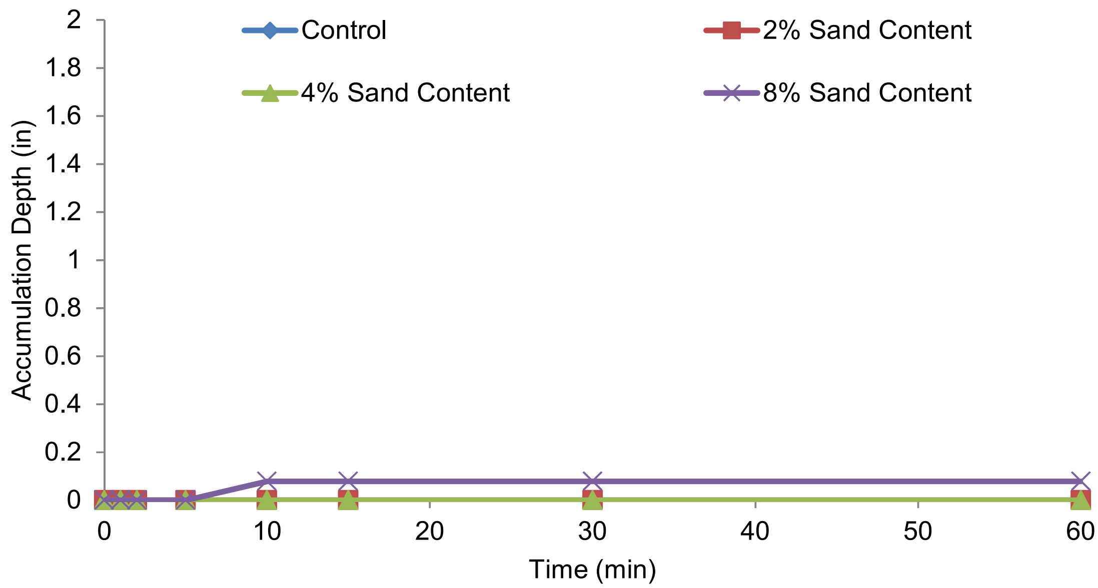

Figure 4.59 Sediment accumulation in 0.4 lb/gal Super Gel-X.

Pure polymer slurry, SlurryPro CDP, was prepared for testing. SlurryPro CDP is a white to light gray dry granular material. This product is intended to be used as a standalone drilling fluid. The viscosity and density of this material was tested previously, but accumulation testing had not been carried out. Several different mix ratios were prepared for accumulation testing. The initial properties of the polymer drilling fluid are listed in Table 4.5. The accumulation results for these mixes are shown in Figures 4.60 through 4.63.

Table 4.5 SlurryPro CDP initial properties

Mix Ratio (lb/gal)		Density (pcf)	Viscosity (sec/qt)	Initial Sand Content (%)	pH
½ Manuf. Rec. Min	0.0031	62.64	33.79	0	10.38
Manuf. Rec. Min	0.0062	62.64	37.24	0	10.36
Manuf. Rec. Max	0.0126	62.67	40.32	0	10.37
2x Manuf. Rec. Max	0.0252	62.69	93.44	0	10.39

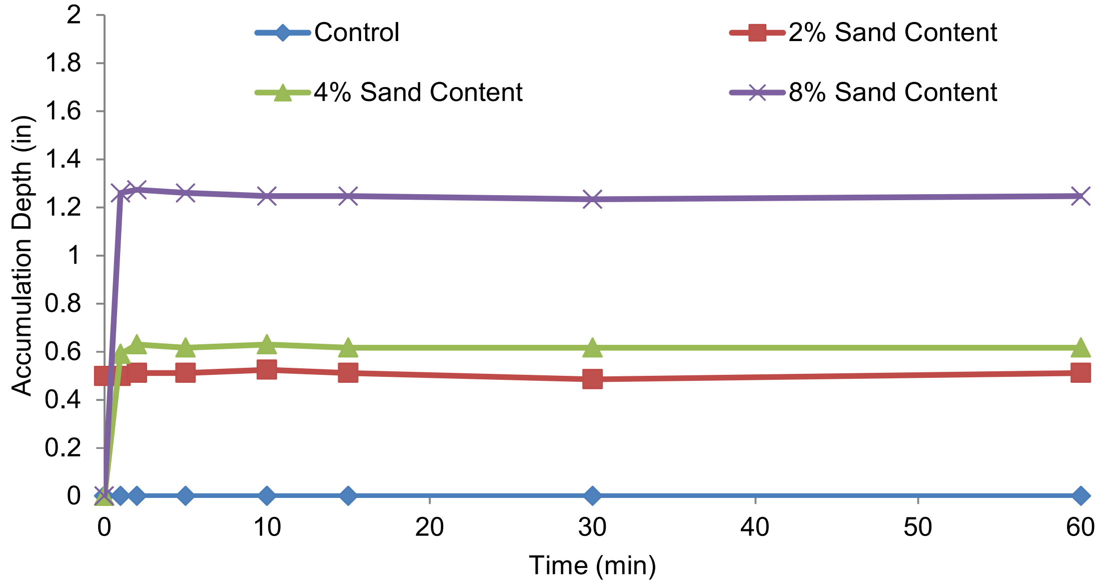

Figure 4.60 Sediment accumulation in 0.31 lb/100 gal SlurryPro CDP.

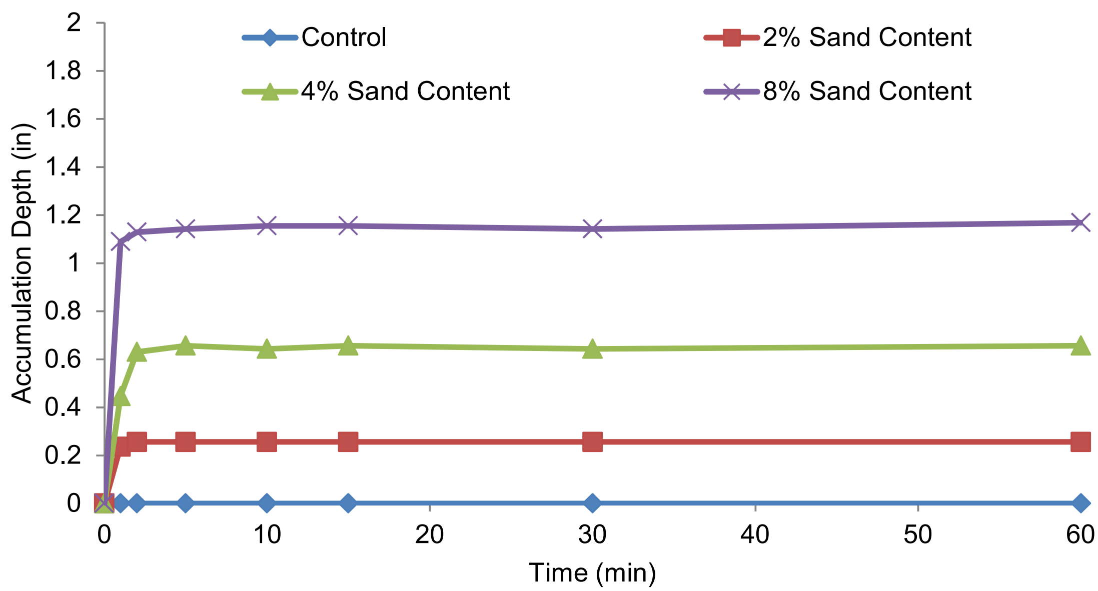

Figure 4.61 Sediment accumulation in 0.62 lb/100 gal SlurryPro CDP.

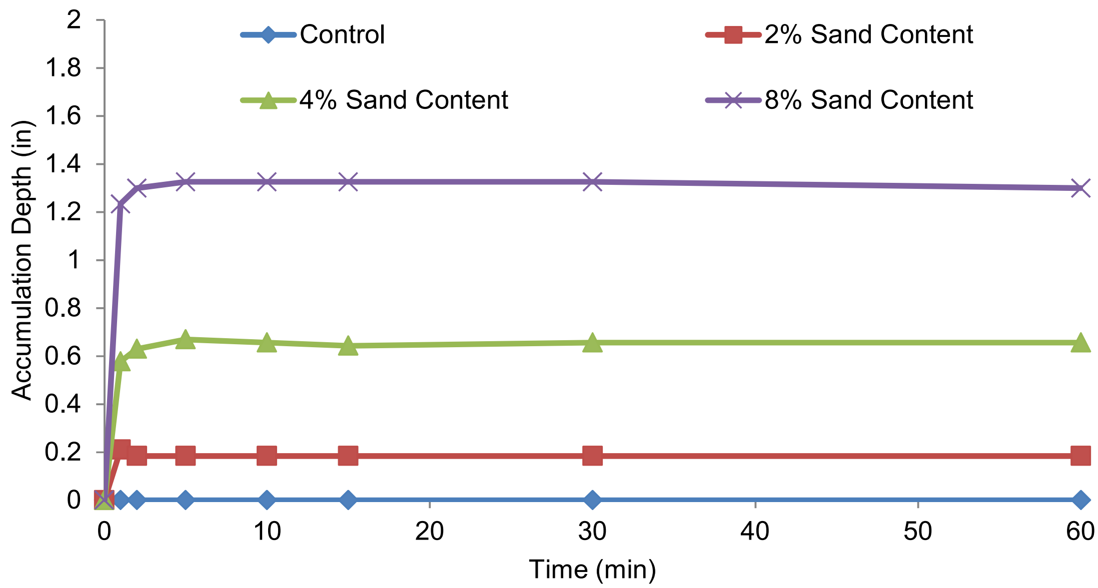

Figure 4.62 Sediment accumulation in 1.26 lb/100 gal SlurryPro CDP.

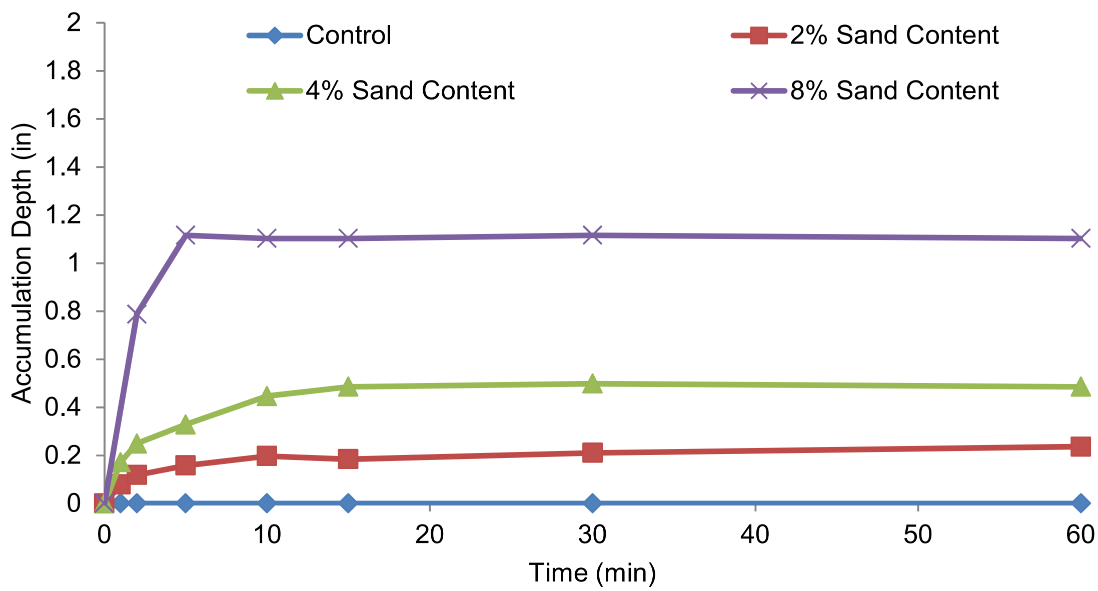

Figure 4.63 Sediment accumulation in 2.52 lb/100 gal SlurryPro CDP.

Accumulation of sediment in attapulgite slurry was investigated as well. Two mix ratios were selected for settlement testing. The initial properties of the attapulgite are shown in Table 4.6. The accumulation of sediment was drastically reduced by increasing the mix ratio from 0.40 lb/gal to 0.55 lb/gal. The results of the accumulation testing are given in Figures 4.64 and 4.65.

Table 4.6 Attapulgite initial properties

Mix Ratio (lb/gal)	Density (pcf)	Viscosity (sec/qt)	Initial Sand Content (%)	pH
0.4	64.14	28.62	<0.25	10.30
0.55	64.18	29.60	0.25	10.22

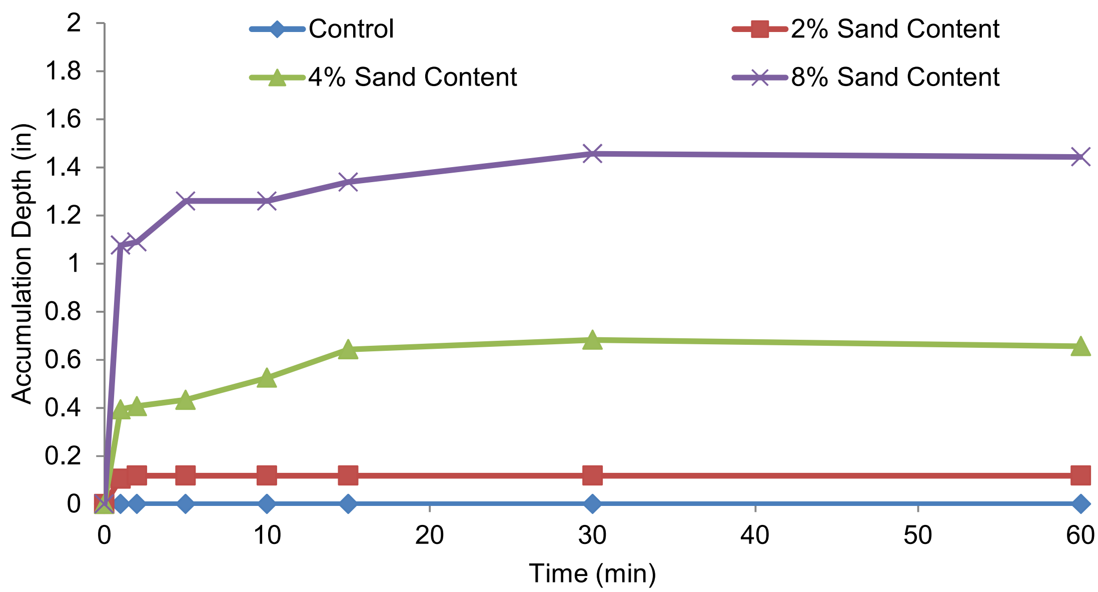

Figure 4.64 Sediment accumulation in 0.4 lb/gal Florigel attapulgite.

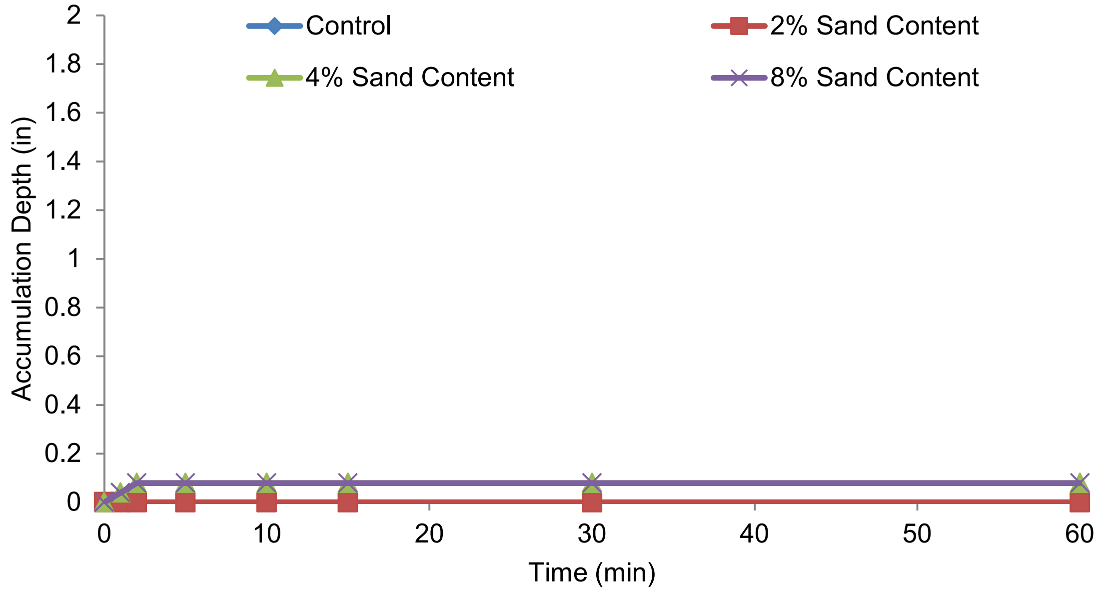

Figure 4.65 Sediment accumulation in 0.55 lb/gal Florigel attapulgite.

4.4.3 Slurry Additive Testing

After testing these products, mineral slurry was selected for treatment with polymer additives. A pure bentonite product was prepared at a mix ratio of 0.3 lb/gal with NO-SAG additive at a rate of 0.6 lb/100 gal. The slurry parameters immediately after mixing are listed in Table 4.7. The results of the accumulation testing are shown in Figure 4.66.

Table 4.7 PureGold with NO-SAG initial properties

Mix Ratio (lb/gal)		Density (pcf)	Viscosity (sec/qt)	Initial Sand Content (%)	pH
NO-SAG (lb/100gal)	PureGold (lb/gal)				
0.6	0.3	63.88	32.25	0.25	10.21

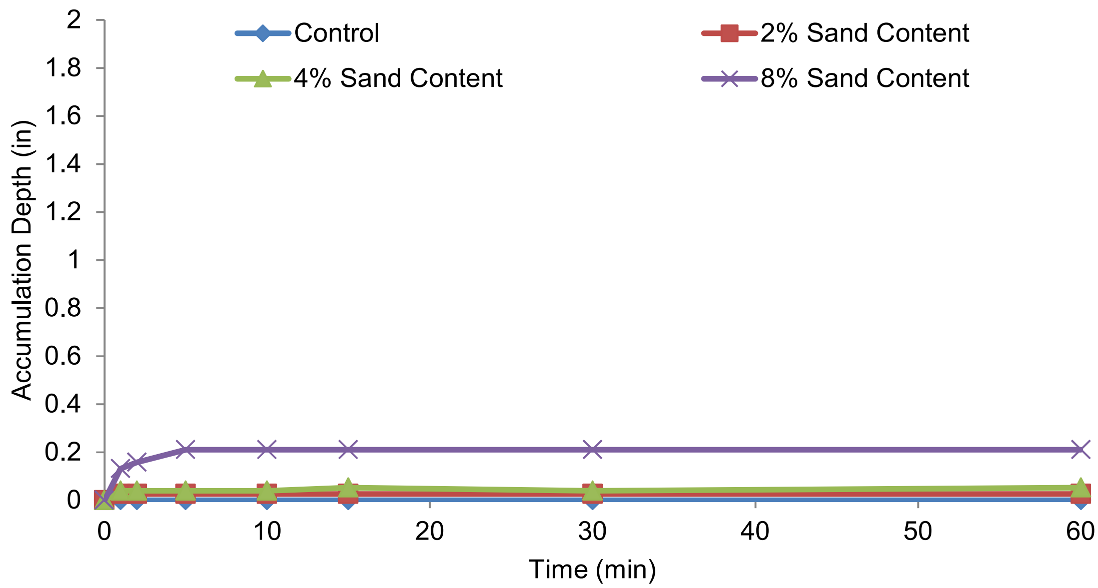

Figure 4.66 Sediment accumulation in 0.3 lb/gal CETCO PureGold with NO-SAG.

The Wyo-Vis “DP” was added to the slurry at a rate of 0.42 lb/100 gal, which is within the manufacturer’s recommended range of addition of 0.25 lb/100 gal to 1.0 lb/100 gal. The properties of the treated slurry are listed in Table 4.8. Accumulation testing results are presented in Figure 4.67.

