USF UNIVERSITY OF SOUTH FLORIDA

Civil & Environmental Engineering

RAPID HYDRATION OF MINERAL SLURRIES FOR DRILLED SHAFTS
BDK-84-977-03

FINAL REPORT

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Disclaimer

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	squareinches	645.2	square millimeters	mm^2
ft^2	squarefeet	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
yd^3	cubic yards	0.765	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 SI 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	1.307	cubic yards	yd^3

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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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. The time required to prepare a slurry is not specified, but the performance of the slurry is in the form of viscosity, density, sand content, and pH tolerances. This study presents a methodology by which new slurry can be rapidly prepaired thus saving construction time. This is especially helpful where small projects can not warrant large amounts of slurry storage space or equipment.</td></tr>
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External contributions from local drilled shaft contractors served to be invaluable in assessing the present state of practice in the preparation of mineral slurry. To this end, Case Atlantic Inc, Coastal Caisson Inc, and R.W. Harris, Inc were most helpful.

The Association of Drilled Shaft Contractors (ADSC) is also recognized by all involved in this project for both training all student research in their annual slurry school and contributing one of the venturi hoppers used in the study. Dennis Wiksten is hereby most notably recognized.

An additional thanks again is extended to the R.W. Harris, Inc drill crew who volunteered to implement the rapid eductor slurry mixing system and providing feedback as to its value to field applications.

Finally, the study could not have been made possible in its present form without the close coordination with C.E. Hooton Sales and their willingness to accommodate the project needs. The principal investigator would like to extend his warmest thanks to Ramona Cannon for her sincere support.

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 from hydrostatic mineral slurry pressure. Due to the time required to prepare mineral slurries, a method of preparing slurry in a timely fashion was identified for this project with specific focus on small applications where large slurry mixing/containment systems are not practical. Improved methods of quickly preparing slurry were further identified as advantageous for large projects to enhance the overall constructability of all shaft projects.

The efficiency of the hydration process stems from the initial contact between the powder and water. Slowly applied amounts of powder to moving or agitated water mix more thoroughly and readily. This project identified a system for mixing slurry for drilled shaft applications using a combination of off the shelf components that have been largely overlooked by the drilled shaft industry. The mixing system developed can mix slurry that meets state slurry specifications at a rate of 220 gallons of slurry per minute.

Both small and large scale versions were field tested by operators of a subsurface exploratory drill crew and a production drilled shaft team constructing 60, 72, and 84 inch diameter shafts. Preliminary results of the field implementation for drilled shaft applications are promising wherein the production crew was able to adjust the system mix ratios to produce slurry suitable for direct introduction into the excavation without use of a holding tank.

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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, respectively. Depending on the slurry type (mineral, polymer, or natural), a lower to higher differential fluid level is required, respectively. 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 shows 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.

Due to the time required to hydrate clay minerals, a method of preparing slurry in a timely manner was identified for this project with specific focus on small applications where large slurry mixing/containment systems are not practical. Improved methods of quickly preparing slurry were further identified as advantageous for large projects to enhance the overall constructability of all shaft projects (e.g. replacing lost slurry or contaminated slurry, etc.).

1.1 Background

The most widely accepted 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). In all cases, however, mineral slurries require adequate mixing to ensure proper hydration and produce the desired fluid properties. The efficiency of the hydration process stems from the initial contact between the powder and water. Slowly applied amounts of powder to moving or agitated water mix more thoroughly and readily, whereas dumping bags of powder into large mixing vats only produces large clumps of dry powder encased in a skin of partially hydrated clay. If not mechanically broken apart they will never become slurry.

Understanding the parameters affecting the use and mixing of mineral slurry has a cost saving benefit for the state of Florida; the ability to prepare slurry without needless delays will reduce some of the time required for construction especially on sites where limited equipment storage is available (e.g. roadside construction of shafts for miscellaneous structures). This study collected information from all 50 states' transportation departments with regards to slurry specifications, contractors, slurry manufactures, and providers of alternative mechanisms.

1.2 Report Organization

The overall organization of this report is outlined below wherein four chapters provide the following: a comprehensive background, the present state of the art equipment and slurry products, advancements in slurry mixing methods / equipment, and recommendations for the useful application of 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 shaft construction, clay chemistry, and state specification throughout the United States is provided in this chapter. Methods of testing slurry are discussed with emphasis on the physical meaning of how each test result affects shaft construction.

The readily available slurry products (mineral powder) are introduced in Chapter 3 along with the equipment and methodologies used to prepare slurry. Results from comparative tests conducted on several different slurry products are presented wherein the most common mixing equipment was used.

Results of the Chapter 3 tests were used to sculpt an equipment development program which is presented and discussed in Chapter 4. This program began by assessing the performance of other mixing devices (not used for shaft slurry) and concluded in an enhanced version of these devices assembled in a configuration conducive to large-quantity slurry mixing/preparation. Recommendations for the use of the developed device are presented in Chapter 5 as well as a summary of project findings.

An appendix follows Chapter 5 that contains the drilled shaft slurry specifications from each of the fifty states.

Chapter Two: Background

This chapter provides an overview of mineral slurry mixing for drilled shaft applications which includes: mineral powders, clay hydration chemistry, mixing equipment, field practice, and slurry testing equipment.

2.1 Problem Statement

The purpose of this study was to identify potential methods of rapidly hydrating mineral slurry for drilled shaft construction with the ultimate goal of developing a device for preparing small to mid-sized slurry volumes on the order of 2000 gallons.