Table 4.8 PureGold with Wyo-Vis “DP” initial properties

Mix Ratio (lb/gal)		Density (pcf)	Viscosity (sec/qt)	Initial Sand Content (%)	pH
Wyo-Vis DP (lb/100 gal)	PureGold (lb/gal)				
0.42	0.3	63.7	56.16	<0.25	10.33

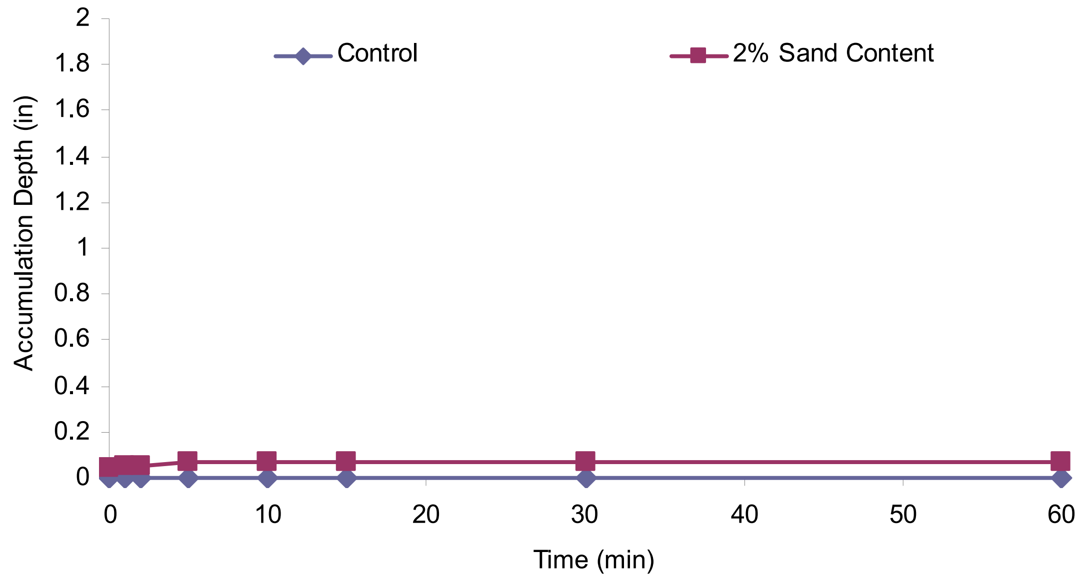

Figure 4.67 Sediment accumulation in 0.3 lb/gal CETCO PureGold with Wyo-Vis DP.

Only the Control test and the 2% Sand Content test produced visible results while testing the slurry treated with Wyo-Vis DP. The material in the 4% Sand Content test was too thick to accurately determine the accumulation. The sediment in the 8% Sand Content test remained stuck together in a long trail running from top to bottom of the test cylinder, making it impossible to evenly distribute the sediment within the cylinder, as shown in Figure 4.68.

Figure 4.68 Sediment Clumping

Following the mineral slurry modification testing, both NO-SAG and Wyo-Vis "DP" were tested as standalone drilling fluids. Although NO-SAG is not advertised as a standalone drilling fluid, the materials influence on sediment suspension in clean water was of interest. Potable water was pretreated with soda ash prior to the incorporation of the NO-SAG. The initial parameters of the fluid are listed in Table 4.9.

Table 4.9 NO-SAG initial properties

Mix Ratio (lb/100 gal)	Density (pcf)	Viscosity (sec/qt)	Initial Sand Content (%)	pH
1.77	62.24	33.37	0	10.47

Determining the true density of the fluid proved extremely difficult, since air became entrained into the fluid while mixing. The fluid did not release the entrapped air, and remained foamy for several hours. The foamy mixture is visible in Figure 4.69. The results for the sand fallout testing are shown in Figure 4.70.

Figure 4.69 Foamy Mixture of NO-SAG and water

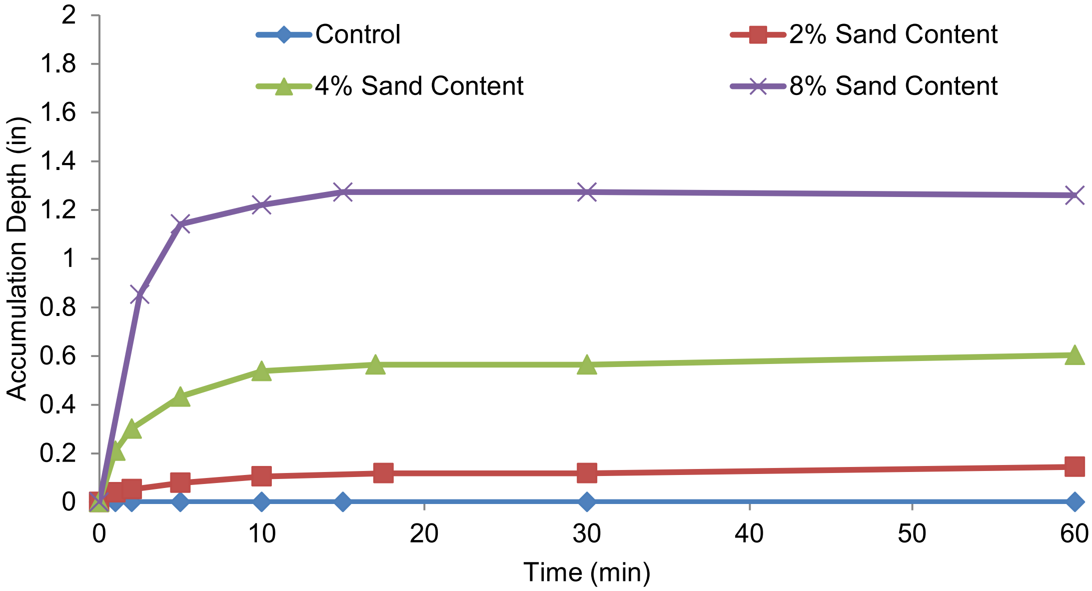

Figure 4.70 Sediment accumulation in 1.77 lb/100 gal NO-SAG

Wyo-Vis DP was mixed at a ratio of 0.25 lb/100gal (although the manufacturer's recommended addition rate for sandy applications calls for 0.2 lb/gal bentonite as well). The initial parameters of the Wyo-Vis "DP" slurry are shown in Table 4.10. The accumulation results are shown in Figure 4.71.

Table 4.10 Wyo-Vis DP initial properties

Mix Ratio (lb/100gal)	Density (pcf)	Viscosity (sec/qt)	Initial Sand Content (%)	pH
0.25	62.62	34.55	0	10.43

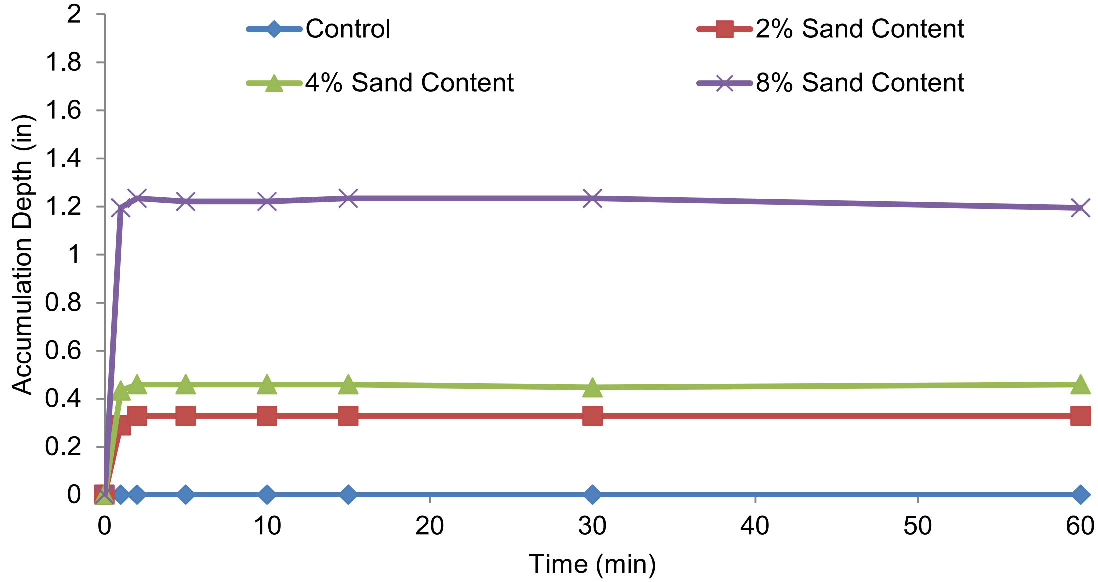

Figure 4.71 Sediment accumulation in 0.25 lb/100 gal Wyo-Vis DP.

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Chapter Five: Conclusions and Recommendations.

Slurry properties for drilled shafts are designed and monitored to assure that wet shaft construction techniques produce quality foundation elements. Therein, the density, viscosity, pH and sand content are tested to assure conformance to FDOT specifications both prior to introduction to an excavation and prior to concreting. Until recently, FDOT allowed only mineral slurry to be used to stabilize drilled shaft excavations when using the wet method. However, synthetic or polymer slurries have been approved for less critical structures such as mast arms, cantilever signs, overhead sign trusses, high mast light poles or other miscellaneous structures. As a result, mineral and polymer slurries now have dedicated specifications to address the unique mechanics involved in stabilizing a slurry-stabilized excavation. However, there exist a multitude of available products that enhance mineral slurry properties by way of polymer additives. To that end, this study focused on the performance of pure mineral slurries, polymer fortified mineral slurries and polymer enhanced mineral slurries with the goal of identifying whether or not current state specifications were sufficient. Further, the study sought to identify whether polymer fortified and polymer enhanced mineral slurries should be tested under mineral or polymer specifications.

The study addressed the use of polymer additives in mineral slurries by performing two forms of testing: API Filter Press tests and sand sedimentation tests. Although not used by FDOT, the API developed the filter test method to assess the filter cake potential of a given slurry product. The second test method was developed in an earlier study (Mullins, 2005) to assess the suspension capacity (gel strength) of a slurry by simply recording the sand fallout from a column of soil laden slurry. A brief overview of the test is presented in the ensuing sections accompanied by conclusions drawn from these results.

5.1 API Filter Press Conclusions

API filter tests were performed on existing slurry products to determine a baseline for slurry additives. Initial testing included six products, three pure mineral and three polymer modified mineral slurries. This series of tests included all standard slurry property tests as well as the filter press test. Figures 5.1 through 5.3 show the results of density, viscosity and flow rate on these products, respectively. Current state specifications require the density of the slurry to be a minimum of 64 pcf for freshwater applications and 66 pcf for saltwater applications. Therefore, the minimum mix ratio of dry slurry product is approximately 0.45 lb/gal for freshwater applications and 0.95 lb/gal for saltwater applications regardless of the product (Figure 5.1). This stems from the similarity in specific gravity of these materials. As a result, bentonite slurries (fresh water) should start around 0.45 lb/gal at the time of introduction while attapulgite slurries (salt water) should start around 0.95 lb/gal.

The current state specifications require the Marsh funnel viscosity to between 28 and 40 sec/qt. Figure 5.2 shows the minimum mix ratio to be approximately 0.2 lb/gal to meet the minimum 28 sec/qt viscosity. However, from Figure 5.3, a viscosity of 28 sec/qt allows the slurry to flow at high rates implying a suitable filter cake does not form at such low mix ratios. Flow rates stabilize around 0.8 ml/min for all the slurry products except for the attapulgite slurry, but all stabilize at a minimum viscosity near 30 sec/qt. A recommended minimum viscosity of 30 sec/qt provides reduced flow rates (<0.8 ml/min) which then corresponds to a minimum mix ratio of 0.35 lb/gal on the basis of viscosity. Recall from above, 0.45 lb/gal is required to meet the minimum density criterion. Understanding that the preferred specifications are performance driven, a 30 sec/qt Marsh funnel viscosity and minimum density will necessitate suitable mix ratios. Note: Florigel High Yield (attapulgite) had a 20 times higher flow rate than bentonite slurries, as seen in Figure 5.3.

At a mix ratio of 0.45 lb/gal, a viscosity of 32 sec/qt results for bentonite products. Figure 5.4 shows the individual state specifications for viscosity guidelines (Mullins, 2010). When considering attapulgite (Figure 3.17), higher mix ratios are required to obtain a stable flow rate which also corresponds to 30 sec/qt. Five of the states have adopted more viscous minimum slurry criteria ranging between 30 and 32 sec/qt. This is in keeping with the findings of this study on the basis of the API filter press testing.

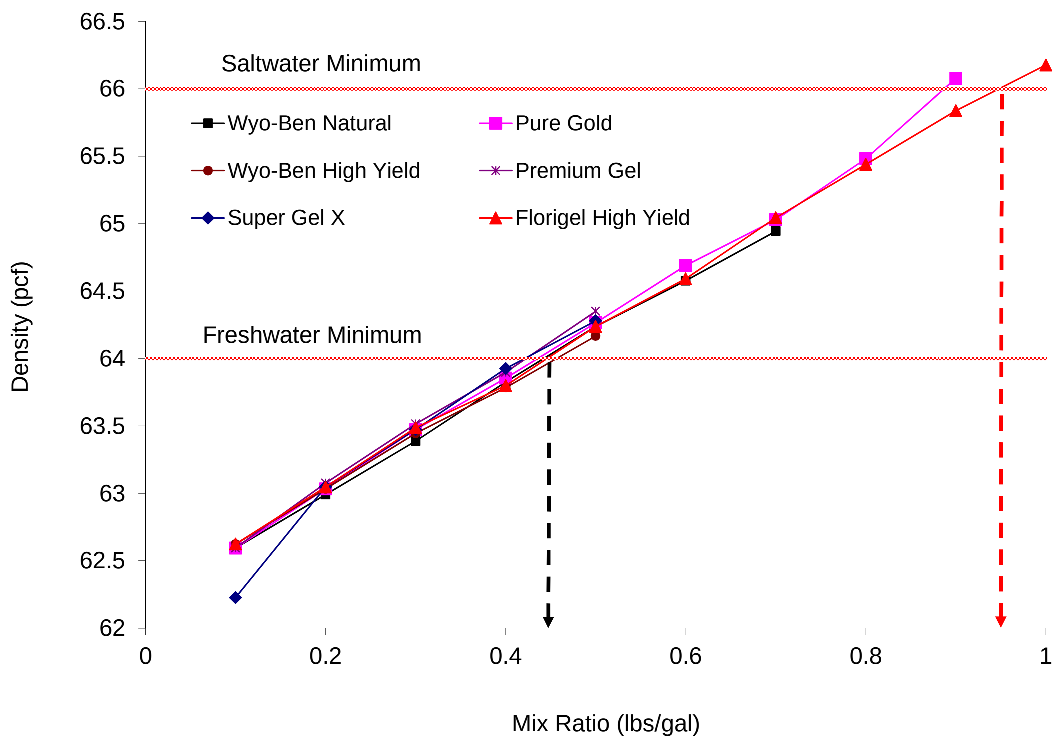

Figure 5.1 Density as a function of mix ratio for all the mineral slurries tested.

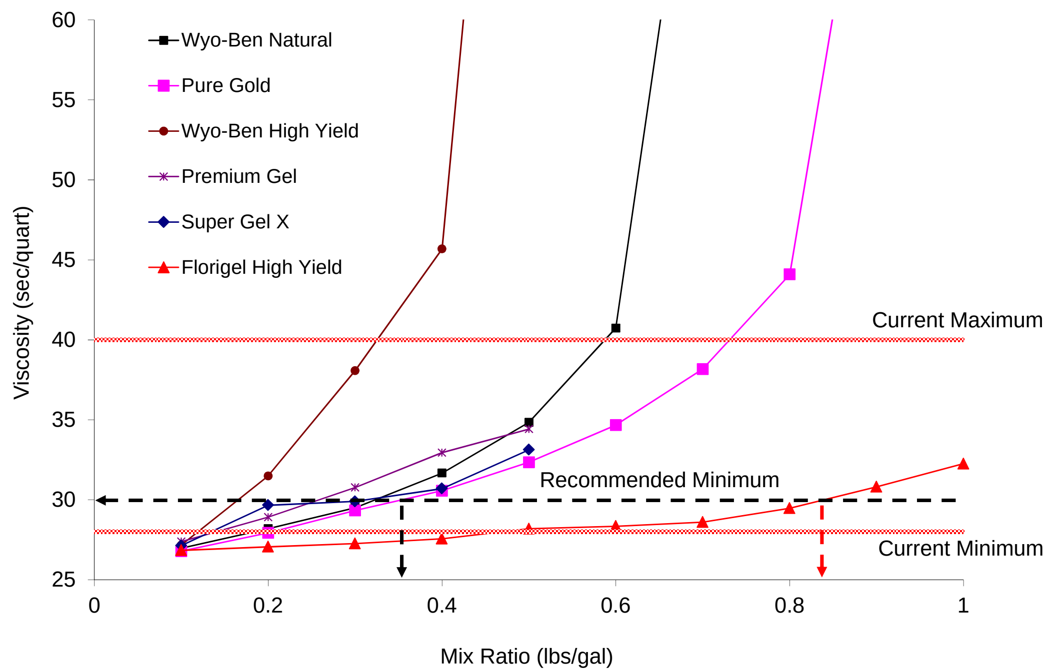

Figure 5.2 Viscosity as a function of mix ratio with recommended changes to the minimum state viscosity specification.

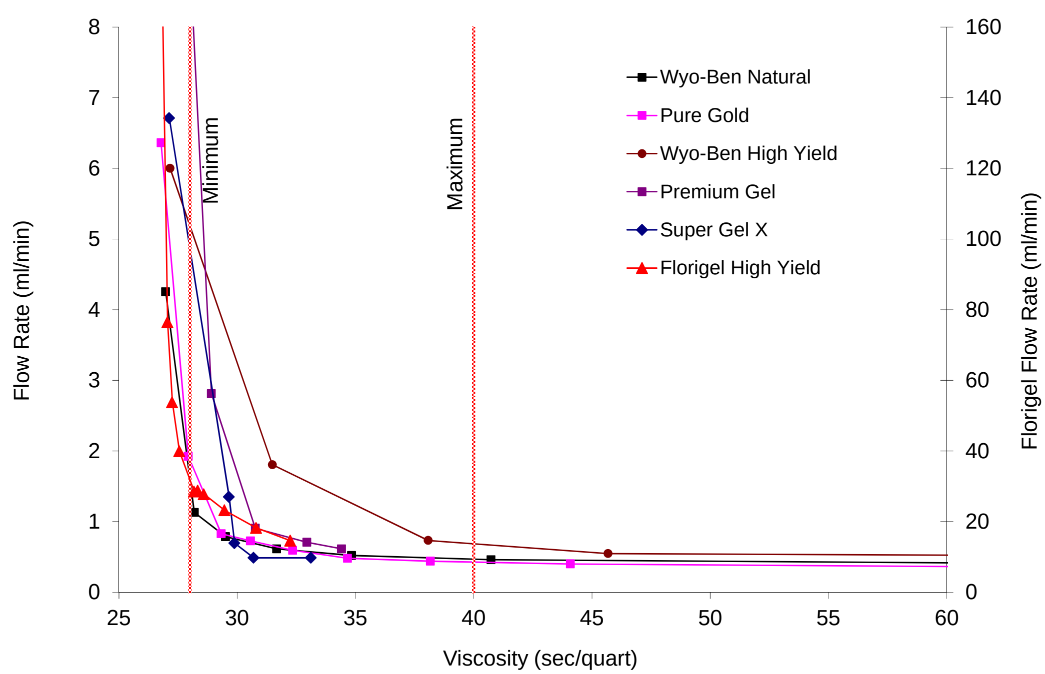

Figure 5.3 Stable infiltration flow rates at viscosity values above 30 to 32 sec/qt.

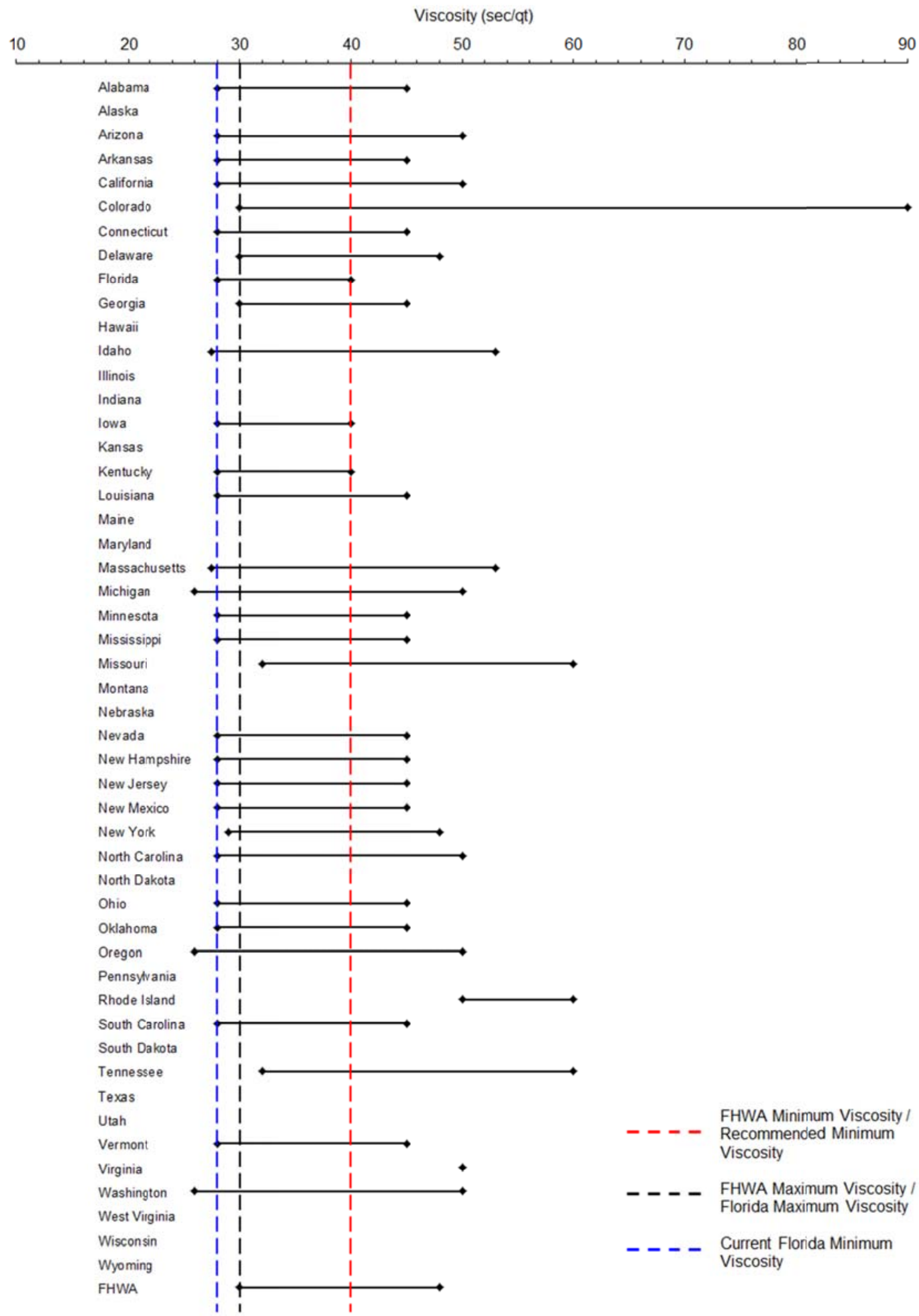

Figure 5.4 Specifications for 41 of 50 states and FHWA for slurry viscosity.