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 field testing of presently available and/or used methods of mixing slurry, (3) modification and testing of new slurry mixing systems, (4) develop recommendations/guidelines, quarterly reporting, and final report preparation.*

2.2 Mineral Slurry Products

For the purposes of this study and drilled shaft excavations for the state of Florida, two types of mineral slurry are applicable: bentonite and attapulgite. Bentonite, also called sodium bentonite or sodium montmorillonite, is a better product for all sites except those with brackish or salt water. For those sites, the attapulgite (also known as palygorskite) is required. A discussion of the interaction with the ground water properties will follow in the ensuing section.

Readily available bentonite slurry products (in Florida) come primarily from two manufacturers: Wyoben, Inc. and Cetco, a subsidiary of AMCOL International Corporation. Both manufacturers use Wyoming grade sodium bentonite and both produce a full line of slurry products including: pure bentonite, high yield bentonite, polymer additives for mineral slurries, and polymer products to be used completely without minerals. Standard yield bentonite products (pure bentonite) produce approximately 90 barrels (bbl) of slurry per ton of dry powder. The unit of measure, barrel (bbl), refers to the standard unit for crude oil or 42 gallons. Depending on the industry that uses the unit, it could mean a volume anywhere from 26 – 53 gallons; the slurry application herein refers to the petroleum industry definition**.** Although not the focus of this study, polymer fortified bentonite slurry products (often termed high yield) can produce a 220 – 235 bbl yield or 2.4 to 2.6 times more slurry for the same weight of product. The yield for those products compares two slurries of equal viscosity and not density.

Attapulgite, the alternate mineral slurry, is mined and manufactured primarily in the Meigs-Quincy district which can also be referred to as the Meigs-Attapulgus-Quincy district. Meigs, Georgia and Quincy, Florida provide the rough extents of the mine-able attapulgite with Attapulgus, Georgia (named after the mined material there) being roughly in the center of the district. Attapulgite is one of two common minerals also know as fuller's earth; the other is calcium montmorillonite. Prior to its use as a construction material it was primarily used as a filtering material for different types of mineral or vegetable oils. Three manufacturers actively mine and process the attapulgite: Active Minerals International, LLC., BASF, and Zemex. The Floridin brand no longer represents the company by the same name but rather is now produced by Active Minerals and is mined in the Quincy, Florida area. This is the type tested in this study.

This study used two pure bentonite products (one from each manufacturer), two high yield products, and one attapulgite material as shown in Figure 2.1.

Figure 2.1. Readily available Bentonite slurry products.

2.3 Clay Hydration Chemistry

The structure of clay minerals is comprised of two basic units: a silica tetrahedron and an alumina octahedron (Das, 2005). The silica tetrahedron is typically known as a silica sheet whereas the alumina octahedron is referred to as a gibbsite sheet. There are two orientations of the silica and gibbsite sheets, a 1:1 and a 2:1 lattice. A 1:1 lattice consists of one silica and one gibbsite sheet whereas a 2:1 lattice consists of a gibbsite sheet sandwiched between two silica sheets. Kaolinite is a common 1:1 clay, whereas montmorillonite is a common 2:1 clay.

Focusing on the montmorillonite group there can be two main groupings of the clay dependent on the exchangeable cations that are found in between each 2:1 clay particle lattice in an area referred to as the interlayer zone. Calcium montmorillonite, which has Ca exchange ions, is commonly referred to as Cheto-type montmorillonite and is characterized by low swelling (ability to take on water) properties. Wyoming-grade montmorillonite is a sodium montmorillonite characterized by a Na exchangeable ions and a high swelling capacity. This high swelling capacity is why sodium montmorillonite, commonly referred to as bentonite, is used in slurry applications.

The association between clays and water stems from the negative charge present on the surfaces of the clay. When clay comes in contact with water the cations in the solution are attracted to the negatively charged clay surface in an attempt to remain electrically neutral. A high concentration of cations builds around the surface of the clay particle. This concentration of cations has a tendency to diffuse towards the water and away from the surface clay; however, due to the electrical attraction of the cation to the clay, equilibrium is established. The clay surface itself and the surrounding layer of positively charged cations is known as the Gouy layer, or commonly referred to as the double layer.

Hydration of clays can be characterized by water molecules being clustered around cations in a non-random manner (Eslinger and Pevear, 1988). When 2:1 clay is placed in solution water begins to form discrete layers in the interlayer spaces. As the layers continue to build up around the clay particles the attraction between the water molecule and the cations is diminished due to the increased distance between them. Eventually, the swelling of the clay becomes controlled by osmosis of water through the multiple layers.

As swelling continues the individual 2:1 plates are separated farther until the plates are completely dissociated from one another. This complete dissociation of particles is what gives the clay its viscous characteristics. However, this complete disassociation only occurs in clays that have a low layer charge and an available interlayer cation with a hydration energy equivalent or greater than that of Na (Eslinger and Pevear, 1988). Sodium montmorillonite, characterized by its Na cation and low layer charge, is a clay that experiences complete disassociation.

As the concentration of clay particles, and in turn, the salinity of the solution increases the electrical repulsion between clay particles decreases due to the lower tendency for cations to diffuse away from the clay surface. Eventually, the salinity will increase to such a point that the Gouy layers overlap one another and particles will begin to clump together (flocculate). This clumping of particles leads to a lower viscosity. Hence, in high salinity solutions, such as salt water applications, sodium montmorillonite is unable to maintain viscosity and therefore is a inappropriate choice of mineral slurry.