Test Pressure. Several tests were conducted to determine the effect of the applied pressure during a filter press test (Figures 3.19, 3.20, and 3.21). These tests revealed that slurries prepared with sufficient material exhibited relatively constant flow rates, regardless of the applied pressure. Therefore, filter press testing of slurries may be carried out with pressures lower than the 100 psi prescribed by API without adversely affecting the test results. Test pressures may also be tailored to match the greatest anticipated pressure within the excavation.

Test Duration. A standard filter press test, as outlined in the procedures by API, shall be concluded once 30 minutes has elapsed or 25 ml of fluid has been expelled. Lean slurry mixtures (≤ 0.3 lb/gal bentonite and ≤ 0.5 lb/gal attapulgite) exhibit relatively high flow rates, resulting in test durations of less than 30 minutes. If samples are taken periodically over a longer duration, however, the flow rate of these materials decreases significantly, and stabilizes after a short period. Selected tests were carried out utilizing the same setup procedures as outlined by API while allowing the tests to run for two hours or until the full volume of the filter press was evacuated. Three slurries consisting of 0.1 lb/gal Wyo-Ben NaturalGel, 0.1 lb/gal Wyo-Ben Extra High Yield, and 0.1 lb/gal Florigel Attapulgite were prepared for the extended filter press test. Figure 5.5 shows the results of the extended test for all three products.

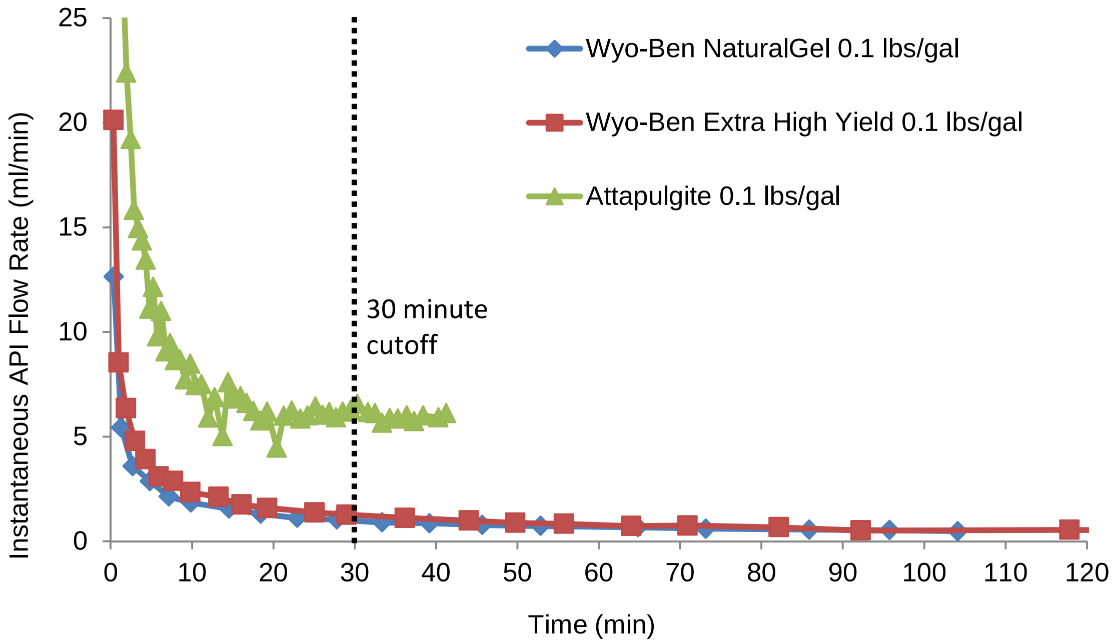

Figure 5.5 Extended filter press results versus elapsed time.

For each test, the flow rate was calculated at approximately 5 ml filtrate intervals. For each of the products, the flow rate stabilized after approximately 15 minutes. Therefore, the 30 minute test duration specified within the API filter press test procedures is conservative, and allows sufficient time for the filter cake to form. The total volume of filtrate which was expelled for each of the products, however, far exceeded the 25 ml cutoff point prescribed by the API procedures. Figure 5.6, shown below, presents the instantaneous flow rates for each of the products with respect to the volume of filtrate passed.

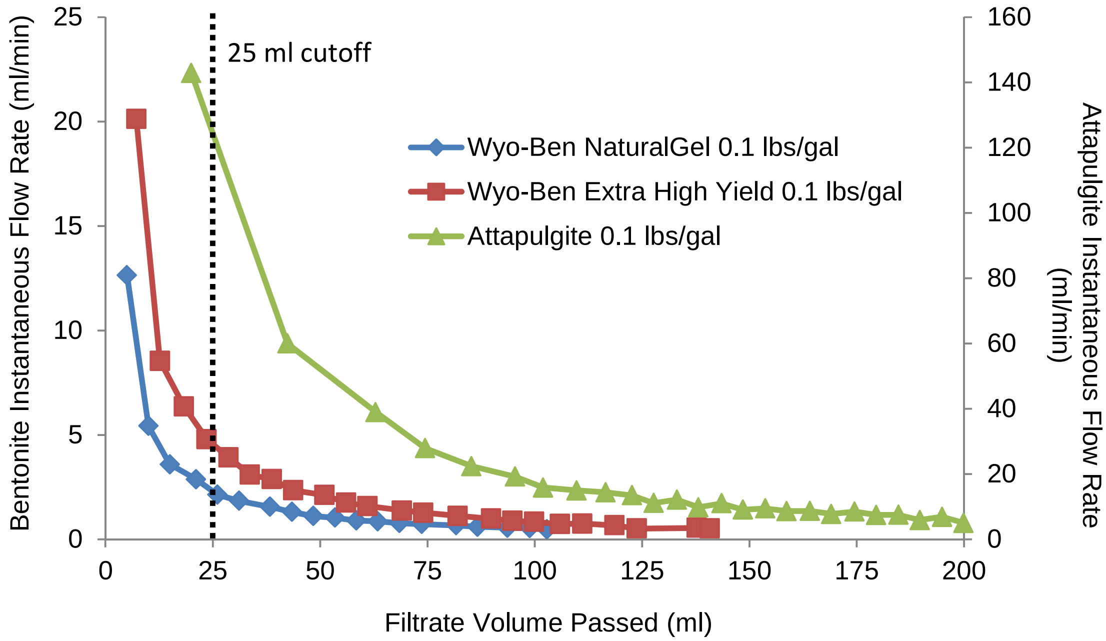

Figure 5.6 Extended filter press results versus filtrate volume.

By limiting the volume of filtrate which may be passed, the procedures established by API restrict the results of the filter press test, preventing the expulsion of enough slurry to develop a significant filter cake. Furthermore, by taking a single reading at the conclusion of the test, a single average flow rate is found, which may not be representative of the final filter cake efficiency. This effect is most notable on products with exceptionally high initial flow rates, such as attapulgite. Figures 5.7, 5.8, and 5.9 highlight the difference between instantaneous and API flow rates of the different products tested.

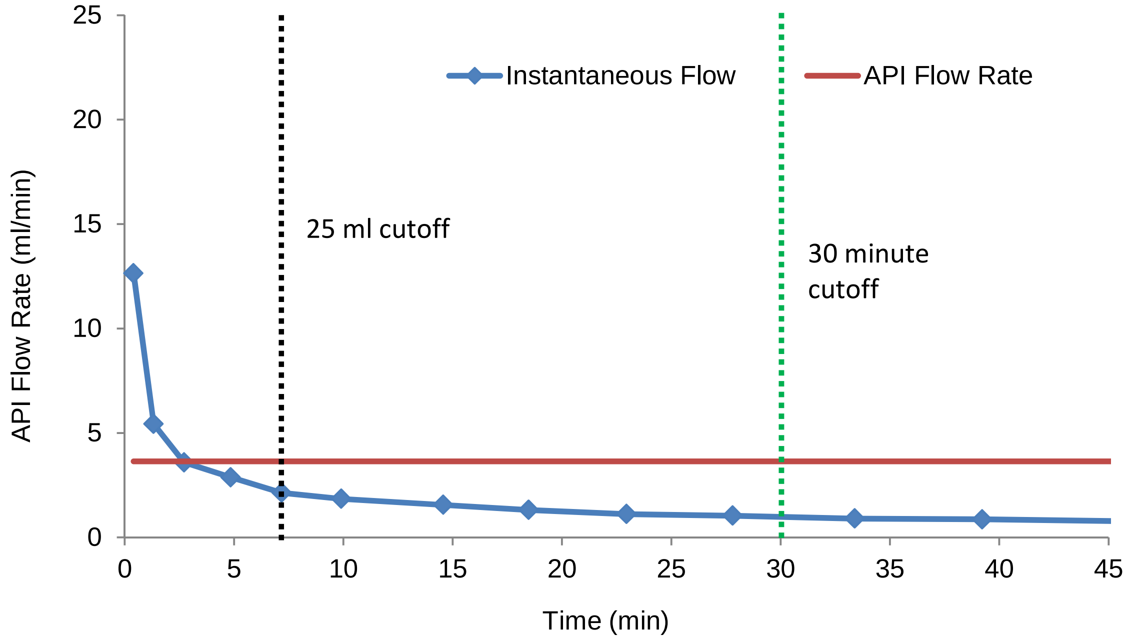

Figure 5.7 Instantaneous and average flow rates for Wyo-Ben NaturalGel (0.1 lb/gal).

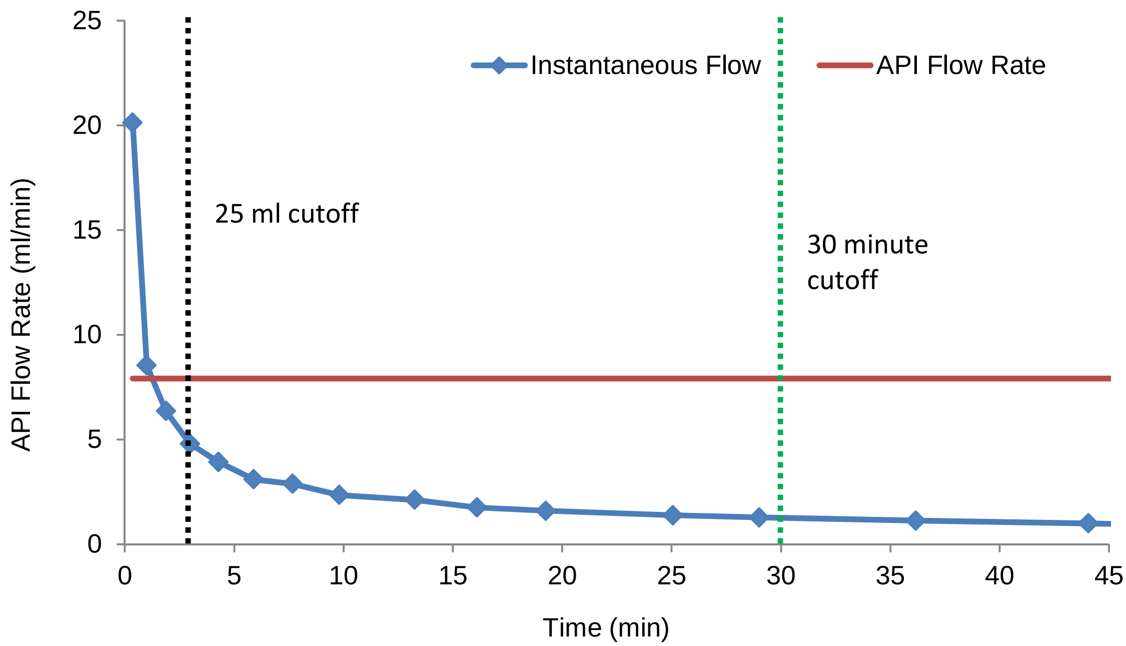

Figure 5.8 Instantaneous and average flow rates for Wyo-Ben Extra High Yield (0.1 lb/gal).

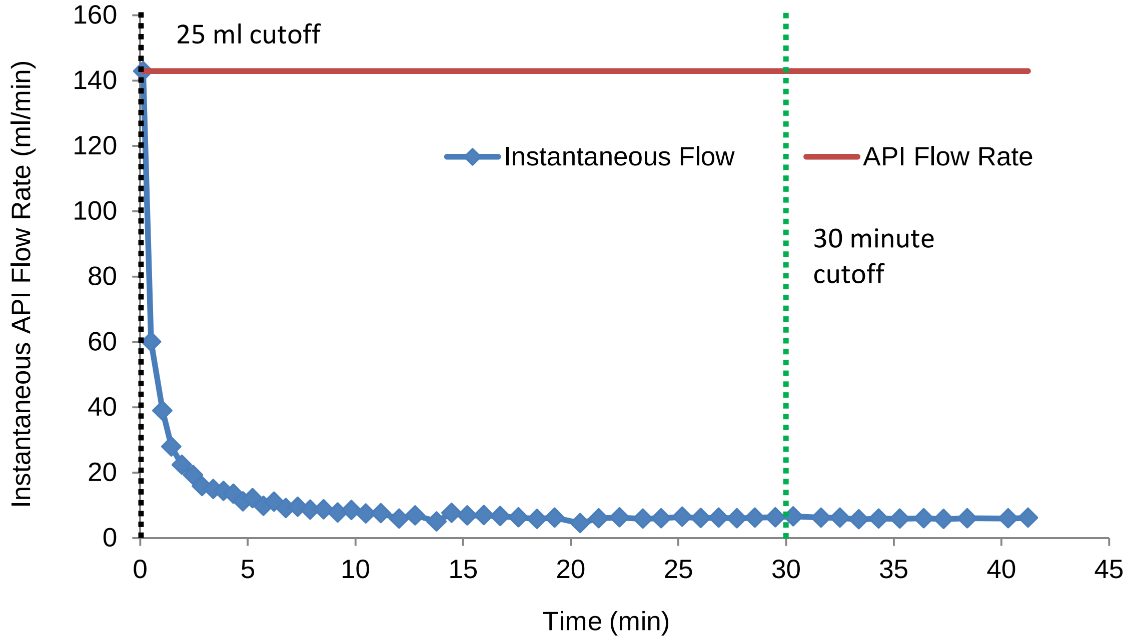

Figure 5.9 Instantaneous and average flow rates for Florigel Attapulgite (0.1 lb/gal).

For the selected testing (Figures 5.7, 5.8, and 5.9), the average flow rates were higher than the final instantaneous flow rates by factors of 7.6, 15.1, and 23.4, respectively. Therefore, it is recommended that API filter press tests should be run for 30 minutes, and flow rates should be measured regularly throughout the test duration as shown.

Additives. The addition of additives to pure bentonite slurry showed an increase in the slurry viscosity and reductions in the flow rate. Therein, two slurry additives were tested with pure bentonite: (1) Wyo-Vis "DP" which is intended to be used as a viscosifier and (2) NO-SAG which is intended to increase suspension. Figures 5.10 and 5.11 show the effect of Wyo-Vis "DP" additive on a pure bentonite slurry. Minimal Wyo-Vis "DP" per mix ratio was required to achieve the recommended minimum viscosity (30 sec/qt). However, at the same mix ratios, Wyo-Vis "DP" had a greater effect on the flow rate (Figure 5.11). Note: mineral mix ratios are expressed in lb/gal and additive concentrations are expressed in lb/100gal.

The amount of Wyo-Vis "DP" required to achieve target viscosities (30, 35, or 40 sec/qt) is shown in Figure 5.12. This ranged from 0 lb/100gal (for the 0.3-0.4 lb/gal mix ratios) to 0.27 lb/100 gal (0.1 lb/gal mix ratio) depending on the initial mix ratio. The manufacturer specified mix ratios range from 0.25 to 1 lb/100 gal depending on soil type which are up to 4 times more than that required to produce a 40 second viscosity. Therefore for the recommended concentrations, the slurry would exceed the maximum viscosity specification even before it was introduced into the excavation.

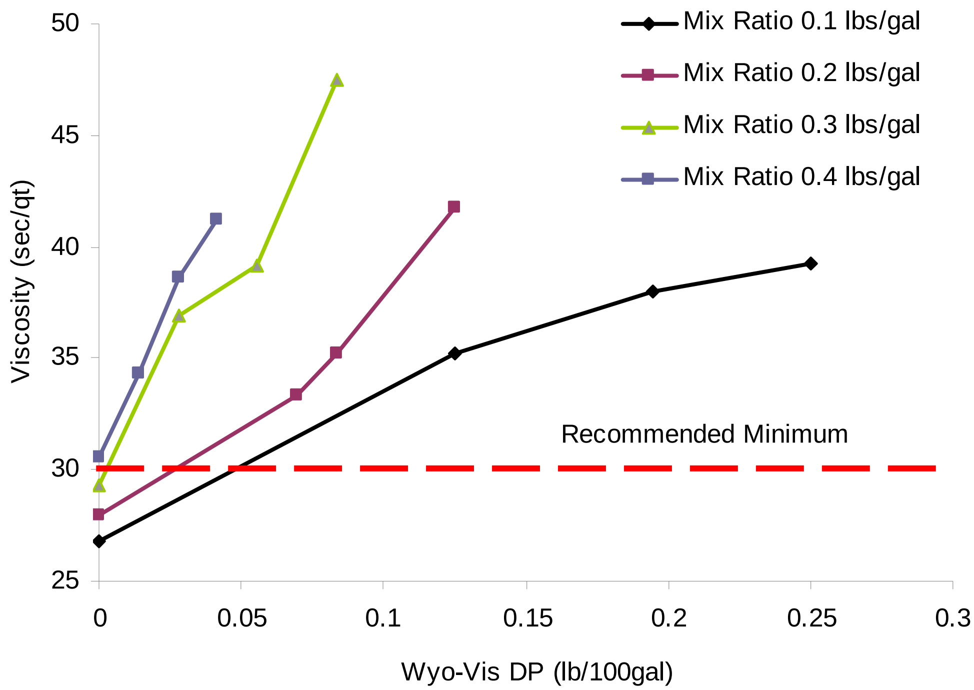

Figure 5.10 Viscosity increase as a function of additive concentration.

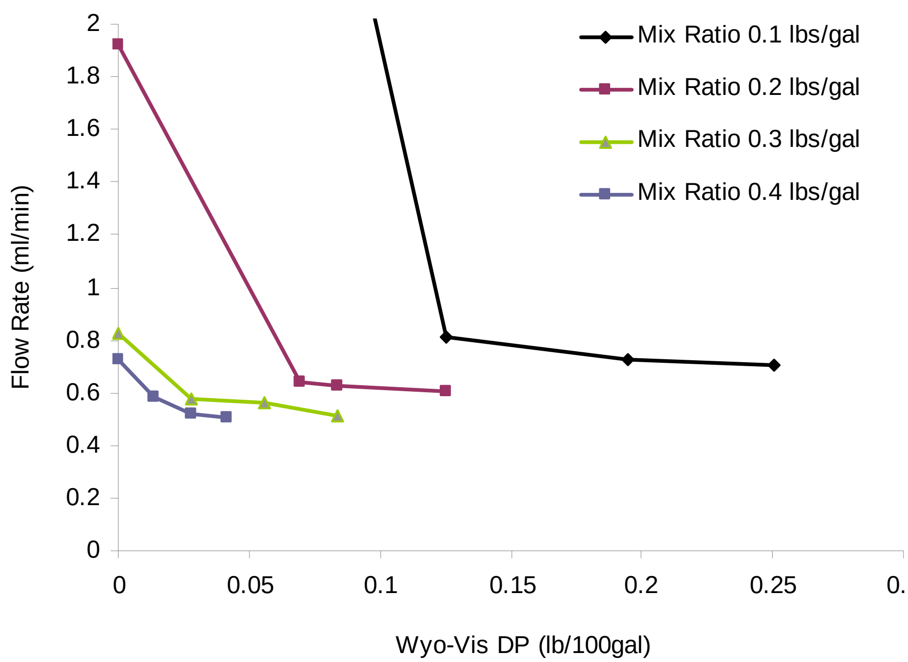

Figure 5.11 Flow rate decrease with increased additive concentrations.

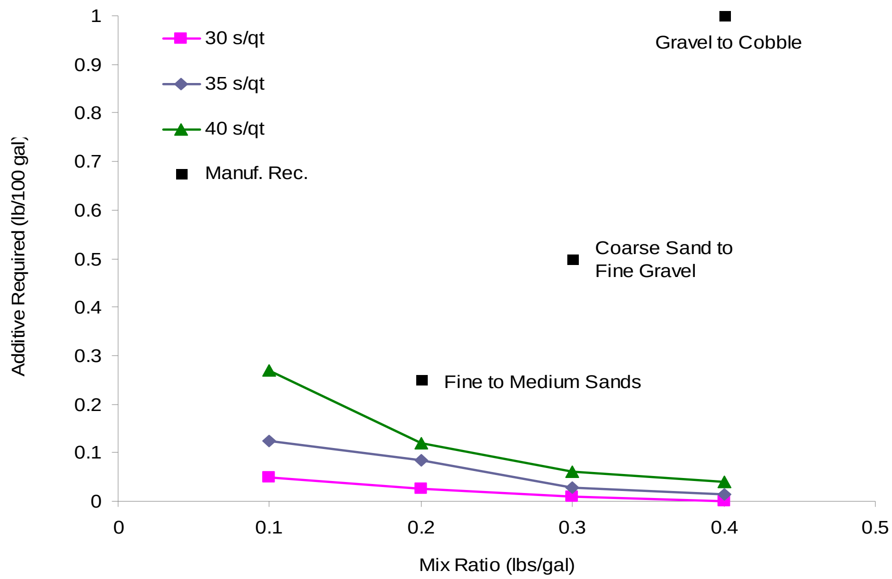

Figure 5.12 Amount of Wyo-Vis "DP" required to produce a desired viscosity for pure bentonite slurry.

Despite the intent to only affect suspension and not viscosity, there was a notable change in viscosity as a function of the NO-SAG additive concentration. From these tests, the amount of NO-SAG required to achieve a target viscosity (30, 35, or 40 sec/qt) could be determined (Figure 5.13). This ranged from 0 to 2.0 lb/100 gal depending on the initial mix ratio (bentonite concentration).

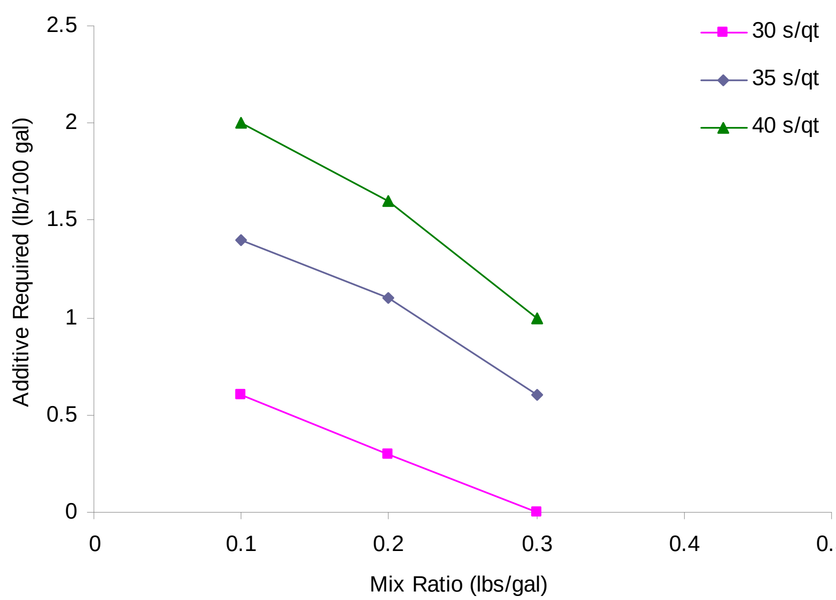

Figure 5.13 Amount of NO-SAG to produce a desired viscosity for a pure bentonite product.

5.2 Sand Content Conclusions

The tests performed to demonstrate gel strength by way of sand suspension showed that pure bentonite products, when mixed to have the recommended minimum viscosity and state minimum density, performed better than polymer fortified slurries. Figure 5.14 shows the percent sand retained in suspension for various slurries wherein each slurry started at an initial sand content between 1 and 8 percent. Therein, between 85 and 100 percent of the sand was retained in suspension at sand contents up to 8 percent. Of those slurries that met FDOT specifications (three shown with blue boxes around the product name) 85-100 percent was suspended when the initial sand content was 4 percent. This concludes that when the slurry is within the recommended limits, the state specification for up to 4 percent sand content is reasonable. Of the six pure polymer slurry mixtures produced, all suspended sand reasonably while meeting FDOT polymer specifications. Large scale settling column tests also showed little fallout from mineral slurries with sand contents over 16 percent when a sufficient mix ratio was used (Figures 4.19 and 4.20).

Considering only pure bentonite when mixed at higher ratios, slurries were able to suspend a greater percentage of sand, as shown in Figure 5.15. Therefore, the gel strength of pure bentonite slurries increases with increasing mix ratios. Recall, the minimum mix ratio to meet FDOT specifications is 0.45 lb/gal, which explains why two of the samples retained sand poorly (0.3 < 0.45lb/gal).

Similarly, attapulgite slurry demonstrated increased sand suspension capability when mixed at higher concentrations. Figure 5.16 highlights the sand suspension properties of attapulgite slurry. Again, very high mix ratios are required to meet FDOT specifications (0.95 lb/gal) which would aid suspension characteristics. Likewise, polymer fortified slurries, typically referred to as “High Yield” products, exhibit increased gel strength when prepared at higher mix ratios, as shown in Figure 5.17.

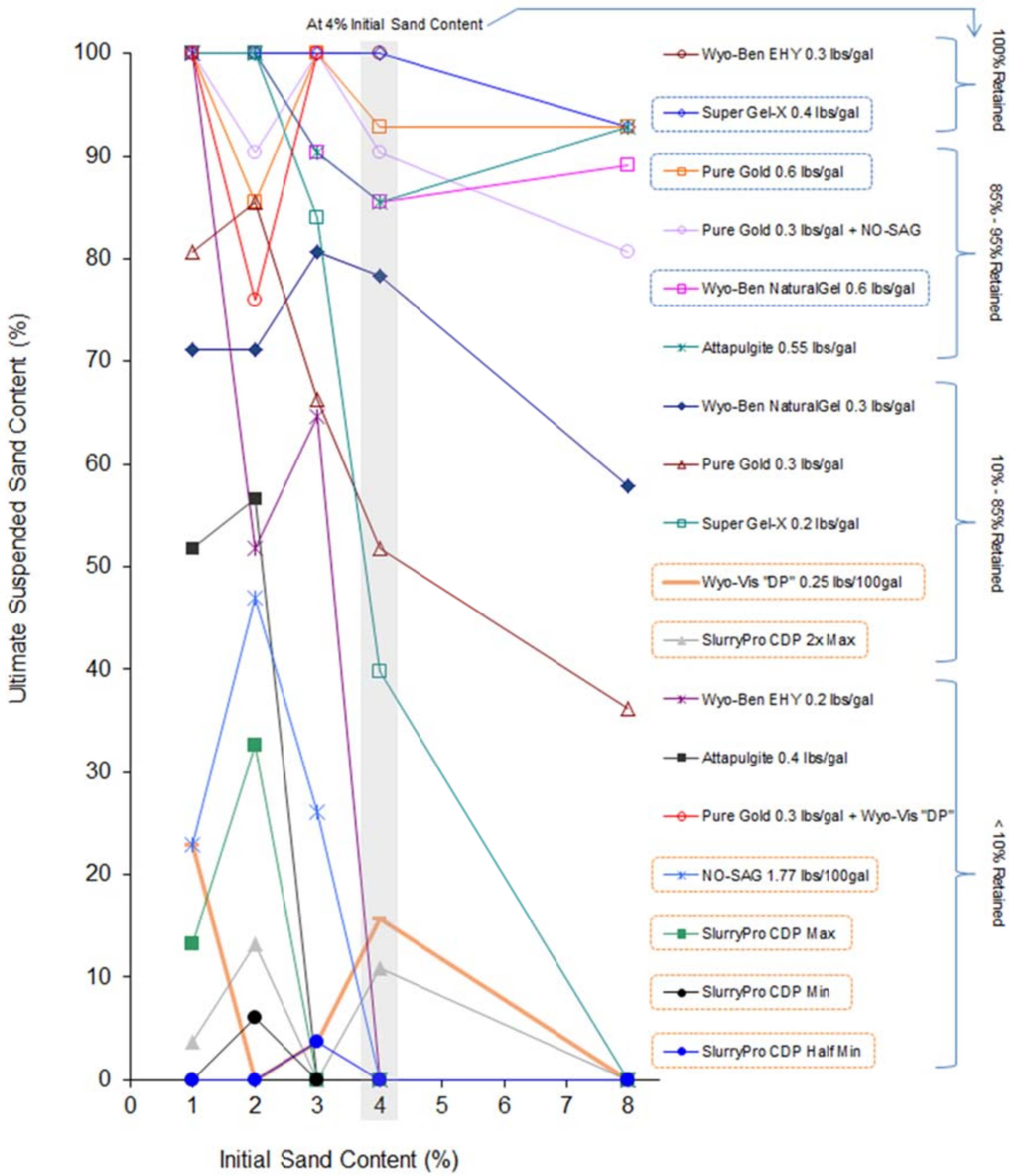

Figure 5.14 Retained sand in suspension for all tested slurries (boxed mineral (blue) and polymer (orange) meet FDOT slurry specifications).

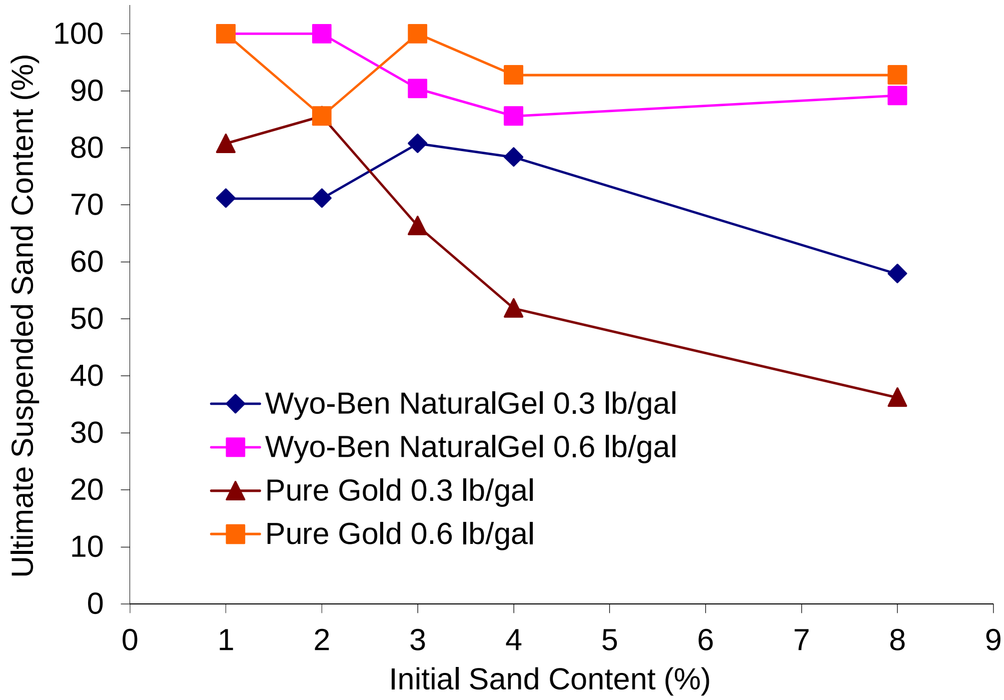

Figure 5.15 Pure bentonite slurry sand suspension.

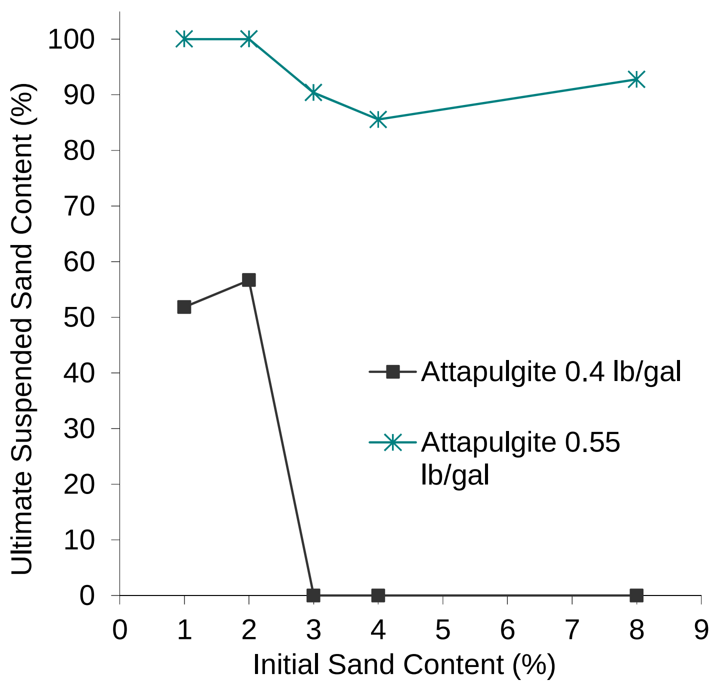

Figure 5.16 Attapulgite slurry sand suspension.

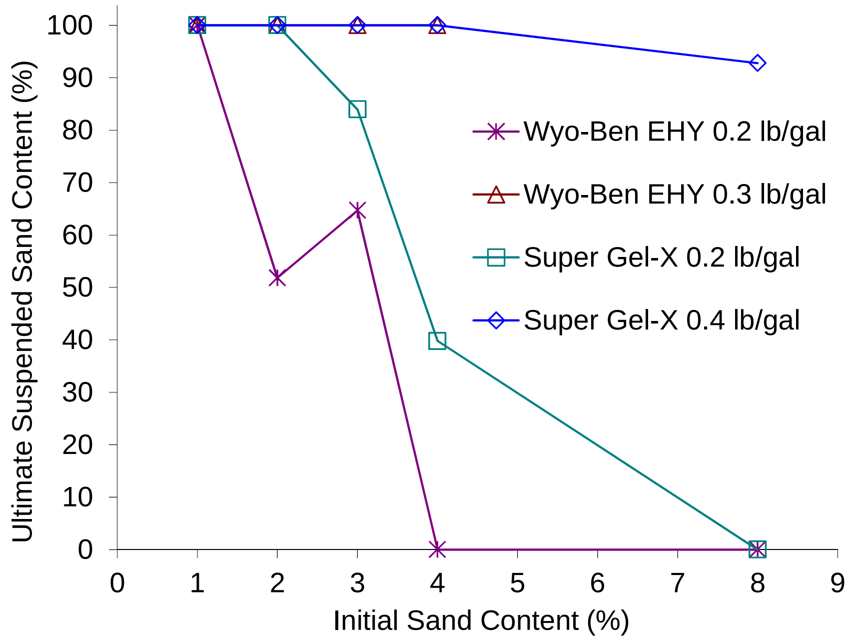

Figure 5.17 Polymer fortified ("High Yield") slurry sand suspension.

Figure 5.18 shows that the NO-SAG suspension enhancer drastically improved the suspension performance of a bentonite slurry with a low mix ratio (0.3 lb/gal). Therein, 85 percent of a 8 percent sand content remained in suspension. However, the additive did not offset the need for additional density (63.2 < 64 pcf required). Wyo-Vis "DP" did not aid in the suspension of sands; rather, it slightly hindered the suspension capability of the sand. This was most likely due to the tendency of the sand to form large clumps which could not be suspended (Figure 4.68), but would be easily removed during the clean out process.

Unlike all mineral slurries, pure polymer slurries exhibited little to no sand suspension capabilities. All polymer slurries were unable to suspend much sand, if any, for any period of time, as demonstrated in Figure 5.19. This demonstrates that the state polymer slurry specification for sand content up to 0.5 percent is justified.

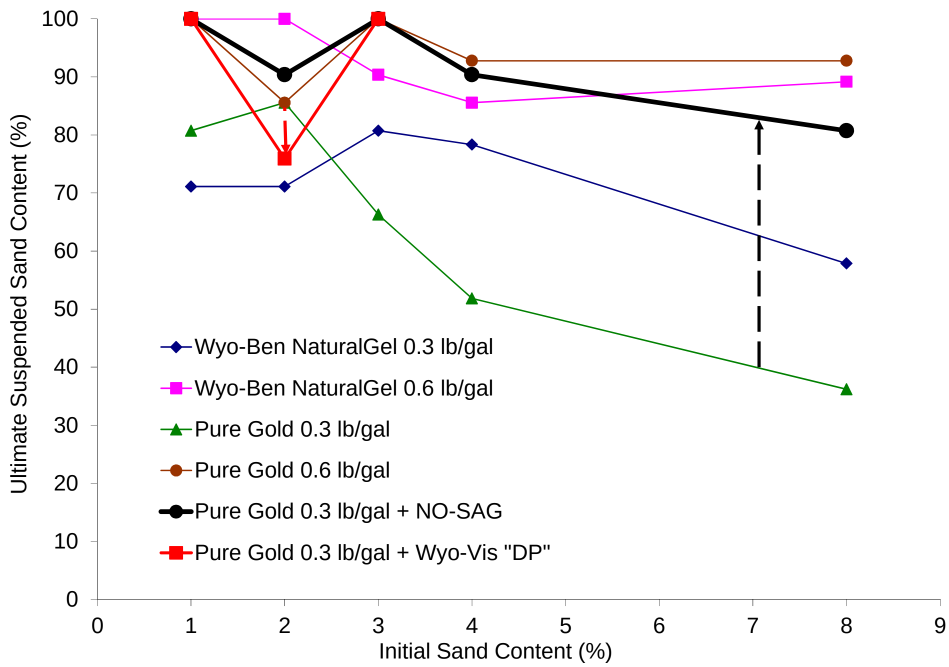

Figure 5.18 Effect of WyoVis and NO-SAG on suspension performance.

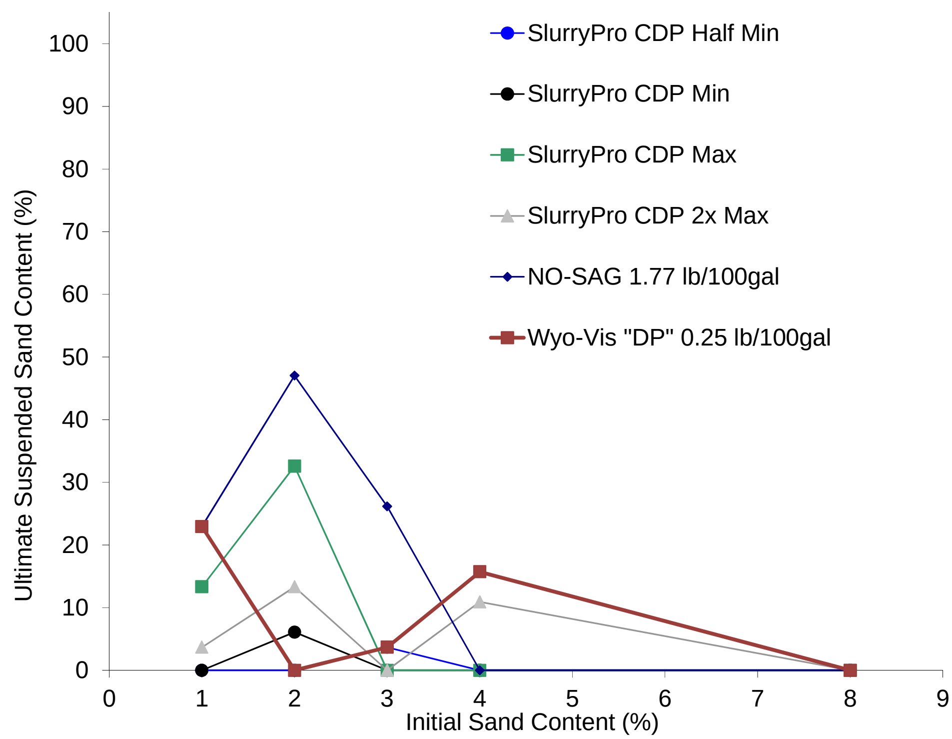

Figure 5.19 Polymer slurry sand suspension.

5.3 Recommendations

Based on the findings of this study, polymer additives can be used to modify and enhance mineral slurries without changing the effectiveness of the base mineral material. It is not possible that quantities of the tested materials could be used at levels that would override the filter cake development that makes mineral slurry preferred for many applications. Therein, very small amounts of additives drive the viscosity above the acceptable specifications (over 40 sec/qt). In the cases where too little mineral product or too much polymer additive is attempted, the minimum density specification cannot be met.

Regardless of whether or not polymer additives are used or not, the API filter press tests showed that current specifications could be changed to increase the minimum acceptable viscosity to 30 sec/qt. This assures the mineral slurry is performing as anticipated and not on the threshold of ineffectiveness.