2.4 Mineral Slurry Testing

Slurry Requirements
Mineral based drill slurry is heavier than water and is viscous enough to suspend small particle cuttings. When maintained correctly, the slurry level (at least 4ft above ground water) provides lateral pressure in excess of the active earth pressure while also eliminating ground water intrusion. This coupled with the filter-cake that quickly forms on the excavation walls - as the net higher pressure slurry moves slowly into the surround soil - provides stability to the excavation even with the motion of the drilling tool up and down the excavation walls. The health of the slurry is best measured by the pH which indicates whether or not excavation has encountered organics (low pH) or other materials that compromise the integrity of the clay to water bond. Required values of density, viscosity, pH, and sand content are provided in the FDOT 455-Standard Specifications for Road and Bridge Construction (2010) and are shown in Table 1 (FDOT, 2010). Of these values, this study was charged to address methods of quickly obtaining the necessary density and viscosity; the remaining parameters, pH and sand content, are not pertinent to slurry preparation with the exception of initial water quality.

Table 2.1. Drill slurry properties.

Slurry Property	Range of Acceptable Results (lb/ft^3)	Test Method
Density	64 – 73 pcf (fresh water) 66 – 75 pcf (salt water)	Mud density balance: FM 8-RP13B-1
Viscosity	28-40 sec	March 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

Similar specifications are in place in 41 of 50 states in the country. Figures 2.2 – 2.5 show these trends wherein the states have been assigned numerical values corresponding to their respective alphabetic order. Tabular information from each state is provided in the Appendix as well as the Federal Highway Administration (FHWA) specifications.

Intrinsic to the preparation of properly performing slurry is the time dependency of each of these properties. Even when mixed carefully without clumping, the now wetted mineral absorbs the water slowly over a period of several hours. This does not mean that workable slurry cannot be prepared more quickly than the time required for full hydration, but rather that properties change with time and must be monitored somewhat continuously. Slurries too heavy are not easily displaced during concreting (dependent on sand content as well as mineral content), slurries too light do not supply sufficient lateral stress. Slurries without sufficient viscosity cannot suspend particles; when too viscous concreting complications arise.

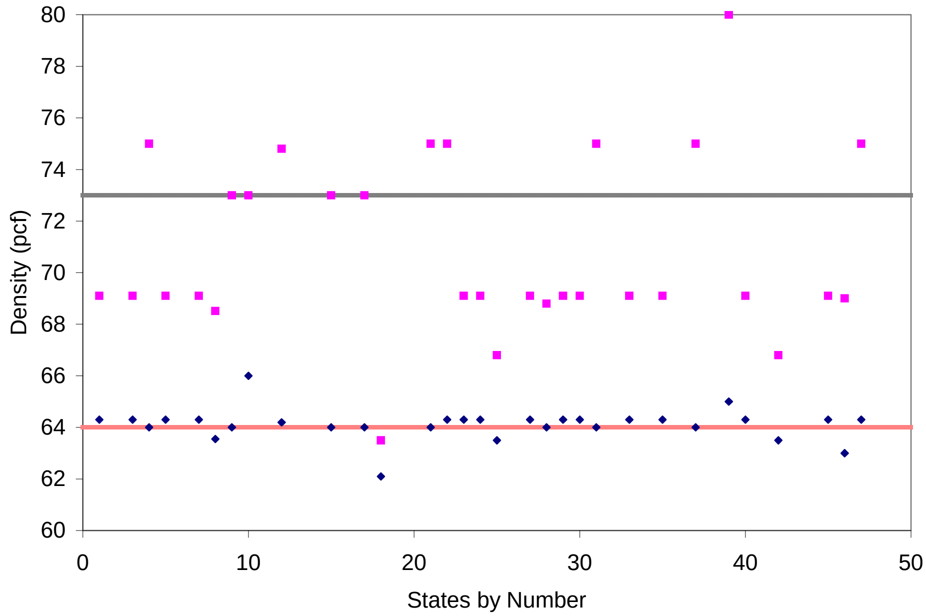

Figure 2.2. Specifications for 41 of 50 states for slurry density.

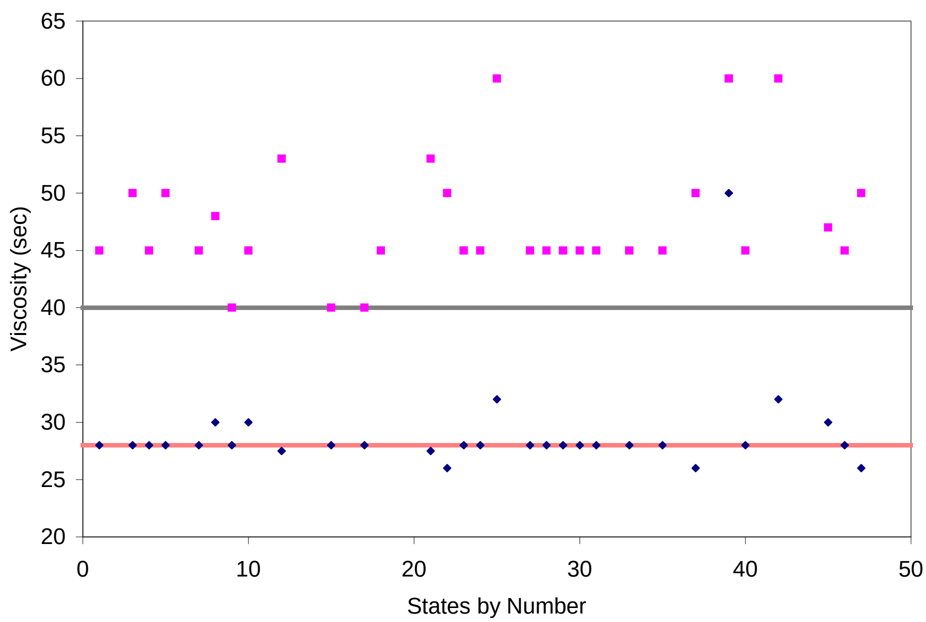

Figure 2.3. Specifications for 41 of 50 states for slurry viscosity.

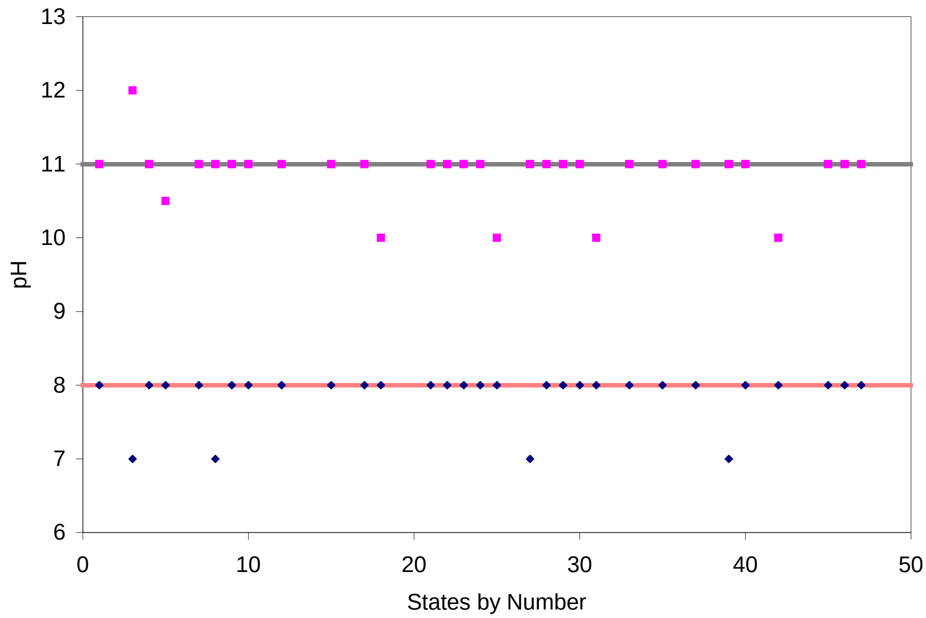

Figure 2.4. Specifications for 41 of 50 states for slurry pH.

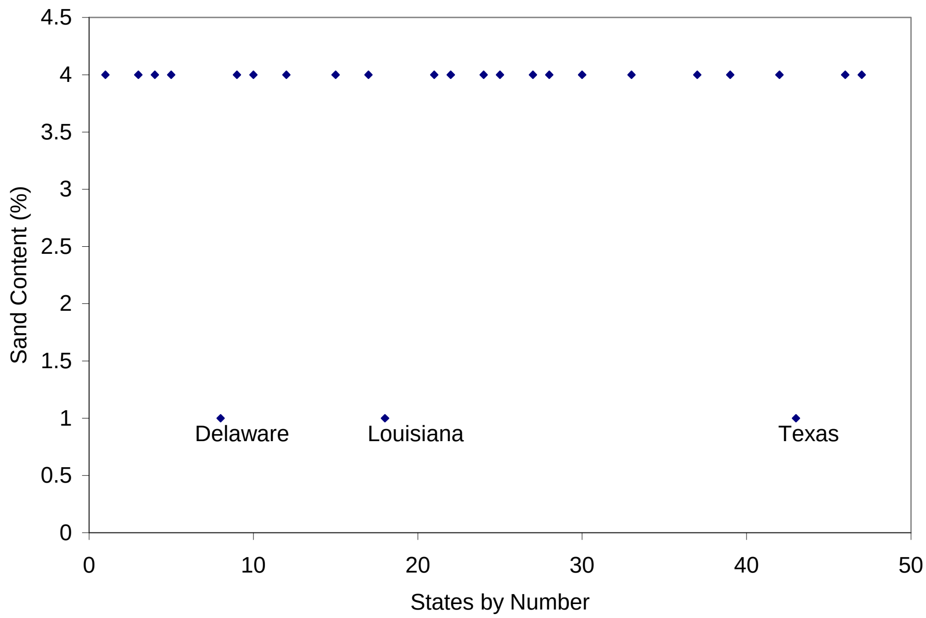

Figure 2.5. Specifications for 41 of 50 states for slurry sand content.

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2.5 Mineral Slurry Mixing Systems

Systems for mixing and cleaning large amounts of slurry range from conventional truck-pulled trailers with 2000 gallon capacities to semi-tractor pulled trailers with 7000 gallon capacities, Figure 2.6 (Tulsa Rig Iron, 2008). For the purposes of this project it should be noted that a common size shaft for miscellaneous structures requires on the order of 2000 gallons depending on water table elevation and soil absorption.

Figure 2.6. Portable slurry mixing and cleaning systems (top 2000 gallon; bottom 7000 gallon).

Aside from holding tanks and de-sanding chambers/systems, these systems typically incorporate a high pressure mud gun (or venturi hopper) with agitators along with a high shear, low pressure mixing tank as the means to prepare slurry from dry powder. The flaw with most of these systems lies in the mud gun. The mud gun attempts to saturate the dry powder as it falls from a hopper similar to the flow from an hour glass. Contact between the dry powder and the water stream occurs only on the upper surface of the stream and the rate of powder infusion is independent of the water flow. Further, as the hopper and water are in direct contact with each other the wetted portions of the hopper cake with dry powder which eventually requires intervention leading to clumps of material scraped into the slurry system. All said, this type of system overcomes these shortcomings with high energy / high shear mixers that might not have been necessary if more suitable means of introducing the dry powder into the water had been used.