Suspension enhancers do improve the sand content retention of mineral slurries whereby the state specified upper limit of 4 percent sand content can be reasonably suspended. However, in all cases where sand suspension was maintained, all other slurry properties were met with the exception of the NO-SAG modified slurry tested at 0.3 lb/gal.

In short, by comparing all test data at once (Figure 5.20) good quality slurry can be achieved by using a mix ratio of 0.45 lb/gal for bentonite slurries which should produce both minimum density (64 pcf) and a 33 sec/qt viscosity. Likewise, when using attapulgite slurry a mix ratio of 0.95 lb/gal will meet the minimum density with a 31 sec/qt viscosity (Figure 5.21). Polymer additives, although variable between manufacturers, should not impinge on present state specifications for mineral slurry properties, but rather will only supplement their performance recognizing that only very low concentrations can be introduced without having the slurry fall out of specification limits.

Finally, Figures 5.20 and 5.21 have been prepared as a quick reference to both show the effect of mix ratios on slurry properties and provide a guide to mineral quantities for slurry preparation.

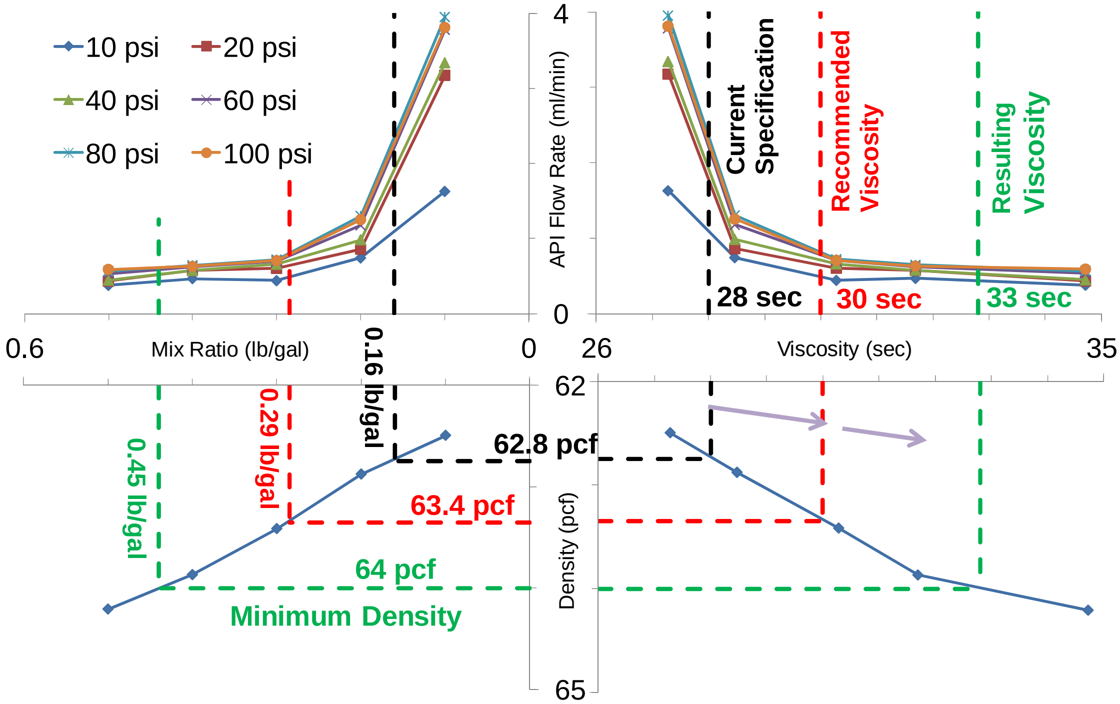

Figure 5.20 Mix ratio selection plots for bentonite.

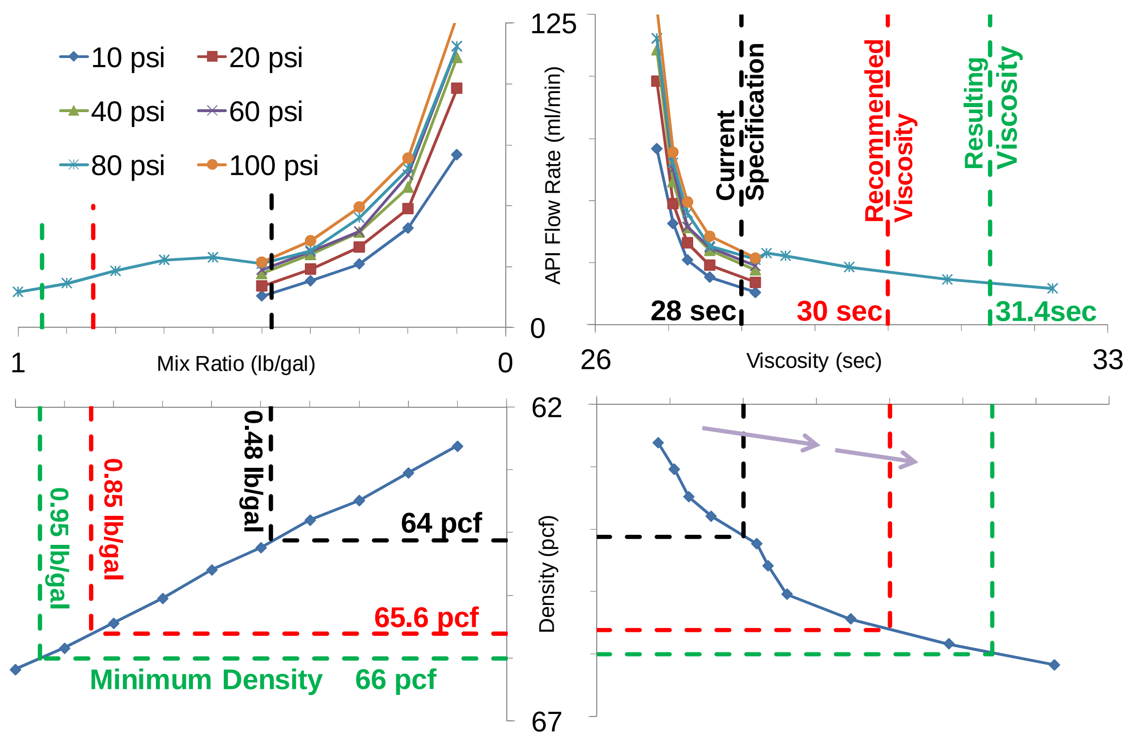

Figure 5.21 Mix ratio selection plots for attapulgite.

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Appendix A: Available Products

Table A.1 CETCO Products (CETCO, 2011)

Product	Description
ACCU-VIS®	ACCU-VIS is a liquid copolymer designed for fast field mixing, viscosity building, and clay/shale stabilization in aqueous drilling fluids. ACCU-VIS is certified to NSF/ANSI Standard 60, Drinking Water Treatment Chemicals - Health Effects.
ACCU-VIS®_BELLE CRUMBLES™	ACCU-VIS/BELLE CRUMBLES blends a granular bentonite with a quick activating liquid polymer to form a slurry that provides an economical way to seal and grout boreholes, well casings, and earthen structures. Once set, the slurry forms a complete grout seal with low permeability.
BARITE	High-grade barium sulfate specially processed for use as a drilling fluid weighting additive. BARITE meets the API Specification 13A, Section 2 requirement for a drilling fluid BARITE.
BENTOGROUT®	BENTOGROUT is an easy mixing, organic-free, high-solids bentonite grout engineered to form a contaminant resistant seal without affecting groundwater chemistry. BENTOGROUT is a technically superior replacement for traditional cement grouts.
BMR™	BMR removes bentonite that has been introduced as a drilling fluid and results in a tough layer of mud sometimes difficult to remove. Additionally, BMR removes naturally occurring clays that intrude into the gravel pack. BMR is certified to NSF/ANSI Standard 60, Drinking Water Treatment Chemicals - Health Effects.

Table A.1 (continued)

Product	Description
C/S GRANULAR™ & CETCO® CRUMBLES	C/S GRANULAR and CETCO CRUMBLES are granular bentonite products composed of polymer-free, dried bentonite in various mesh sizes. CETCO CRUMLBES are coarser in size than C/S GRANULAR. C/S GRANULAR and CETCO CRUMBLES are certified to NSF/ANSI Standard 60, Drinking Water Treatment Chemicals - Health Effects.
CETCO® COARSE CHIPS & PUREGOLD® MEDIUM CHIPS	CETCO COARSE CHIPS are natural sodium bentonite screened to 3/8 inch (0.95 cm) to 3/4 inch (1.90 cm) in size. PUREGOLD MEDIUM CHIPS are natural sodium bentonite screened to 1/4 inch (0.64 cm) to 3/8 inch (0.95 cm) in size. CETCO COARSE CHIPS and PUREGOLD MEDIUM CHIPS are certified to NSF/ANSI Standard 60, Drinking Water Treatment Chemicals - Health Effects.
CETCO® COATED TABLETS	CETCO COATED TABLETS are coated using an aqueous carrier to apply the coating. The coating allows the tablets to reach a discrete depth within the waterwell, piezometer, monitoring well, or annular space. These untreated organic tablets are compressed into 1/4” (0.64 cm) and 3/8” (0.95 cm) sizes. CETCO COATED TABLETS are certified to NSF/ANSI Standard 60, Drinking Water Treatment Chemicals - Health Effects.
CETCO® DEFOAMER	CETCO DEFOAMER is a non-ionic silicone solution designed to reduce surface tension and break foam bubbles over a wide variety of conditions. Defoam in various media encountered in waterwell, large diameter shaft holes, geothermal, and oilfield drilling.

Table A.1 (continued)

Product	Description
CETCO® GRANULAR GROUT	CETCO GRANULAR GROUT mixes into a smooth bentonite grout that has no lumps and pumps easily. CETCO GRANULAR GROUT is dust-free, offers reduced friction going down the tremie pipe, and has a firm set-up with little settling. CETCO GRANULAR GROUT is certified to NSF/ANSI Standard 60, Drinking Water Treatment Chemicals - Health Effects.
CETCO® GROUT	CETCO GROUT is a 20% solids, polymer-free, single-component,easy-to-use sodium bentonite grout available in powdered form. CETCO GROUT allows placement in a low viscosity state. CETCO GROUT is certified to NSF/ANSI Standard 60, Drinking Water Treatment Chemicals - Health Effects.
CETCO® JOINT COMPOUND	CETCO JOINT COMPOUND is a lead-free, premium grade tool joint and drill collar lubricant for heavy duty drilling. This special mixture of the finest blend of copper flakes with a superior base gives maximum protection under extreme temperature and adverse conditions.
CETCO® MX-80 GROUT	CETCO MX-80 GROUT is a granular bentonite product composed of dried bentonite clay with a typical size range between 30 and 100 mesh.
CETCO® TABLETS	CETCO TABLETS are organic free, high-swelling pure sodium bentonite. CETCO TABLETS are compressed into 1/4 (0.63 cm), 3/8” (0.95 cm), and 1/2” (1.27 cm) diameters. CETCO TABLETS are certified to NSF/ANSI Standard 60, Drinking Water Treatment Chemicals - Health Effects.

Table A.1 (continued)

Product	**Description**
CLAY CUTTER™	CLAY CUTTER is a concentrated, non-hazardous, proprietary clay inhibitor that can be used with either polymer or bentonite drilling fluid systems. CLAY CUTTER is an ideal additive for HDD bores in reactive clay soils.
CLAY CUTTER™ DRY	CLAY CUTTER DRY is an easy-mixing, water-soluble, polymer used in horizontal and vertical drilling applications. CLAY CUTTER DRY should be added to fresh or saltwater drilling fluids to increase cuttings returns and reduce torque and drag when drilling in reactive clay soils. This additive may be used in both HDD and Waterwell applications.
DE-CHLOR™	DE-CHLOR is a white granular crystal that neutralizes chlorine in municipal water. Chlorine in water supplies can destroy polymer drilling fluids.
DPA™	DPA cleans casing, screens, gravel packs, and water-bearing formations of deposits consisting of mineral scale. Calcium carbonate, iron, and manganese are the most common. DPA is a granular product and is certified to NS F/ANSI Standard 60, Drinking Water Treatment Chemicals - Health Effects.
DRILL-TERGE™	DRILL-TERGE is a liquid solution of nonionic surfactants formulated to increase detergency and wetting properties of drilling fluids. Designed to control interfacial tension and inhibit the hydration and dispersion of clay and shale.

Table A.1 (continued)

Product	Description
GEOTHERMAL GROUT™	GEOTHERMAL GROUT is a specially blended high solids bentonite that can be mixed with sand in a two-part thermally conductive grouting material to improve the performance of ground source heat loop applications. GEOTHERMAL GROUT is an easy pumping grout that has been carefully developed to efficiently suspend solids (silica sand) for enhanced thermal conductivity. GEOTHERMAL GROUT can be mixed to meet a range of thermal conductivity (TC)from 0.40 to 1.00 Btu/hr/ft/F (0.68 to 1.69 W/mK). GEOTHERMAL GROUT is certified to NSF/ANSI Standard 60, Drinking Water Treatment Chemicals - Health Effects.
GROUNDING GROUT™	GROUNDING GROUT is a high-solids, single-component, organic bentonite grout. GROUNDING GROUT is specially formulated to provide a conductive seal around grounding rods. When used to seal drilled boreholes in which vertical grounding rods are placed, GROUNDING GROUT increases the grounding system's conductivity by lowering the resistivity from 300 ohms/meter with normal soil to 0.76 ohms/meter. GROUNDING GROUT adheres to the entire surface of the grounding rod, providing the smallest surface area and, consequently, offering the greatest effective resistance area. This helps to stabilize the ground resistance despite seasonal changes in temperature and soil moisture content.

Table A.1 (continued)

Product	Description
HIGH TC GEOTHERMAL GROUT™	HIGH TC GEOTHERMAL GROUT is a specially blended high solids bentonite that can be mixed with sand in a two-part, thermally conductive grouting material to improve the performance of ground source heat loop applications. HIGH TC GEOTHERMAL GROUT is an easy pumping grout that has been carefully developed to efficiently suspend solids (silica sand) for enhanced thermal conductivity. HIGH TC GEOTHERMAL GROUT can be mixed to meet a range of thermal conductivity (TC) from 0.40 to 1.21 Btu/hr/ft/F(0.68 – 2.05 W/mK). HIGH TC GEOTHER MAL GROUT is certified to NSF/ANSI Standard 60, Drinking Water Treatment Chemicals - Health Effects.
HYDRAUL-EZ®	HYDRAUL-EZ is a high-yield, 200 mesh sodium bentonite with a special dry polymer additive. It is designed to maintain borehole integrity in horizontally drilled boreholes. HYDRAUL -EZ is certified to NSF/ANSI Standard 60, Drinking Water Treatment Chemicals - Health Effects.
INSTA-CLEAR™ DRY	INSTA-CLEAR DRY is a specially blended dry granular product designed for both polymer and water slurry. When added into either type of slurry, INSTA-CLEAR DRY reacts instantly to settle suspended solids and decrease turbidity. INSTA-CLEAR DRY can be added at the tank or directly to the excavation prior to cleanout.

Table A.1 (continued)

Product	Description
INSTA-FLOC™ DRY	INSTA-FLOC DRY is a specially blended dry granular product designed for polymer slurries and water filled boreholes. When INSTA-FLOC DRY is added, it reacts instantly to settle solids. INSTA-FLOC DRY clears the slurry rapidly of silt and sand build-up. It works fast for water sampling and downhole filming.
INSTA-VIS™ DRY	INSTA-VIS DRY is an easy mixing, water soluble, high molecular weight anionic polymer. This granular polymer improves drilling efficiency in both horizontal and vertically drilled holes by controlling shales and clays, improving lubricity, and increasing viscosity.
INSTA-VIS™ PLUS	INSTA-VIS PLUS is a multi-functional liquid polymer designed to improve drilling efficiency in both horizontal and vertical drilled holes through its rapid field mixing, viscosity development, and clay and shale inhibition. INSTA-VIS PLUS is certified to NSF/ANSI Standard 60, Drinking Water Treatment Chemicals - Health Effects.
MACRO-FILL	MACRO-FILL is a granular, advanced super-absorbent material that rapidly absorbs and retains large volumes of water from aqueous solutions. MACRO-FILL may absorb up to 300 times its weight in freshwater while expanding less than 5% in total volume.
MAGMA FIBER	MAGMA FIBER is a specially formulated, extrusion spun mineral fiber. This coarse, long flexible fiber will give increased circulation by bridging and plugging off voids, fractures, and all types of permeable formations.

Table A.1 (continued)

Product	Description
MARSH FUNNEL & CUP	Viscosity is a measurement of a fluid's resistance to flow: the greater the resistance, the higher the viscosity. As measured by the MARSH FUNNEL , the viscosity of the fluid in question is influenced by the density of the fluid (solids content) and gelation rate (beneficiated solids content). The viscosity of the drilling fluid in use should be based on a combination of the following parameters: drilling rate, pump and output capacity, mud density, cutting size, hole size, and solids removal equipment.
MEDIUM CHIPS	MEDIUM CHIPS are natural sodium bentonite screened to ¼" to ⅜" in size. This product is used to prevent or stop extreme fluid loss in porous geology.
MUD BALANCE	A mud balance is an instrument generally used to determine mud weight that will permit accurate measurement within $^{1}/_{10}$ lb/gal or $^{1}/_{2}$ lb/ft^3. Mud weight can be expressed in lb/gal, lb/ft^3, psi/1,000 ft of depth or specific gravity (S.G.).
MULTI-SEAL	MULTI-SEAL is a select blend of four types of materials normally used for lost circulation. A flake material (cellophane), a granular material (nut shells), fine fibrous material (ground paper), and coarse fibers (cedar fibers). MULTI-SEAL is blended in the proper ratio to produce the most effective seal. MULTI-SEAL contains no fermenting materials or materials that chemically change the rheological properties of the fluid, even polymer mud's.

Table A.1 (continued)

Product	Description
	PREMIUM GEL is a 200 mesh, 90 bbl yield sodium bentonite for freshwater drilling, slurry walls, and tunnel boring. PREMIUM GEL complies with API 13A Section 9, Specifications for Drilling Fluid Materials.
PROSHOT™	PROSHOT is an easy mixing, water soluble polymer used in horizontal and vertical drilling applications. For use in a variety of soils types. Use as a stand alone additive or in combination with SUPER GEL-X or HYDRAUL-EZ.
PUREGOLD® GEL	PUREGOLD GEL is a minimum 80-90 bbl yield, organic-free, untreated, high quality bentonite drilling fluid designed for the groundwater monitoring industry. It complies with API 13A Section 10, Specifications for Drilling Fluid Materials.PUREGOLD GEL is certified to NSF/ANSI Standard 60, Drinking Water Treatment Chemicals - Health Effects.
PUREGOLD® GROUT	PUREGOLD GROUT is an easy mixing, organic-free, high-solids bentonite grout engineered to form a contaminant resistant seal without affecting groundwater chemistry. PUREGOLD GROUT is a technically superior replacement for traditional cement grouts. PUREGOLD GROUT is certified to NSF/ANSI Standard 60, Drinking Water Treatment Chemicals - Health Effects.
PUREGOLD® LUBE	PUREGOLD LUBE is an environmentally safe premium grade lubricant, free of petroleum hydrocarbons and metals. PUREGOLD LUBE is a tool joint lubricant designed for use in environmental drilling.

Table A.1 (continued)

Product	Description
REL-PAC®	REL-PAC is a non-fermenting granular polymer designed for building a low solids drilling fluid with increased borehole stability. REL-PAC is a highly dispersible polymer, which prevents the formation of hard lumps or fish eyes, for maximum product efficiency.
REL-PAC® XTRA-LOW	REL-PAC XTRA-LOW is a low viscosity, non-fermenting dry polymer designed for use as a more efficient filtration control additive in a variety of drilling fluid applications. Intended for use in bentonite and polymer fluids.
SAMPLE BAILER	SAMPLE BAILER has a second ball check located at the top that permits the bailer to secure a sample from a specific depth without influence from the slurry above. Meets contract specifications for collecting slurry samples for testing physical drilling slurry properties.
SAND CONTENT KIT	It is desirable to know the sand content of drilling muds because excessive sand may result in the deposition of a thick filter cake on the wall of the hole, or may settle in the hole about the tools when circulation is stopped, thus interfering with successful operations of drilling tools or setting of casing. High sand content also may cause excessive abrasion of pump parts and pipe connections. Sand sized particles are defined as anything larger than 74 microns. This test can be performed on low solids muds as well as on weighted muds.

Table A.1 (continued)

Product	Description
SAND SEALANT/MULTISEAL	By combining two fluid loss additives together a solution was developed for controlling slurry fluid loss in drilled shafts. SAND SEALANT a specially blended dry powdered mineral and MULTI-SEAL a dry select blend of four types of materials a flake material, a granular material, a fine fibrous material, and course fibers used for fluid loss control. SAND SEALANT/MULTI-SEAL added to a hole filled with SHORE PAC slurry, reduces slurry seepage into saturated open porous permeable cobbles, sands, and gravels.
SC-200™	A liquid surfactant, SC-200 is a safe, clean, and cost-effective approach to waterwell development and rehabilitation. This wetting agent enhances the dispersing efficiency of other well rehabilitation products. SC-200 enables these products to enter into the pores and cracks of the encrustations, thereby accelerating the rehabilitation process.
SHORE PAC®	SHORE PAC is an easy mixing, water soluble polymer supplied as a granular powder. SHORE PAC is designed for preparation of viscous earth-reinforcing fluids or slurries for a variety of drilling, trenching, and walling applications in the geo-construction industry. SHORE PAC is ideal for slurry trenching, diaphragm walls, drilled shafts/bored piles, and tunneling.