2.5.1 Venturi Hoppers

At the heart of virtually all slurry mixing systems (for drilled shaft applications) is a venturi hopper of some form. Venturi hopper/mixers (also called hopper eductors) are the most common mud guns used by slurry mixing systems. To remove possible confusion to the reader, the term eductor in this report will be used solely in reference to the units described later. These devices - designed for granular materials - in concept should provide adequate contact between bentonite powder and water but suffer from two issues as mentioned above: (1) the interface region of the mixer is prone to build-up of the sticky dry powder which then results in breaking off balls of skinned over powder and (2) the feed rate of the powder in the hopper can overwhelm the mixing chamber and is partially dependent on gravity and the cleanliness of the hopper. Although all venturi hoppers induce some clumping, larger scale versions permit even larger clumps. Figure 2.7 shows various venturi hopper systems as used to mix and dissolve granular solids into a solution. The diagram shown (right) makes use of a small amount of the inflow (the motive liquid) to help movement of the granular material

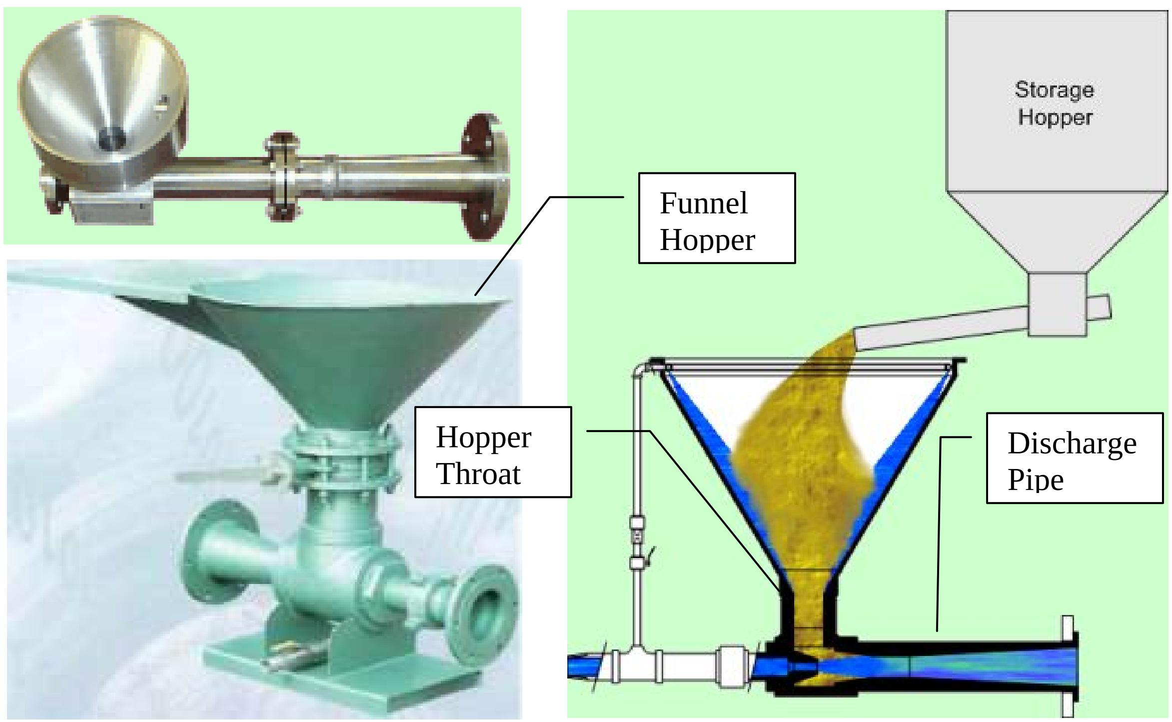


Figure 2.7. Venturi hopper / mixers (Eastern Oils, 2008; Venturi Pumps, 2008).

into the venturi port. This is not desired when using bentonite or polymers as this causes excessive build-up within the hopper. Similarly, the throat of the hopper and the mixing chamber around the high velocity orifice suffer from the same build up. The manufacturers of the stainless unit (top left) claim it can be made from any material and coated for additional corrosion protection. The unit shown bottom left has a flow control lever/valve in the throat of the hopper to presumably regulate particle inflow rate in an effort to minimize clogs. In all cases, dry powder comes into contact with a wet surface that is inherently problematic. Figure 2.8 shows the throat of a venturi hopper shortly after the commencement of bentonite introduction. Figure 2.9 shows the throat of a similar system after introducing dry polymer for an extended period. In both cases, the operator must either push the build-up through or remove the blockage to allow continued use. Commonly, the operator simply pushes the powder through will a stick or similar causing additional back-splash and clogging.

Figure 2.8. Bentonite build-up in throat of venturi hopper.

Figure 2.9. Polymer gel build-up in throat of venturi hopper.

2.5.2 Field Practice

As slurry mixing systems get larger, the state-of-the-art trend is to increase the size of the supply line, the hopper, the throat of the hopper, and the discharge tube. The net effect, aside from increasing fluid flow and mineral powder introduction rates, is to create larger clumps of poorly dispersed mineral powder. Figures 2.10 – 2.13 show equipment used by three local shaft contractors.

The slurry mixing system shown in Figure 2.10 is retrofitted with an agitation pipe aimed toward the bottom of tank to aid in suspending mineral slurry sediment to then be picked up by the recirculation pump. This system uses a 2 inch diameter supply line reduced through a 1 inch diameter nozzle (at base of hopper) and is re-circulated by either a 3 or 4 inch diameter pump. The operational tank volume is 1600 gallons; each batch of slurry requires a minimum of 20 minutes of mixing after the desired weight of dry mineral powder has been introduced. This tank is designed for smaller projects where the tank serves as both the mixing and holding tank all in one. Its smaller size reduces mobilized equipment (and associated expense) but can sometimes hinder production when larger diameter shafts are constructed due to the large amount of slurry required to fill the excavation every time the tool is extracted.

Figure 2.10. 1600 gallon slurry mixing tank (top left), venturi hopper (top right), tank recirculation / agitation system (bottom left), and alternate venturi hopper (bottom right), *Courtesy of R.W. Harris, Inc.*.

A system similar to that in Figure 2.10 is shown in Figure 2.11 with the exception that this tank is dedicated to mixing and then transfers the contents to a separate holding tank via a series of valves plumbed to divert the mixed slurry. The tank has a working volume of 1100 gallons to which 11 bags of pure Bentonite powder is added to produce a 36 second Marsh Funnel viscosity (Florida state specification is 28 to 40 sec). This system uses a 2 inch diameter supply line which passes through a ¾ inch reduction nozzle to produce increased velocity and a localized vacuum at the base of the hopper.

Figure 2.11. 1100 gallon slurry mixing tank (top left), venturi hopper (top right), reduction tube / nozzle (bottom left), and field mix guidelines (bottom right), *Courtesy of Coastal Caisson, Inc.*.

The system shown in Figure 2.12 has an approximate capacity of 9500 gallons. It has a self contained 79 horsepower electric motor that produces flow rates of 1800 GPM through a 4 inch diameter supply line. A restrictor valve in series with a 3 inch diameter line reduction produces the nozzle effect necessary to assist the introduction of dry powder. This approach makes no effort to reduce clumping but rather allows sufficient time to re-circulate the tank contents until the slurry has achieved the desired properties.

Figure 2.12. 9500 gallon slurry mixing tank (top left), venturi port (top right), removable hopper (bottom left), and re-circulation pump pick-up near bottom of tank (bottom right), *Courtesy of Case Atlantic, Inc.*.

Other configurations of commonly used venturi hoppers are shown in Figure 2.13. Depending on flow rates and nozzle design at the base of the hopper, wetting of mineral powder in the hopper may be more pronounced. These units are heavily modified by individual users to ease the process. Note the bag breaking table built into one of these units. Another can be seen to have an extended discharge tube. By extending the discharge tube there is an increased probability of backing up into the hopper which was circumvented here by using a 3 inch diameter extension pipe around the 2 inch diameter discharge tube thus reducing flow resistance.

Figure 2.13. Venturi hopper with breaking table (top left), residual clumps of mineral slurry (top right), venturi hopper with extended discharge pipe (bottom left), and nozzle welded into supply line at base of hopper (bottom right), *Courtesy of Case Atlantic, Inc.*.

2.5.3 Eductor Mixing System

At first glance, eductor mixing systems are a subset of the venturi hopper type systems as they both make use of Bernoulli's venturi principle. However, these cleverly designed devices have significant differences from eductor hoppers designed for granular material dispersal: (1) when properly operated, dry powder never touches a wetted device surface eliminating build-up and clogging, (2) material is mixed proportional to the flow rate of the motive liquid via vacuum feed and not dependent on gravity fall (raveling hour-glass effects), (3) the interface region where dry powder is introduced to the motive liquid is completely surrounded by fluid, and (4) the interface orifice is made from non-stick Teflon.

Figure 2.14 shows an eductor used in a previous USF/FDOT study to mix bentonite slurry along with a diagram of its operation. During that study a fixed volume of water was prepared and re-circulated through the eductor until such time that the desired amount of bentonite powder had been entrained; the motive liquid started as clear water and finished as slurry.