Table A.1 (continued)

Product	**Description**
SLURRY BUSTER™ DRY	SLURRY BUSTER DRY is an industrial grade oxidizing agent used to breakdown SHORE PAC polymer slurry. This white granular solid dissolves completely when applied to SHORE PAC polymer slurry. The active ingredient is a powerful class III oxidizer that ensures rapid and complete slurry degradation. SLURRY BUSTER DRY is supplied in plastic re-sealable pails. SLURRY BUSTER DRY is a highly effective clean-up solution.
SLURRYBOND™	SLURRYBOND is a powdered inorganic mineral formula used for the solidification of high solids drilling slurries. SLURRYBOND is made from non-biodegradable mineral designed for use on waste slurry that fails to pass a Paint Filter Liquids Test (PFLT).
SODIUM BICARBONATE	SODIUM BICARBONATE , NaHCO3 is used to lower the pH of drilling slurry from a pH of 12-13 (alkaline) to a neutral pH range of 8-9. A white powder, SODIUM BICARBONATE is also added to a base drilling fluid as a pH neutralizing additive. A buffer, SODIUM BICARBONATE is added to acidic water to raise the pH to 8-9.

Table A.1 (continued)

Product	**Description**
SODIUM HYDROXIDE	SODIUM HYDROXIDE, NaOH, is a white solid sold in pellet form. SODIUM HYDROXIDE is completely ionic, containing sodium ions and hydroxide ions. The hydroxide ions make SODIUM HYDROXIDE a strong base which reacts with acids to form water and salts. This is what controls the pH of SHORE PAC slurry when drilling in acidic organic peat soil and brackish salt-impacted soil. SODIUM HYDROXIDE is also an alkaline metallic base, making it an ideal pre-treatment additive to enhance flocculation of solids with the INSTA-CLEAR DRY additive.
STONE STOP™	STONE STOP granular sealant is composed of polymer-free, dried minerals in various mesh sizes. STONE STOP is coarser in size than SAND SEALANT and controls slurry loss in extreme conditions.
SUPER PAC™	SUPER PAC is an easy mixing, liquid polymer that enhances the properties of a bentonite drilling fluid. When added to HYDRAUL-EZ or SUPER GEL-X, SUPER PAC creates an ideal fluid for drilling in a variety of conditions.
SUPER PAC™ XTRA-LOW	SUPER PAC XTRA-LOW is a low viscosity, liquid multi-purpose polymer. SUPER PAC XTRA-LOW enhances the beneficial properties of bentonite and polymer drilling fluids.

Table A.1 (continued)

Product	Description
SUPER THIN™	SUPER THIN is a highly concentrated additive engineered to reduce drilling fluid viscosity, assist in settling solids, and disperse the filter cake created by a bentonite drilling fluid. It offers immediate thinning action, reduces gel strength, and is more cost-effective than traditional thinners. SUPER THIN is certified to NSF/ANSI Standard 60, Drinking Water Treatment Chemicals - Health Effects.
SUSPEND-IT™	SUSPEND-IT is an easy mixing biopolymer additive used to control drilling fluid rheology. Designed to enhance gel strength of the drilling fluid for improved suspension and transporting of drill cuttings, gravel, and cobble on long bores. SUSPEND-IT will perform effectively in fresh or saltwater.
VARIFLO® QD	VARIFLO QD is a coarse granular, high-viscosity blend of guar gum formulated for easy and quick dispersion in drilling applications. Coarser granules prevent lumps or encapsulation.
VOLCLAY® CG-50	VOLCLAY CG-50 is a natural, granular, high-swelling Wyoming sodium Bentonite recommended for slurry wall applications. VOLCAY CG-50 can be used to seal earthen structures, general sealing, and slurry wall construction.

Table A.2 Baroid alkalinity agents (Baroid IDP, 2011)

Product	Description
Soda Ash Alkalinity Agent	Used to soften make-up water and raise pH

Table A.3 Baroid bentonite products (Baroid IDP, 2011)

Product	Description
AQUAGEL GOLD SEAL Viscosifier	Premium, high-yielding Wyoming sodium bentonite that contains no polymer additives or chemical treatments
AQUAGEL Viscosifier	Finely ground, premium-grade Wyoming sodium bentonite
BORE-GEL Boring Fluid System	A single sack, boring fluid system specially formulated for use in horizontal directional drilling (HDD) applications
IDP-512	IDP-512 high-yield boring fluid system is specially formulated for use in horizontal directional drilling (HDD), primarily tunneling and microtunneling applications. IDP-512 high-yield boring fluid system is a proprietary blended product using Wyoming sodium bentonite.
QUIK-GEL GOLD High Yield Viscosifier	A selectively mined, premium sodium bentonite
QUIK-GEL Viscosifier	An easy-to-mix, finely ground (200-mesh), premium-grade, high-yielding Wyoming sodium bentonite

Table A.4 Baroid filtration control (Baroid IDP, 2011)

Product	Description
AQUAGEL GOLD SEAL Viscosifier	Premium, high-yielding Wyoming sodium bentonite that contains no polymer additives or chemical treatments
AQUAGEL Viscosifier	Finely ground, premium-grade Wyoming sodium bentonite
BARAD-381	BARAD-381™ cement additive is a dry, free-flowing powder designed to reduce the filtration rate and retard the set of Portland Cement slurries used in water well, minerals exploration and construction applications. When used in conjunction with Portland Cement at the recommended concentration, BARAD-381 cement additive creates a slurry with enhanced flow properties and improved bonding characteristics.
IDP-381 Cement Additive	Dry, free-flowing powder designed to reduce the filtration rate and retard the set of Portland Cement slurries
LIQUI-TROL Modified Cellulosic Polymer Suspension	A modified natural cellulosic polymer
QUIK-TROL Filtration Control Additive	A modified natural cellulosic polymer
QUIK-TROL GOLD PAC Polymer	Highly dispersible PAC polymer
QUIK-TROL LV Filtration Control Additive	A modified natural cellulosic polymer

Table A.5 Baroid foaming agents (Baroid IDP, 2011)

Product	**Description**
AQF-2 Foaming Agent	Anionic surfactant foaming agent
BARA-DEFOAM 500	BARA-DEFOAM® 500 defoamer is designed for topical application to break down foam associated with air/foam drilling operations. BARA-DEFOAM 500 defoamer can be used to defoam most water-based drilling fluids.
QUIK-FOAM High Performance Foaming Agent	A proprietary biodegradable blend of alcohol ethoxy sulfates (AES)
Seadrill S-110 Antifoam	Antifoaming agent

Table A.6 Baroid lost circulation materials (Baroid IDP, 2011)

Product	**Description**
DIAMOND SEAL Absorbent Polymer for Lost Circulation	Water-swellable but not water-soluble, 100% crystalline synthetic polymer
Drilling Paper Lost Circulation Material	Shredded cellulosic fiber
FUSE-IT Lost Circulation Material	Synthetic polymer lost circulation material
N-SEAL Lost Circulation Material	Acid soluble lost circulation material

Table A.7 Baroid lubricants (Baroid IDP, 2011)

Product	**Description**
BARO-LUBE GOLD SEAL Drilling Fluid Lubricant	BARO-LUBE GOLD SEAL
CORE-LUBE Core Barrel Lubricant	Natural linseed-based soft soap
EP MUDLUBE Extreme Pressure Lubricant	Modified tall oil fatty acid
IDP-214 Rod Grease	IDP-214
IDP-496 Torque Reducer	IDP 496
IDP-533 Torque Reducer	IDP-533
LUBRA-BEADS Spherical Bead Lubricant	LUBRABEADS
NXS-LUBE Extreme Pressure Lubricants	Proprietary blend of synthetic components formulated to help provide friction reduction in water-based fluids

Table A.8 Baroid shale/clay stabilizers (Baroid IDP, 2011)

Product	Description
EZ-MUD DP Borehole Stabilizing Dry Polymer	A dry granular synthetic, free-flowing polymer
EZ-MUD GOLD Clay and Shale Stabilizer	Clay and shale stabilizer for inhibition of clay and shale formations in water-based drilling fluids
EZ-MUD PLUS Polymer Emulsion	A high molecular weight version of EZ-MUD with improved properties
EZ-MUD Polymer Emulsion	Polymer emulsion
IDP-415	IDP-415
POLY-BORE Borehole Stabilizing Dry Polymer	A free flowing, water-soluble, easy mixing, 100% dry granular polymer
QUIK MUD D-50 Liquid Polymer Dispersion	Liquid polymer dispersion PHPA copolymer
QUIK MUD GOLD Clay/Shale Stabilizer	Inhibition of clay and shale formations in water-based drilling fluids without substantial increase in viscosity

Table A.9 Baroid slurry modification and disposal (Baroid IDP, 2011)

Product	Description
IDP-428 Gelling Agent	Dry, free-flowing, powder designed to gel spent drilling fluid and/or slurries to a solid waste
SYSTEM FLOC-360 Flocculant	Polymeric flocculant used to flocculate clays and shales

Table A.10 Baroid thinners/dispersants (Baroid IDP, 2011)

Product	**Description**
AQUA-CLEAR PFD Polymer Dispersant	Concentrated liquid polymer dispersant
BARAFOS Thinner/Dispersant	Non-glassy, modified polyphosphate used as a thinner and dispersant in freshwater drilling fluids
IDP-444	IDP-444
SAPP Thinner	A commercial chemical used as a thinner and dispersant in freshwater drilling fluids and as an aid in water well development

Table A.11 Wyo-Ben products (2M Company Inc., 2011)

Product	**Description**
AIR FOAM	Foaming agent for air drilling
BORZAN	Modified xantham gum
DRILL-X	Water wetting agent, drilling detergent
DRIL-SOL	Clay stabilizer, mud conditioner
DRIL-TROL QUD	Dry polymer viscosifier

Table A.11 (continued)

Product	Description
ENVIROPLUG GROUT	Grouting casing, hole abandonment
ENVIROPLUG MEDIUM & ENVIROPLUG COARSE	Hole abandonment, casing seals
ENVIROPLUG NO. 16	Casing Seal
ENVIROPLUG TABLETS	Casing Seal, killing over flowing holes
EXTRA HIGH YIELD	Quick viscosifying bentonite
G-150 GUAR	Guar gum viscosifier
GROUT-WELL	Grouting casing, hole abandonment
GROUT-WELL DF	Grout casing, hole abandonment
HYDROGEL	API grade 200 mesh bentonite
KWIK-VIS "D"	Dry polymer viscosifier
NATRUALGEL	API grade 200 mesh bentonite
PLUGSZ-IT	Loss circulation additive
PLUGSZ-IT Max	Coarse loss circulation additive
SW 101	Seawater viscosifier
TD-16	Gouting casing hole abandonment
THERM-EX GROUT	Backfill for closed loop heat pump
THINZ-IT	Liquid mud thinner
TRUBORE	Concentrated viscosifier/ fluid loss control
UNI-DRILL	Liquid polymer mud conditioner
WYOFOAMER	Premium all-purpose foamer
WYO-VIS	Liquid viscosifier
WYO-VIS "DP"	Dry viscosifier

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Appendix B - State Specifications

Table B.1 Alabama slurry specifications (ALDOT, 2008).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	64.3* - 69.1* {1030* - 1110*}	64.3* - 75.0* {1030* - 1200*}	Density Balance
Viscosity Seconds/qt {Seconds/L)	28 – 45 {30 – 48}	28 – 45 {30 – 48}	Marsh Cone
pH	8 – 11	8 – 11	pH paper, pH Meter
Sand Content Percent by Volume	N/A	N/A	N/A

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	Alabama has no polymer slurry specifications		
Viscosity Seconds/qt {Seconds/L}			
pH			
Sand Content Percent by Volume			

*Increase by 2 pounds per cubic foot (32 kg/m^3) in salt water

a. Tests should be performed when the slurry temperature is above 39° F.

b. If desanding is required, sand content shall not exceed 4 percent (by volume) at any point in the borehole as determined by the American Petroleum Institute sand content test.

Source: United States. Alabama Department of Transportation. *Standard Specifications for Highway Construction. 2008.*

Table B.2 Alaska slurry specifications (AlaskaDOT, 2004)

Mineral Slurry Specification

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	Alaska has no specification for drilled shaft slurry		
Viscosity Seconds/qt {Seconds/L}			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	Alaska has no specification for drilled shaft slurry		
Viscosity Seconds/qt {Seconds/L}			
pH			
Sand Content Percent by Volume			

Source: United States. Alaska Department of Transportation and Public Facilities.

Standard Specifications for Highway Construction. 2004.

Table B.3 Arizona slurry specifications (AZDOT, 2008).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	64.3 – 69.1	64.3 – 75.0*	Density Balance
Yield Point {Pascals} Or Viscosity Seconds/qt	1.25 – 10 28 – 50	10 Maximum 28 – 50	Rheometer Marsh Cone
pH	7 – 12	7 – 12	pH paper, pH meter
Sand Content Percent by Volume	0 – 4	0 – 2	API Sand Content Kit

* 85 lb/ft^3 maximum when using Barite.

a. Range of results above 68°F.

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	Arizona has no polymer slurry specifications. Only mentions: "The level of polymer slurry shall be maintained at or near the ground surface or higher, if required to maintain boring stability."		
Yield Point {Pascals} Or Viscosity Seconds/qt			
pH			
Sand Content Percent by Volume			

Source: United States. Arizona Department of Transportation. *Standard Specifications for Road and Bridge Construction*. 2008.

Table B.4 Arkansas slurry specifications (Ellis 2010).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	64 – 75	None Specified	Mud Balance ASTM D4380
Viscosity (Seconds/qt) {Seconds/L}	28 – 45	None Specified	API RP13B-1 Section 2 Marsh Funnel and Cup
pH	8 – 11	None Specified	ASTM D4972
Sand Content Percent by Volume	N/A	N/A	N/A

a. Range of results at 60°F (20°C).

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	64 Maximum (fresh water applications)	N/A	(Mud Balance) ASTM D4380
Viscosity Seconds/qt {Seconds/L}	40 to 90 (or as approved by the Engineer)	N/A	API RP13B-1 Sect. 2 (Marsh Funnel & Cup)
pH	8-10	N/A	ASTM D4972
Sand Content Percent by Volume	N/A	1% Max	(Sand Screen Set) ASTM D4381

a. Range of results at 60°F (20°C).

Source: United States. Arkansas State highway and Transportation Department. *Special Provision Job No. 110229 Slurry Displacement Drilled Shaft*. 2005.

Table B.5 California slurry specifications (Caltrans, 2008).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	64.3* – 69.1*	64.3* - 75.0*	Mud Weight (Density) API 13B-1 Section 1
Viscosity Seconds/qt	(Bentonite) 28 – 50 (Attapulgite) 28 – 40	None Specified	Marsh Funnel and Cup API 13B-1 Section 2.2
pH	8 – 10.5	8 – 10.5	Glass Electrode pH meter, pH paper
Sand Content Percent by Volume	Volume≤4.0	Volume≤4.0	

* When approved by the Engineer, slurry may be used in salt water, and the allowable densities may be increased by up to 2 lb/ft^3. Slurry temperature shall be at least 40°F when tested.

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	The physical properties of synthetic slurries should be carefully monitored during drilling of the hole and before concrete placement. Because these slurries in general do not suspend particles, the permissible density and sand content values are much lower than those allowed for mineral slurries. The density and sand content values should be tested and the values maintained within the limits stated in the contract specifications to allow for quick settlement of suspended materials. The synthetic slurry's pH value should be tested and maintained within the limits stated in the contract specifications to prevent destabilization of the slurry.		
Viscosity Seconds/qt			
pH			
Sand Content Percent by Volume			

Source: United States. California Department of Transportation Division of Engineering Services. *Foundation Manual*. 2008.

Table B.6 Colorado slurry specifications (CDOT, 2006).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density g/ml	Less than 1.10	Less than 1.10	Mud Weight (Density) API 13B-1 Section 1
Viscosity Seconds/qt	(Bentonite) 30-90 seconds Or less than 20cP	None Specified	Marsh Funnel and Cup API 13B-1 Section 2.2
pH	8 – 10.5	8 – 10.5	pH indicator paper Strips or electrical pH meter
Sand Content Percent by Volume	Less than 5%	Less than 5%	Screen

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density g/ml	No specification for Polymer Slurries		
Viscosity Seconds/qt			
pH			
Sand Content Percent by Volume			

Source: United States. Colorado Department of Transportation. *Permanent Changes to Project Dated Special Provisions, Revision of Section 503.* 2006.

Table B.7 Connecticut slurry specifications (ConnDOT, 2009).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	64.3* – 69.1*	64.3* - 75.0*	Density Balance
Viscosity Seconds/qt	28 – 45	28 – 45	Marsh Funnel
pH	8 – 11	8 – 11	pH paper, pH meter
Sand Content Percent by Volume	N/A	N/A	N/A

* Increase by 2 lb/ft^3 in salt water.

Polymer Slurry Specifications

<table>
<tr><th>Property
(Units)</th><th>At Time of Slurry
Introduction</th><th>In Hole at Time of
Concreting</th><th>Test
Method</th></tr>
<tr><td>Density
lb/ft^3</td><td rowspan="3" colspan="3">Connecticut has no polymer slurry specifications.

“If polymer slurry, or blended mineral-polymer slurry, is proposed, the Contractor’s slurry management plan shall include detailed provisions for controlling the quality of the slurry, including tests to be performed, the frequency of those tests, the test methods, and the maximum and/or minimum property requirements that must be met to ensure that the slurry meets its intended functions in the subsurface conditions at the construction site and with the construction methods that are to be used. The slurry management plan shall include a set of the slurry manufacturer’s written recommendations and shall include the following tests, as a minimum: Density test (API 13B-1, Section 1), viscosity test (Marsh funnel and cup, API 13B-1, Section 2.2, or approved viscometer), pH test (pH meter, pH paper), and sand content test (API sand content kit, API 13B-1, Section 5).”</td></tr>
<tr><td>Viscosity
Seconds/qt</td></tr>
<tr><td>pH</td></tr>
</table>

Source: United States. Connecticut Department of Transportation. *Connecticut DOT Guide Drilled Shaft Spec.* 2009.

Table B.8 Delaware slurry specifications (DELDOT, 2009).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	63.55 – 68.51 {1025 – 1105}	63.55 – 74.41 {1025 – 1200}	Density Balance
Viscosity Seconds/ft {Seconds/L}	849.5 – 1359.2 {30 – 48}	849.5 – 1359.2 {30 – 48}	Marsh Cone
pH	7 – 11	7 – 11	pH paper, pH meter
Sand Content Percent by Volume	1 MAX	4 MAX	200 Sieve Retain

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	No state specification pertaining to slurry parameters defined. Refers to FHWA guidelines.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Source: Keith Gray (Bridge Engineer, DELDOT), email message to author, March 7, 2009.

Table B.9 Florida slurry specifications (FDOT, 2010).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 $\{kg/m^3\}$	64 – 73* 66 – 75** {1030 – 1170*} {1060 – 1200**}	N/A	Mud Density Balance FM 8-RP13B-1
Viscosity Seconds/qt {Seconds/L}	28 – 40 {28 – 40}	N/A	Marsh Cone Method FM 8-RP13B-2
pH	8 – 11	N/A	Electric pH meter, pH paper FM 8-RP13B-4
Sand Content Percent by Volume	4% MAX	N/A	FM 8-RP13B-3

* Fresh water @ 68°F (20°C)

** Salt water @ 68°F (20°C)

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 $\{kg/m^3\}$	62 to 64 lb/ft3 (fresh water) 64 to 66 lb/ft3 (salt water)	62 to 64 lb/ft3 (fresh water) 64 to 66 lb/ft3 (salt water)	Mud Density Balance FM 8-RP13B-1
Viscosity Seconds/qt {Seconds/L}	Range Published By The Manufacturer for Materials Excavated	Range Published By The Manufacturer for Materials Excavated	Marsh Cone Method FM 8-RP13B-2
pH	Range Published By The Manufacturer for Materials Excavated	Range Published By The Manufacturer for Materials Excavated	Electric pH meter, pH paper FM 8-RP13B-4
Sand Content Percent by Volume	0.5% or less	0.5% or less	FM 8-RP13B-3

a. Range of results at 68° F
b. The Engineer will not allow polymer slurries during construction of drilled shafts for bridge foundations.

Table B.9 (continued)

c. Materials manufactured expressly for use as polymer slurry for drilled shafts may be used as slurry for drilled shaft excavations up to 60 inches in diameter installed to support mast arms, cantilever signs, overhead truss signs, high mast light poles or other miscellaneous structures.
d. A representative of the manufacturer must be on-site or available for immediate contact to assist and guide the construction of the first three drilled shafts at no additional cost to the Department.
e. Use polymer slurry only if the soils below the casing are not classified as organic, and the pH of the fluid in the hole can be maintained in accordance with the manufacturer's published recommendations.