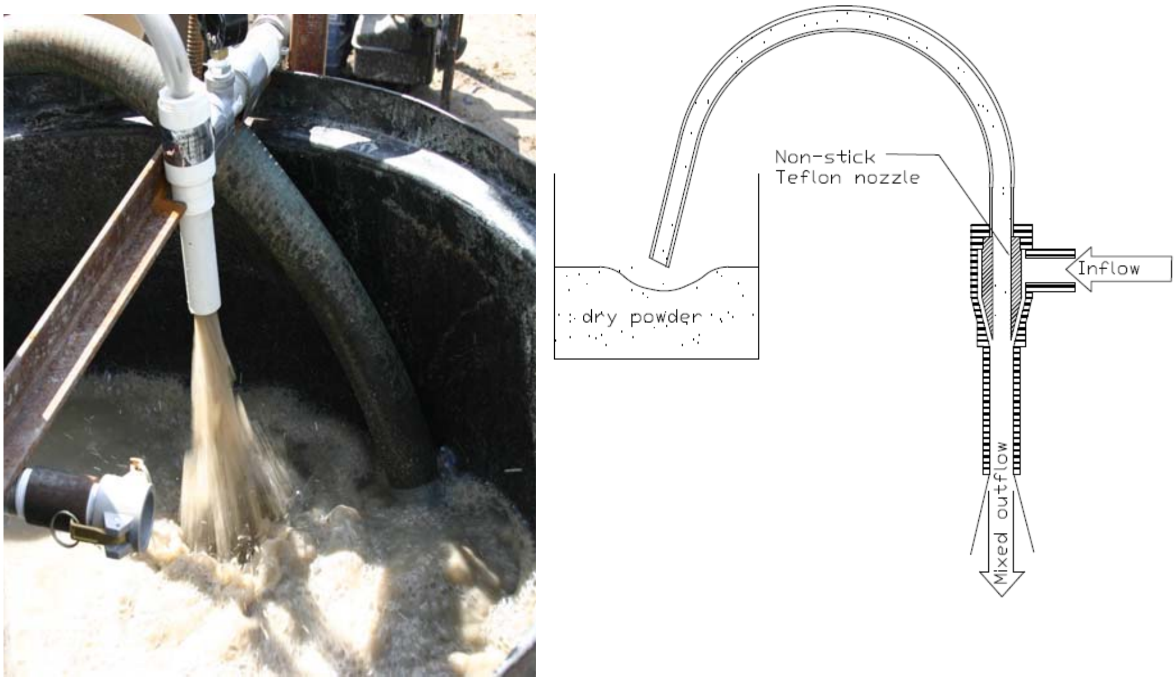


Figure 2.14. Vacuum-feed eductor used to mix bentonite slurry in previous study (Mullins, 2005).

This device is commonly used in the municipal water treatment plants to mix large quantities of poorly dispersing chemical additives with water. Likewise, it is used by food processing plants to mix a variety of solutions involving sticky materials like guar gum powder, fine powdered sugars, etc. To date, the manufacturer is unaware of it being used for drilled shaft construction in the U.S. although they have overseas accounts where it is thought to be used in that way.

2.5.4 Eductor Optimization

The eductor shown above (Figure 2.14) was optimized in the early 1960’s wherein numerous orifice sizes were tested which resulted in the present day unit. Testing targeted polymer dispersion for the sugar industry and not bentonite which may have left un-explored configurations. Conceptually, larger diameter units are not necessarily better as the wetting surface area does not increase proportional to the volume of dry powder (Figure 2.15).

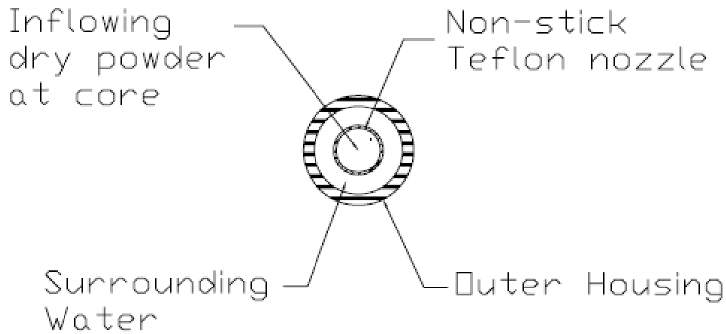


Figure 2.15. Cross-section of eductor showing powder / water interface (mixing zone).

At the point of contact between the dry powder and water, the nozzle thickness pinches off to a zero cross-sectional area and the wetted perimeter of the dry powder is the inner diameter of the nozzle (or powder core). If the wetted surface area or core diameter is doubled, the volume of dry powder is quadrupled which may affect the effectiveness of the mixing. A readily available alternative is to add eductors in parallel thereby maintaining present efficiency and proportionally increasing productivity. Methods of increasing efficiency, either by sizing up or increase number of units, will be explored and tested to identify an optimal solution. At present, the devices mix slurry perfectly - without the aid of high shear re-circulating pumps - but at a slow rate (5-8 lbs/min). If it is assumed that 2-2.5 lbs of powder per cubic ft of slurry are required, then a single unit would take up to 3 hours to process a target volume of 2000 gallons. Although it is tempting to simply use multiple units to obtain a reasonable time, complications may arise in providing appropriate flow rate and pressure, etc. In addition, larger sized units may perform reasonably well.

For this study, the manufacturer agreed to provide guidance on adapting the existing devices and produced a variation that met the needs of the project as it became necessary. Results of these adaptations are discussed in Chapter 4.

2.6 Overview

The rapid preparation of mineral slurry for drilled shaft applications is dependent on the mineral, the size of the mineral powder, the equipment used for its mixing, and the time before it is put into service. Present products and testing methods were evaluated and will be in part discussed in Chapter 3 with the goal of finding shortfalls in present practices that might be easily resolved. A new method of rapidly preparing slurry for drilled shaft applications was sought for the construction of drilled shafts on both small (high mast light or signage foundations) and large (bridge piers) shaft projects. The successful completion of this goal has the potential to benefit both the state of Florida and the drilled shaft industry alike.

Chapter Three: Mineral Product Testing

This chapter provides an overview of mineral product testing using standard mixing and testing practices.

3.1 Initial Mineral Slurry Testing

The test matrix of readily available mineral slurry products involved four of five products mixed at ratios of 0.25 lbs/gal, 0.5 lbs/gal, and 1 lbs/gal (dry powder to water volume). The Wyo Ben Extra High Yield was not initially tested.

The mixing system used for all tests included a venturi hopper fed by a high shear centrifugal pump with a 2" diameter inlet and outlet. Each mix started with 200 gallons of potable water recirculated until all the slurry powder was entrained at a pumping rate of 12000 gph. The total time to introduce the dry powder was approximately 1 minute which corresponds to one exchange of the total fluid volume. Mix ratios with lower powder concentrations took slightly less time although a constant powder introduction rate was not attempted. Figure 3.1 shows the general setup used to introduce the powder and mix / re-circulate the slurry.