Source: United States. Florida Department of Transportation . *Standard Specifications for Road and Bridge Construction*. 2010.

Table B.10 Georgia slurry specifications (GDOT,2006).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 $\{kg/m^3\}$	66 – 73 {1060 – 1170}	N/A	N/A
Viscosity Seconds/qt {Seconds/L}	30 – 45 {32 – 48}	N/A	Marsh Funnel
pH	8 – 11	N/A	N/A
Sand Content Percent by Volume	N/A	4%	N/A

a. Perform sand content tests on slurry samples taken from the bottom of the shaft after placement of the reinforcing cage, but immediately before pouring concrete. Do not place concrete until all testing produces acceptable results.
b. If sidewalls are unstable, or if artesian flow is present, use a weighing additive to increase the slurry density
c. pH may be adjusted with soda ash.
d. When sand content exceeds 4%, desanding or other equipment must be used.
e. Tests must be performed at 39°F (4°C), slurry temperature.

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 $\{kg/m^3\}$	64 – 67 {1025 – 1073}	N/A	N/A
Viscosity Seconds/qt {Seconds/L}	30 – 125 {32 – 132}	N/A	Marsh Funnel
pH	8 – 11	N/A	N/A
Sand Content Percent by Volume	N/A	≤1	N/A

A weighing additive may be used to increase the density of the polymer slurry if the sidewalls are unstable or if artesian flow is present.

Source: United States. State of Georgia Department of Transportation. *Special Provision Section 524 – Drilled Caisson Foundations*. 2006.

Table B.11 Hawaii slurry specifications (HDOT, 2005).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	Slurry Drilling is not permitted*		
Viscosity Seconds/qt {Seconds/L}			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	Slurry Drilling is not permitted*		
Viscosity Seconds/qt {Seconds/L}			
pH			
Sand Content Percent by Volume			

*Wet Construction Method – This method includes using water to maintain stability of shaft perimeter while advancing excavation to final depth, and placing reinforcing cage and shaft concrete.

Reuse drilling water only if permitted by the Engineer and contingent upon control of unit weight to no more than 62.5 pounds per cubic foot and Marsh funnel viscosity to not more than 27 seconds per quart, at the time drilling water is introduce into the borehole.

Source: United States. State of Hawaii Department of Transportation. *Standard Specifications*. 2005.

Table B.12 Idaho slurry specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	No specifications pertaining to slurry parameters available at time of study.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

a. Temperature shall be at least 39°F (4°C) when tested.

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	No specifications pertaining to slurry parameters available at time of study.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Table B.13 Illinois slurry specifications (IDOT, 2007).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	No specifications pertaining to slurry parameters available.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	No specifications pertaining to slurry parameters available.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Source: United States. Illinois Department of Transportation. *Standard Specifications for Bridge Construction*. 2007.

Table B.14 Indiana slurry specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	Drilled shafts not permitted.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	Drilled shafts not permitted.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Source: United States. Indiana Department of Transportation. *Standard Specifications*. 2010.

Table B.15 Iowa slurry specifications (Iowa DOT, 2008).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	No state specification pertaining to slurry parameters defined. Refers to FHWA guidelines		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	Polymer slurry not permitted		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Source: United States. Iowa Department of Transportation. *Standard Specifications with GS-01015 Revisions.* October 2008.

Table B.16 Kansas slurry specifications (KSDOT, 2007)

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	Drilled shafts permitted but no specifications pertaining to slurry parameters available.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	Drilled shafts permitted but no specifications pertaining to slurry parameters available.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Source: United States. Kansas Department of Transportation. *Standard Specifications for State Road and Bridge Construction*. 2007.

Table B.17 Kentucky slurry specifications (KYTC, 2008).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	No state specification pertaining to slurry parameters defined. Refer to FHWA Guidelines		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	No state specification pertaining to slurry parameters defined.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Source: United States. Kentucky Transportation Cabinet. *Special Note 11C for Excavation and Embankment*. 2008.

Table B.18 Louisiana slurry specifications (LaDOT, 2002).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	64.3 – 69.1 {1030 – 1107}	64.3 – 75.0 {1030 – 1202}	Mud Balance API 13B Section 1
Viscosity Seconds/qt {Seconds/0.95L}	28 – 45 {28 – 45}	28 – 45 {28 – 45}	Marsh Funnel API 13B Section 2
pH	8 – 11	8 – 11	pH paper, pH meter API 13B Section 6
Sand Content Percent by Volume	4	4	Sand Screen Set API 13B Section 4

a. Slurry shall not stand for more than 4 hours in the excavation without agitation.

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density	995 – 1018 kg/m3 (62.1 – 63.5 pcf)	1000 – 1018 kg/m3 (62.4 – 63.5 pcf)	Mud Balance (API 13B- Sec 1)
Viscosity Seconds/qt {Seconds/0.95L}	45 sec/.95 liter (45 sec/quart)	45 sec/.95 liter (45 sec/quart)	Marsh Funnel (API 13B- Sec 2)
pH	8 – 10	8 - 10	pH Paper pH Meter (API 13B-Sec6)
Sand Content Percent by Volume	1	1	Sand Screen Set (API 13B- Sec 4)

a. The slurry shall not stand for more than 4 hours in the excavation without agitation

Source: United States. Louisiana Department of Transportation. *Drilled Shaft Inspection Manual, Shaft Construction.* 2002.

Table B.19 Maine slurry specifications (MDOT, 2002).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	Drilled shafts permitted but no specifications pertaining to slurry parameters available.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	Drilled shafts permitted but no specifications pertaining to slurry parameters available.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Source: United States. Maine Department of Transportation. *Standard Specifications*. 2002.

Table B.20 Maryland slurry specifications (MDOT, 2008).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	No specifications pertaining to slurry parameters available.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	No specifications pertaining to slurry parameters available.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Source: United States. Maryland Department of Transportation. *Standard Specifications for Construction and Materials.* 2008.

Table B.21 Massachusetts slurry specifications **(**MDH, 2003).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	No specifications pertaining to slurry parameters available at time of study.		
Viscosity Seconds/qt {Seconds/L}			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	No specifications pertaining to slurry parameters available at time of study.		
Viscosity Seconds/qt {Seconds/L}			
pH			
Sand Content Percent by Volume			

Table B.22 Michigan slurry specifications (MDOT, 2008).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	64.3 – 75	N/A	Mud Weight API 13B-1 Section 1
Viscosity Seconds/qt	26 – 50	N/A	Marsh Funnel and Cup API 13B-1 Section 2.2
pH	8 – 11	N/A	Glass Electrode, pH meter, pH paper
Sand Content Percent by Volume	N/A	N/A	N/A

a. Slurry temperature shall be at least 40°F when tested.
b. Use of mineral slurry in sat water installations will not be allowed.

Polymer Slurry Specifications

<table>
<tr><th>Property
(Units)</th><th>At Time of Slurry Introduction</th><th>In Hole at Time of Concreting</th><th>Test
Method</th></tr>
<tr><td>Density
lb/ft^3</td><td colspan="3" rowspan="2">Synthetic slurries shall be used in conformance with the manufacturer's recommendations, the quality control plan specified in subsection 3.02.B.5 of this Special Provision, and these Special Provisions. The sand content of synthetic slurry prior to final cleaning and immediately prior to placing concrete shall be less than 2.0 percent, in accordance with API 13B-1, Section 5.</td></tr>
<tr><td>Viscosity
Seconds/qt</td></tr>
</table>

Source: United States. Michigan Department of Transportation. *Standard Specifications for Construction.* 2012.

Table B.23 Minnesota slurry specifications (MnDOT, 2005).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 $\{kg/m^3\}$	64.3 – 69.1 {1030 – 1107}	64.3 – 75.0 {1030 – 1201}	Density Balance
Viscosity Seconds/qt {Seconds/L}	28 – 45 {30 – 48}	28 – 45 {30 – 48}	Marsh Cone
pH	8 – 11	8 – 11	pH paper, pH meter
Sand Content Percent by Volume	N/A	N/A	N/A

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 $\{kg/m^3\}$	No specifications pertaining to slurry parameters available.		
Viscosity Seconds/qt {Seconds/L}			
pH			

a. Mineral slurries shall be employed in the drilling process unless other drilling fluids are approved by the Engineer.

Source: United States. Minnesota Department of Transportation. *Standard Bridge Special Provisions.* 2005.

Table B.24 Mississippi slurry specifications (MDOT, 2007).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 $\{kg/m^3\}$	64.3* – 69.1* {1030* – 1105*}	64.3* – 75.0* {1030** – 1200*}	Density Balance
Viscosity Seconds/qt {Seconds/L}	28 – 45 {30 – 48}	28 – 45 {30 – 48}	Marsh Cone
pH	8 – 11	8 – 11	pH paper, pH meter
Sand Content Percent by Volume	N/A	N/A	N/A

* Increase by 2 lb/ft^3 (30 kg/m^3) in salt water.

a. Tests should be performed when slurry temperature is above 41°F (5°C).
b. If desanding is required, sand content shall not exceed 4% (by volume) at any point in the borehole as determined by the American Petroleum Institute sand content test.

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 $\{kg/m^3\}$	Mineral slurries shall be employed when slurry is used in the drilling process, unless other drilling fluids are approved in writing by the Engineer. No Polymer Specification Available.		
Viscosity Seconds/qt {Seconds/L}			
pH			

Source:United States. Mississippi Department of Transportation. *Special Provision No. 907-803-18M, Deep Foundations*. 2007.

Table B.25 Missouri slurry specifications (MODOT, 2007).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 $\{kg/m^3\}$	63.5 – 66.8 {1017 – 1129}	63.5 – 70.5 {1017 – 1129}	Density Balance
Viscosity Seconds/qt {Seconds/L}	32 – 60 {34 – 60}	32 – 60 {34 – 60}	Marsh Funnel
pH	8 – 10	8 – 11	pH paper, pH meter
Sand Content Percent by Volume	<4	<10	API Sand Content Kit
Maximum Contact Time* Hours	N/A	4	N/A

a. All values without agitation and sidewall cleaning.
b. Higher viscosities may be required to maintain excavation stability in loose or gravelly sand deposits.
c. All values for freshwater without additives.

Polymer Slurry Specifications

Emulsified Polymer			
Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 $\{kg/m^3\}$	< 63 {1009}	< 63 {1009}	Density Balance
Viscosity Seconds/qt {Seconds/L}	33 – 43* {35 – 45}*	33 – 43* {35 – 45}*	Marsh Funnel
pH	8 - 11	8 - 11	pH Paper or pH Meter
Sand Content Percent by Volume	< 1	< 1	API Sand Content Kit
Maximum Contact Time Without Agitation and Sidewall Cleaning	72 hrs		

*Higher viscosities may be required to maintain excavation stability in loose or gravelly sand deposits.

Table B.25 (continued)

Dry Polymer			
Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 $\{kg/m^3\}$	< 63 {1009}	< 63 {1009}	Density Balance
Viscosity Seconds/qt {Seconds/L}	50 – 80* {53 – 85}*	50 – 80* {53 – 85}*	Marsh Funnel
pH	7 - 11	7 - 11	pH Paper or pH Meter
Sand Content Percent by Volume	< 1	< 1	API Sand Content Kit
Maximum Contact Time Without Agitation and Sidewall Cleaning	72 hrs		

*Higher viscosities may be required to maintain excavation stability in loose or gravelly sand deposits.

a. All values for freshwater without additives.

Source:United States. Missouri Department of Transportation. *Supplemental Specifications to 2004 Missouri Standard Specifications for Highway Construction.* 2007.

Table B.26 Montana slurry specifications (MDT,2011)

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	Mineral slurry use not permitted.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	Slurry must be in conformance with Manufacturer's recommendations		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

The following synthetic slurries are approved as slurry systems:

Product	*Manufacturer*
Novagel	Geo-Tech Services, LLC 220 North Zapata Highway, Suite 11A Laredo, TX 78043-4464
ShorePac GCV	CETCO 1500 West Shure Drive Arlington Heights IL, 60004
SlurryPro CDP	KB International, LLC Suite 216, 735 Broad Street Chattanooga, TN 37402-1855
Super Mud*	PDS Company 8140 East Rosecrans Ave. Paramount, CA 90723-2754

*Approval as a product applies to the liquid product only.
Submit other proposed synthetic slurry products for approval. Submit proposed additives for approval.

Source: United States. Montana Department of Transportation. *Special Provisions: Synthetic Slurry for Drilled Shafts*. 2011.

Table B.27 Nebraska slurry specifications (NDOR, 2011)

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	Mineral slurry not allowed without engineer approval.		
Viscosity Seconds/qt			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	Manufacturer specifications required upon engineer approval.		
Viscosity Seconds/qt			
pH			
Sand Content Percent by Volume			

Source: Jordan Larsen (Nebraska Department of Roads Bridge Foundation Engineer) in discussion with author, August 2011.

Table B.28 Nevada slurry specifications (NDOT, 2001).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kN/m^3}	No specifications pertaining to slurry parameters available at time of study.		
Viscosity* Seconds/qt			
pH			
Sand Content Percent by Volume			

* The Marsh Funnel Test is conducted using one quart of fluid, not one liter.

a. Testing shall be performed when the slurry temperature is above 40°F (4°C). The sand content shall not exceed 4% (by volume) at any point in the bore hole as determined by the American Petroleum Institute sand content test.

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kN/m^3}	No specifications pertaining to slurry parameters available at time of study.		
Viscosity* Seconds/qt			
pH			

Table B.29 New Hampshire slurry specifications (NHDOT, 2010).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 $\{kN/m^3\}$	64.3 – 69.1* {410 – 440*}	64.3 – 75.0* {410 – 478*}	Density Balance
Viscosity Seconds/qt {Seconds/0.945L}	28 – 45 {28 – 45}	28 – 45 {28 – 45}	Marsh Funnel
pH	8 – 11	8 – 11	pH paper, pH meter
Sand Content Percent by Volume	N/A	N/A	N/A

* Upper limit assumes that the slurry is being reused after having been treated. Initial mixing of mineral powder and fresh water should be no higher than 65.5 lb/ft^3 (717 kN/m^3) unless additional density is obtained with weighting agents. Increase by 2 lb/ft^3 (12.5 kN/m^3) in salt water.

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 $\{kN/m^3\}$	64.3 – 69.1* {410 – 440*}	64.3 – 75.0* {410 – 478*}	Density Balance
Viscosity Seconds/qt {Seconds/0.945L}	28 – 45 {28 – 45}	28 – 45 {28 – 45}	Marsh Funnel
pH	8 – 11	8 – 11	pH paper, pH meter

* Upper limit assumes that the slurry is being reused after having been treated. Initial mixing of mineral powder and fresh water should be no higher than 65.5 lb/ft^3 (717 kN/m^3) unless additional density is obtained with weighting agents. Increase by 2 lb/ft^3 (12.5 kN/m^3) in salt water.

Source: United States. New Hampshire Department of Transportation. *Standard Specifications.* 2010.

Table B.30 New Jersey slurry specifications (NJDOT, 2007).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	64.3 – 69.1*	64.3 – 75.0*	Mud Balance API 13B ASTM D 4380
Viscosity Seconds/qt	28 – 45*	28 – 45*	Marsh Funnel and Cup API 13B Section 2
pH	8 – 11	8 – 11	pH paper, pH meter API 13B Section 6
Sand Content Percent by Volume	4	4	N/A

* Increase by 2 lb/ft^3 in salt water.

a. Perform tests when slurry temperature is above 40°F.
b. Ensure that the sand content does not exceed 4% (by volume) at any point in the borehole as determined by the API sand content test when the slurry is introduced.
c. Perform tests to determine density, viscosity and pH value during the shaft excavation to establish a consistent working pattern. Perform a minimum of 4 sets of tests during the first 8 hours of slurry use. When the results show consistent behavior, the Contractor may decrease the testing frequency to 1 set per every 4 hours of slurry use.
d. One sec/qt = 1.06 sec/L.

Source: United States. New Jersey Department of Transportation. *Standard Specifications for Road and Bridge Construction.* 2007.

Table B.30 (continued)

Polymer Slurry Specifications

<table>
<tr><th>Property
(Units)</th><th>At Time of Slurry
Introduction</th><th>In Hole at Time of
Concreting</th><th>Test
Method</th></tr>
<tr><td>Density
lb/ft^3
{kg/m^3}</td><td colspan="2" rowspan="4">No specifications pertaining to slurry parameters available.</td><td>API 13B-1, Section 1</td></tr>
<tr><td>Viscosity
Seconds/qt
{Seconds/L}</td><td>(Marsh funnel and cup, API 13B-1), Section 2.2 or approved viscometer</td></tr>
<tr><td>pH</td><td>pH meter, pH paper</td></tr>
<tr><td>Sand Content
Percent by Volume</td><td>API sand content kit, API 13B-1, Section 5</td></tr>
</table>

Provide a slurry management plan to the RE that includes a set of the slurry manufacturer’s written recommendations and results of the following tests, as a minimum:

1. Density Test (API 13B-1, Section 1).
2. Viscosity Test (Marsh funnel and cup, API 13B-1), Section 2.2 or approved viscometer.
3. pH Test (pH meter, pH paper).
4. Sand Content Test (API sand content kit, API 13B-1, Section 5).

Also include the tests to be performed, the frequency of those tests, the test methods, and the maximum and minimum property requirements that must be met to ensure that the slurry meets its intended functions. Ensure that all test reports are signed, and provide them to the RE on completion of each drilled shaft.

Source: United States. New Jersey Department of Transportation. *Standard Specifications for Road and Bridge Construction*. 2007.

Table B.31 New Mexico slurry specifications (NMDOT, 2007).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	N/A	64.0 – 75.0	Density Balance
Viscosity Seconds/qt	28 – 45	N/A	Marsh Cone
pH	8 – 10	8 – 10	pH paper
Sand Content Percent by Volume	N/A	0 – 4	API Method

a. Premix the slurry according to the manufacturer's directions. Prevent the slurry from "setting up" in the shaft. Dispose of the slurry offsite in accordance with Section 107.14.8, "Disposal of Other Materials and Debris."

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	62.4 - 64	62.4 - 64	Density Balance
Viscosity Seconds/qt	50-120	50-120	Marsh Cone
pH	8 – 11.7	8 – 11.7	pH paper
Sand Content Percent by Volume	0-1	0 – 1	API Method

a. Premix the slurry according to the manufacturer's directions. Prevent the slurry from "setting up" in the shaft. Dispose of the slurry offsite in accordance with Section 107.14.8, "Disposal of Other Materials and Debris."
b. Perform tests when the slurry temperature is above 40 °F.
c. Table pertains to Emulsified or Dry Phpa Polymer

Source: United States. New Mexico State Department of Transportation. *Standard Specifications for Highway and Bridge Construction.* 2007.

Table B.32 New York slurry specifications (NYSDOT, 2008).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	1030 – 1106	1030 – 1200	Density Balance
Viscosity Seconds/L	29 – 48	29 – 48	Marsh Cone
pH	8 – 11	8 – 11	pH paper, pH meter
Sand Content Percent by Volume	N/A	N/A	N/A

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	**Polymer Slurry.** Provide a polymer slurry with sufficient viscosity and gel characteristics to hold the hole open, and transport excavated material to a suitable screening system. Polymer slurry may be made from PHPA (emulsified), vinyl (dry), or natural polymers. Desand the polymer slurry so that the sand content is less than 1 percent (by volume) prior to concrete placement, as determined by the American Petroleum Institute sand content test.		
Viscosity Seconds/L			
pH			

Source: United States. New York State Department of Transportation. Standard Specifications. 2008.

Table B.33 North Carolina slurry specifications (NCDOT, 2012).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 $\{kg/m^3\}$	64.3 – 72 {1030 – 1107}	64.3 – 75.0 {1030 – 1201}	Mud Weight API 13B-1 Section 1
Viscosity Seconds/qt {Seconds/0.95L}	28 – 50	28 – 45	Marsh Funnel and Cup API 13B-1 Section 2.2
pH	8 – 11	8 – 11	Glass Electrode pH meter
Sand Content Percent by Volume	Vol≤4	Vol≤2	Sand API 13B-1 Section 5

a. Slurry temperature of at least 40°F (4.4°C) required.
b. American National Standards Institute/ American Petroleum Institute Recommended Practice
c. Increase density requirements by 2 lb/ft^3 in salt water
d. pH paper is also acceptable for measuring pH.

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 $\{kg/m^3\}$	≤64	≤64	Mud Weight API 13B-1 Section 1
Viscosity Seconds/qt {Seconds/L}	32 – 135	32 - 135	Marsh Funnel and Cup API 13B-1 Section 2.2
pH	8 – 11.5	8 – 11.5	Glass Electrode pH meter
Sand Content Percent by Volume	≤0.5	≤0.5	Sand API 13B-1 Section 5

Table B.33 (continued)

The following polymer slurries are approved for use:

SlurryPro CDP	KB Technologies Ltd. 3648 FM 1960 West, Suite 107 Houston, TX 77068 (800) 525-5237
Super Mud	PDS Company 105 West Sharp Street El Dorado, AR 71730 (800) 243-7455
Shore Pac	CETCO Construction Drilling Products 1500 West Shure Drive, 5th Floor Arlington Heights, IL 60004 (800) 527-9948
Novagel Polymer	Geo-Tech Drilling Fluids 220 North Zapata Hwy, Suite 11A Laredo, TX 78043 (210) 587-4758

SLURRYPRO CDP
KB Technologies Ltd.
Acceptable Range of Values

Property (units)	**At Time of Slurry Introduction**	**In Excavation Immediately Before Concrete Placement**	**Test Method**
Density, pcf (kg/m^3)	Less than or equal to 67 (1073)	Less than or equal to 64 (1025)	Mud Weight (Density) API 13B-1 Section 1
Viscosity, sec./quart (sec./0.95 liters)	50 – 120	Less than or equal to 70	Marsh Funnel and Cup API 13B-1 Section 2.2
pH	6 – 11.5	6 – 11.5	pH Paper or Glass Electrode pH Meter
Sand Content (percent)	Less than or equal to 0.5	Less than or equal to 0.5	Sand API 13B-1 Section 5

Notes:

1. Perform tests when the slurry temperature is above 40°F (4.4°C).
2. Increase density by 2 pcf (32 kg/m^3) in saltwater.

Table B.33 (continued)

SUPER MUD PDS Company Acceptable Range of Values			
Property (units)	**At Time of Slurry Introduction**	**In Excavation Immediately Before Concrete Placement**	**Test Method**
Density, pcf (kg/m^3)	Less than or equal to 64 (1025)	Less than or equal to 64 (1025)	Mud Weight (Density) API 13B-1 Section 1
Viscosity, sec./quart (sec./0.95 liters)	32 – 60	Less than or equal to 60	Marsh Funnel and Cup API 13B-1 Section 2.2
pH	8 – 10	8 – 10	pH Paper or Glass Electrode pH Meter
Sand Content (percent)	Less than or equal to 0.5	Less than or equal to 0.5	Sand API 13B-1 Section 5

Notes:

1. Perform tests when the slurry temperature is above 40°F (4.4°C).
2. Increase density by 2 pcf (32 kg/m^3) in saltwater.

Table B.33 (continued)

SHORE PAC CETCO Construction Drilling Products Acceptable Range of Values			
Property (units)	**At Time of Slurry Introduction**	**In Excavation Immediately Before Concrete Placement**	**Test Method**
Density, pcf (kg/m^3)	Less than or equal to 64 (1025)	Less than or equal to 64 (1025)	Mud Weight (Density) API 13B-1 Section 1
Viscosity, sec./quart (sec./0.95 liters)	32 – 98	Less than or equal to 75	Marsh Funnel and Cup API 13B-1 Section 2.2
pH	8 – 10	8 – 10	pH Paper or Glass Electrode pH Meter
Sand Content (percent)	Less than or equal to 0.5	Less than or equal to 0.5	Sand API 13B-1 Section 5

Notes:

1. Perform tests when the slurry temperature is above 40°F (4.4°C).
2. Increase density by 2 pcf (32 kg/m^3) in saltwater.

Table B.33 (continued)

NOVAGEL POLYMER Geo-Tech Drilling Fluids Acceptable Range of Values			
Property (units)	**At Time of Slurry Introduction**	**In Excavation Immediately Before Concrete Placement**	**Test Method**
Density, pcf (kg/m^3)	Less than or equal to 67 (1073)	Less than or equal to 64 (1025)	Mud Weight (Density) API 13B-1 Section 1
Viscosity, sec./quart (sec./0.95 liters)	45 – 104	Less than or equal to 104	Marsh Funnel and Cup API 13B-1 Section 2.2
pH	6.5 – 11.5	6.5 – 11.5	pH Paper or Glass Electrode pH Meter
Sand Content (percent)	Less than or equal to 0.5	Less than or equal to 0.5	Sand API 13B-1 Section 5

Notes:

1. Perform tests when the slurry temperature is above 40°F (4.4°C).
2. Increase density by 2 pcf (32 kg/m^3) in saltwater.

Source: United States. North Carolina Department of Transportation. *Standard Specifications*. 2012.

Table B.34 North Dakota slurry specifications (NDDOT, 2010).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	No specifications pertaining to slurry parameters available at time of study.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	No specifications pertaining to slurry parameters available at time of study.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Table B.35 Ohio slurry specifications (ODOT, 2010).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	64.3 – 69.1 {1030 – 1107}	64.3 – 75.0 {1030 – 1201}	Density Balance
Viscosity Seconds/qt {Seconds/L}	28 – 45 {30 – 48}	28 – 45 {30 – 48}	Marsh Cone
pH	8 – 11	8 – 11	pH paper, pH meter
Sand Content Percent by Volume	N/A	N/A	N/A

a. Range of values for 68°F.

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	Only use polymer slurry after demonstrating to the Engineer that the stability of the hole perimeter can be maintained while advancing the excavation to its final depth by excavating a trial hole of the same diameter and depth as that of the production shafts. Use the same polymer slurry in the trial hole as proposed for the production shafts. If using different sizes of the shafts at the project, use the same size trial hole as that of the largest diameter shaft, except the depth of the trial hole need not be more than 40 feet (12 meters). Only one trial hole per project is required. Do not use the trial hole excavation for a production shaft. After completing the trial hole excavation, fill the hole with sand. The acceptance of the polymer slurry does not relieve the Contractor of responsibility to maintain the stability of the excavation. Polymer slurry shall conform to the manufacturer's requirements.		
Viscosity Seconds/qt {Seconds/L}			
pH			

Source: Ohio Department of Transportation. *Construction and Material Specifications.* 2010.

Table B.36 Oklahoma slurry specifications (ODOT, 2009).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 $\{kg/m^3\}$	64.3 – 69.1 {1030 – 1107}	64.3 – 75.0 {1030 – 1200}	Density Balance
Viscosity Seconds/qt {Seconds/L}	28 – 45 {30 – 48}	28 – 45 {30 – 48}	Marsh Cone
pH	8 – 11	8 – 11	pH paper, pH meter
Sand Content Percent by Volume	N/A	N/A	N/A

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 $\{kg/m^3\}$	62.4 – 63 {1000 – 1010}	62.4 – 63.5 {1000 – 1017}	Density Balance
Viscosity Seconds/qt {Seconds/L}	30 – 40 {32 – 42}	30 – 40 {32 – 42}	Marsh Cone
pH	9 – 11	9 – 11	pH paper, pH meter
Sand Content Percent by Volume	< 1	< 1	N/A

a. Perform tests when slurry temperature is above 40°F [4°C]

b. Density values are for fresh water. Increase density values 2.0 lb/ft^3 [32 kg/m^3] for salt water

Source: United States. Oklahoma Department of Transportation. *Standard Specifications Book.* 2009.

Table B.37 Oregon slurry specifications (ODOT, 2008).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	64 – 75	64 – 75	Mud Density API 13B-1 Section 1
Viscosity Seconds/qt	26 – 50	26 – 50	Marsh Funnel and Cup API 13B-1 Section 2.2
pH	8 – 11	8 – 11	pH paper, pH meter, Glass Electrode
Sand Content Percent by Volume	4 MAX	4 MAX	Sand API 13B-1 Section 5

a. Maintain slurry temperature at 40°F or more during testing.

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	**(b) Synthetic Slurries** - Select synthetic slurries from the QPL. Use synthetic slurries according to the manufacturer's recommendations and the Contractor's quality control plan. The sand content of synthetic slurry shall be less than 2.0 percent (API 13B-1, Section 5) prior to final cleaning and immediately prior to concrete placement.		
Viscosity Seconds/qt			
pH			
Sand Content Percent by Volume	<2	<2	Sand API 13B-1 Section 5

a. Maintain slurry temperature at 40°F or more during testing.
b. Do not use blended slurries.

Source: United States. Oregon Department of Transportation. *Standard Specifications*. 2008.

Table B.38 Pennsylvania slurry specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	No specifications pertaining to slurry parameters available at time of study.		
Viscosity Seconds/qt {Seconds/L}			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	No specifications pertaining to slurry parameters available at time of study.		
Viscosity Seconds/qt {Seconds/L}			
pH			
Sand Content Percent by Volume			

Table B.39 Rhode Island slurry specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	No specifications pertaining to slurry parameters available at time of study.		
Viscosity Seconds/qt			
pH			
Sand Content Percent by Volume			

a. Temperature must be at least 40°F during testing.
b. Maximum of 25cc fluid loss by pressure; API 13A.

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	No specifications pertaining to slurry parameters available at time of study.		
Viscosity Seconds/qt			
pH			
Sand Content Percent by Volume			

Table B.40 South Carolina slurry specifications (SCDOT, 2007)

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	64.3 – 69.1	64.3 – 75.0	Density Balance API 13B-1 Section 1
Viscosity Seconds/qt	28 – 45	28 – 45	Marsh Cone API 13B-1 Section 2.2
pH	8 – 11	8 – 11	pH paper, pH meter
Sand Content Percent by Volume	N/A	N/A	N/A

a. Perform tests when the slurry temperature is above 40° F.
b. If desanding is required, do not allow sand content to exceed 4% (by volume) at any point in the borehole as determined by the American Petroleum Institute Sand Content Test (API 13B-1, Section 5).

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	64.3 – 69.1	64.3 – 75.0	Density Balance API 13B-1 Section 1
Viscosity Seconds/qt	28 – 45	28 – 45	Marsh Cone API 13B-1 Section 2.2
pH	8 – 11	8 – 11	pH paper, pH meter

Source: United States. South Carolina Department of Transportation. *Standard Specifications for Highway Construction*. 2007.

Table B.41 South Dakota slurry specifications (SDDOT, 2004)

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	Drilled shafts permitted but no specifications pertaining to slurry parameters available.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	Drilled shafts permitted but no specifications pertaining to slurry parameters available.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Source: United States. South Dakota Department of Transportation. *Standard Specifications*. 2004.

Table B.42 Tennessee slurry specifications (TDOT, 2006).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	63.5 – 66.8	63.5 – 70.5	Density Balance
Viscosity Seconds/qt	32 – 60	32 – 60	Marsh Funnel
pH	8 – 10	8 – 10	pH paper, pH meter
Sand Content Percent by Volume	Vol<4	Vol<10	API Sand Content Kit
Maximum Contact Time Hours	N/A	N/A	N/A

Polymer Slurry Specifications

Emulsified Polymer			
Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 $\{kg/m^3\}$	< 63	< 63	Density Balance
Viscosity Seconds/qt {Seconds/L}	33-43*	33-43*	Marsh Funnel
pH	8 - 11	8 - 11	pH paper or meter
Sand Content Percent by Volume	< 1	< 1	API Sand Content Kit
Maximum Contact Time Without Agitation or Sidewall Cleaning	72 hrs	72 hrs	

*Higher viscosities may be required to maintain excavation stability in loose or gravelly sand deposits.

Table B.42 (continued)

Dry Polymer			
Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 $\{kg/m^3\}$	< 63	< 63	Density Balance
Viscosity Seconds/qt {Seconds/L}	50 – 80*	50 – 80*	Marsh Funnel
pH	7 - 11	7 - 11	pH paper or meter
Sand Content Percent by Volume	< 1	< 1	API Sand Content Kit
Maximum Contact Time Without Agitation or Sidewall Cleaning	72 hrs	72 hrs	

*Higher viscosities may be required to maintain excavation stability in loose or gravelly sand deposits.

Source: United States. Tennessee Department of Transportation. *Special Provisions Item 625: Drill Shaft Specifications.* 2006.

Table B.43 Texas slurry specifications (TxDOT, 2004).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Specific Gravity	≤1.10	≤1.15	
Viscosity Seconds/qt {Seconds/L}	N/A	≤45	
pH			
Sand Content Percent by Volume	Vol≤1	Vol≤6	

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Specific Gravity	"Do not use PHPA (partially hydrolyzed polyacrylamide) polymeric slurry or any other fluid composed primarily of a polymer solution."		
Viscosity Seconds/qt {Seconds/L}			
pH			
Sand Content Percent by Volume			

Source: United States. Texas Department of Transportation. *Standard Specifications*. 2004.

Table B.44 Utah slurry specifications (UDOT, 2008)

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	Slurry drilling is not permitted.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	Slurry drilling is not permitted.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Source: United States. Utah Department of Transportation. *Standard Specifications*. 2008.

Table B.45 Vermont slurry specifications (AOT, 2009).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 $\{kg/m^3\}$	64.3 – 69.1 {1030 – 1107}	64.3 – 75.0 {1030 – 1201}	Density Balance API 13B-1 Section 1
Viscosity Seconds/qt {Seconds/L}	28 – 45 {30 – 47}	28 – 45 {30 – 47}	Marsh Cone API 13B-1 Section 2.2
pH	7 – 11	7 – 11	pH paper, pH meter
Sand Content Percent by Volume	N/A	≤4	Sand API 13B-1 Section 5

a. These tests shall be done per the American Petroleum Institute RP 13B-1 Standard Procedure for field testing Water Based Drilling Fluids.

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 $\{kg/m^3\}$	63 – 64 {1009 – 1025}	63 – 64 {1009 – 1025}	Density Balance API 13B-1 Section 1
Viscosity Seconds/qt {Seconds/L}	45 min {48 min}	45 min {48 min}	Marsh Cone API 13B-1 Section 2.2
pH	7 – 11	7 – 11	pH paper, pH meter
Sand Content Percent by Volume	N/A	< 1	Sand API 13B-1 Section 5

a. These tests shall be done per the American Petroleum Institute RP 13B-1 Standard Procedure for field testing Water Based Drilling Fluids.
b. Range of values for polymer slurry at 68° F [20° C]
c. The use of a blended mineral-polymer slurry is not permitted.
d. Polymer slurry (vinyl (dry) or natural polymers) shall be made from Partially-Hydrolyzed Polyacrylamide Polymer (PHPA) (emulsified). The polymer slurry product must be approved for use by the Agency.

Source: United States. Vermont Agency of Transportation. *Bennington AC NH 019-1(51) Construction Special Provisions*. 2009.

Table B.46 Virginia slurry specifications (VDOT, 2010).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	63 – 65	65 – 67	Mud Balance API 13B-1 Section 1
Viscosity Seconds/qt	50 max.	50 max.	Marsh Cone Method API 13B-1 Section 2.2
pH	8 – 10	8 – 10	pH paper, pH meter
Sand Content Percent by Volume	0.3% max	1% max	API 13B -1

a. Density values shall be increased by two pounds per cubic foot (lb/ft^3) in salt water.
b. At time of concreting, sand content at any point in the drilled shaft excavation shall not exceed 1% (by volume); test for sand content as determined by the American Petroleum Institute.
c. Minimum mixing time shall be 15 minutes.
d. Storage time to allow for hydration shall be minimum of 4 hours.

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	63 – 65	65 – 67	Mud Balance API 13B-1 Section 1
Viscosity Seconds/qt	50 max.	50 max.	Marsh Cone Method API 13B-1 Section 2.2
pH	8 – 10	8 – 10	pH paper, pH meter
Sand Content Percent by Volume	0.3% max	1% max	API 13B -1

(a) Density values shall be increased by two pounds per cubic foot (lb/ft^3) in salt water.

(b) At time of concreting, sand content at any point in the drilled shaft excavation shall not exceed 1% (by volume); test for sand content as determined by the American Petroleum Institute.

(c) Minimum mixing time shall be 15 minutes.

(d) Storage time to allow for hydration shall be minimum of 4 hours.

Source: United States. Virginia Department of Transportation. *Special Provisions for Drilled Shafts*. 2010.

Table B.47 Washington slurry specifications (WSDOT, 2009).

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	64.3 – 75	64.3 – 75	Mud Balance API 13B-1 Section 1
Viscosity Seconds/qt	26 – 50	26 – 50	Marsh Funnel and Cup API 13B-1 Section 2.2
pH	8 – 11	8 – 11	pH paper, pH meter
Sand Content Percent by Volume	4 MAX	4 MAX	Sand API 13B-1 Section 5

a. Use of mineral slurry in salt water installations will not be allowed.

Polymer Slurry Specifications

<table>
<tr><th>Property (Units)</th><th>At Time of Slurry Introduction</th><th>In Hole at Time of Concreting</th><th>Test Method</th></tr>
<tr><td>Density lb/ft^3</td><td colspan="3" rowspan="4">B. Synthetic Slurries
1. Synthetic slurries shall be used in conformance with the manufacturer's recommendations, the quality control plan specified in subsection 3.02.B.5 of this Special Provision, and these Special Provisions.</td></tr>
<tr><td>Viscosity Seconds/qt</td></tr>
<tr><td>pH</td></tr>
<tr><td>Sand Content Percent by Volume</td></tr>
</table>

“The submittal shall include a detailed plan for quality control of the selected slurry, including tests to be performed, test methods to be used, and minimum and/or maximum property requirements which must be met to ensure that the slurry functions as intended, considering the anticipated subsurface conditions and shaft construction methods, in accordance with the slurry manufacturer's recommendations and these Special Provisions. As a minimum, the slurry quality control plan shall include the following tests:

Property	**Test Method**
Density	Mud Weight (Density), API 13B-1, Section 1
Viscosity	Marsh Funnel and Cup, API 13B-1, Section 2.2
PH	Glass Electrode, pH Meter, or pH Paper
Sand Content	Sand, API 13B-1, Section 5”

Table B.47 (continued)

Synthetic slurries shall be used in conformance with the manufacturer's recommendations, the quality control plan specified in subsection 3.02.B.5 of this Special Provision, and these Special Provisions. The following synthetic slurries are approved as slurry systems, with additives that have been load tested for the California Department of Transportation:

Product	**Manufacturer**
Novagel	*Geo-Tech Services, LLC*

220 North Zapata Highway, Suite 11A
Laredo, TX 78043-4464

ShorePac GCV	*CETCO*

1500 West Shure Drive
Arlington Heights IL, 60004

SlurryPro CDP	*KB International, LLC*

Suite 216, 735 Broad Street
Chattanooga, TN 37402-1855

*Super Mud**	*PDS Company*

8140 East Rosecrans Ave.
Paramount, CA 90723-2754

**Approval as a product applies to the liquid product only.*

Other synthetic slurry products may be approved for use provided the product meets the acceptance criteria established by WSDOT, including status as an approved synthetic slurry (with load tested additives) with the California Department of Transportation (Caltrans).

Source: United States. Washington State Department of Transportation. *Bridge Special Provisions.* 2011.

Table B.48 West Virginia slurry specifications (WVDOT, 2000).

Mineral Slurry Specifications

<table>
<tr><th>Property
(Units)</th><th>At Time of Slurry
Introduction</th><th>In Hole at Time of
Concreting</th><th>Test
Method</th></tr>
<tr><td>Density
kg/m^3</td><td colspan="3" rowspan="4">When the use of slurry is anticipated, details of the methods to mix, circulate, and de-sand slurry. Any request to use a slurry displacement method for the construction of caissons shall also provide information for the Engineer's approval as follows:
1. Detailed description of proposed construction method.
2. Concrete mix, as modified for use with the slurry displacement method.
3. Components and proportions in proposed slurry mixture.
4. Tests proving slurry mixture will not degrade rock or interfere with bond.
5. Methods to agitate slurry mixture prior to concrete placement.
6. Methods to clean slurry mixture for re-use.
Disposal methods for used slurry.</td></tr>
<tr><td>Viscosity
Seconds/L</td></tr>
<tr><td>pH</td></tr>
<tr><td>Sand Content
Percent by Volume</td></tr>
</table>

Polymer Slurry Specifications

<table>
<tr><th>Property
(Units)</th><th>At Time of Slurry
Introduction</th><th>In Hole at Time of
Concreting</th><th>Test
Method</th></tr>
<tr><td>Density
kg/m^3</td><td colspan="3" rowspan="4">No specific polymer slurry specifications</td></tr>
<tr><td>Viscosity
Seconds/L</td></tr>
<tr><td>pH</td></tr>
<tr><td>Sand Content
Percent by Volume</td></tr>
</table>

Source: United States. West Virginia Department of Transportation. *West Virginia Division of Highways: Supplemental* Specifications. 2000.

Table B.49 Wisconsin slurry specifications

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	No specifications pertaining to slurry parameters available at time of study.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	No specifications pertaining to slurry parameters available at time of study.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Table B.50 Wyoming slurry specifications (WYDOT, 2010)

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	Drilled shafts permitted but no specifications pertaining to slurry parameters available.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	Drilled shafts permitted but no specifications pertaining to slurry parameters available.		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Source: United States. Wyoming Department of Transportation. *Standard Specifications*. 2010.

Table B.51 Federal Highway Administration slurry specifications (FHWA, 2003)

Mineral Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	64.3 – 69.3	64.3 – 74.9	Density Balance
Viscosity Seconds/L	30 – 48	30 – 48	Marsh Cone
pH	8 – 11	8 – 11	pH paper, pH meter
Sand Content Percent by Volume	4 MAX	4 MAX	API 13B-1

Polymer Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	No specifications pertaining to slurry parameters available		
Viscosity Seconds/L			
pH			
Sand Content Percent by Volume			

Source: United States. United States Department of Transportation Federal Highway Administration. *Standard Specifications for the Construction of Roads and Bridges on Federal Highway Projects*. 2003.