Figure 3.1. Venturi hopper used for initial testing.

Relatively little care was taken to prevent piling powder in the hopper. As a result, some material build-up could be seen near the throat of the hopper upon completion. Figures 3.2 - 3.5 show the slurry density results and Figures 3.6 - 3.9 show the viscosity results, for all products tested. Figure 3.10 summarizes the test results in terms of mix ratio and that ratio required to reach FDOT slurry specifications. These results are also compiled in tabular form in Table 3.1.

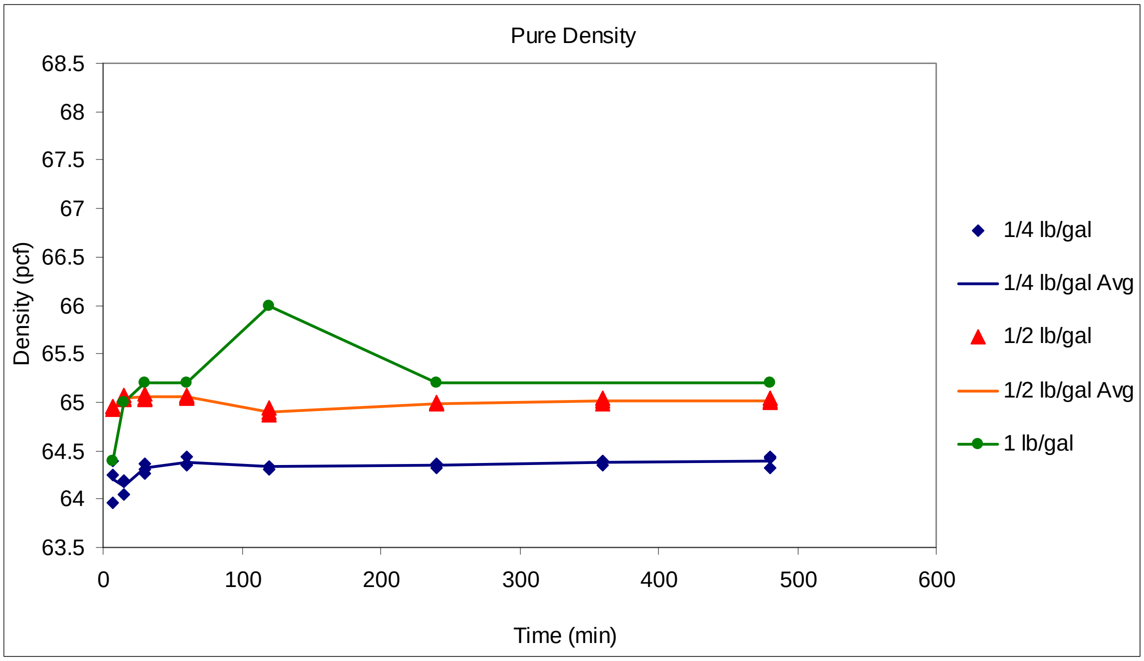


Figure 3.2. Density versus time for Pure Gold.

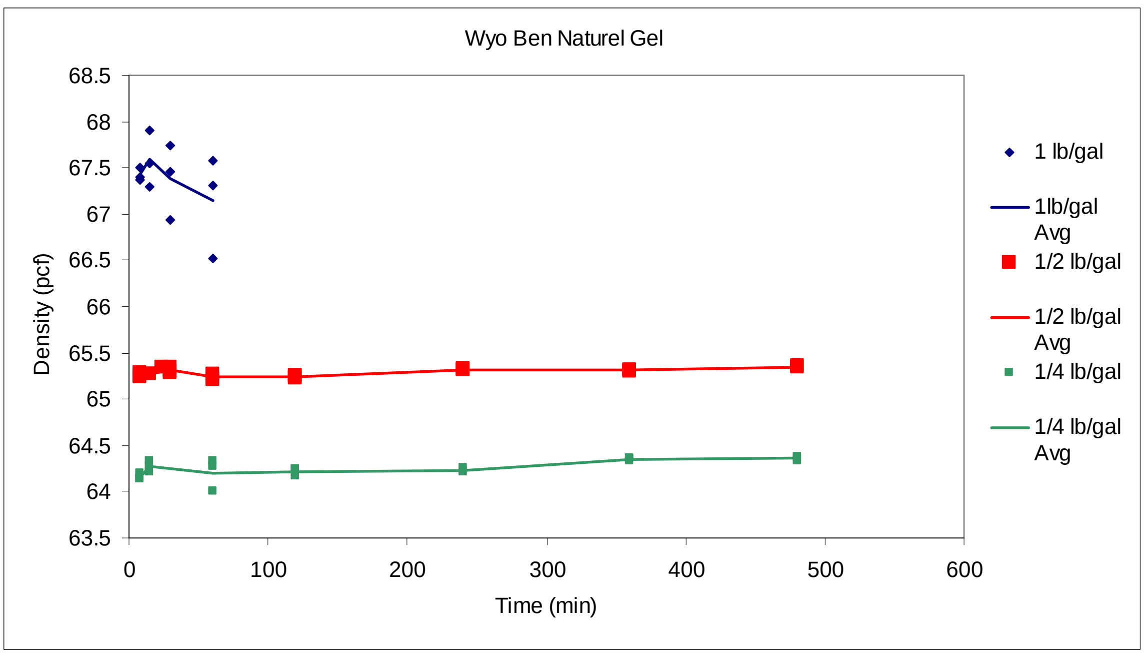


Figure 3.3. Density versus time for Wyo Ben Natural.

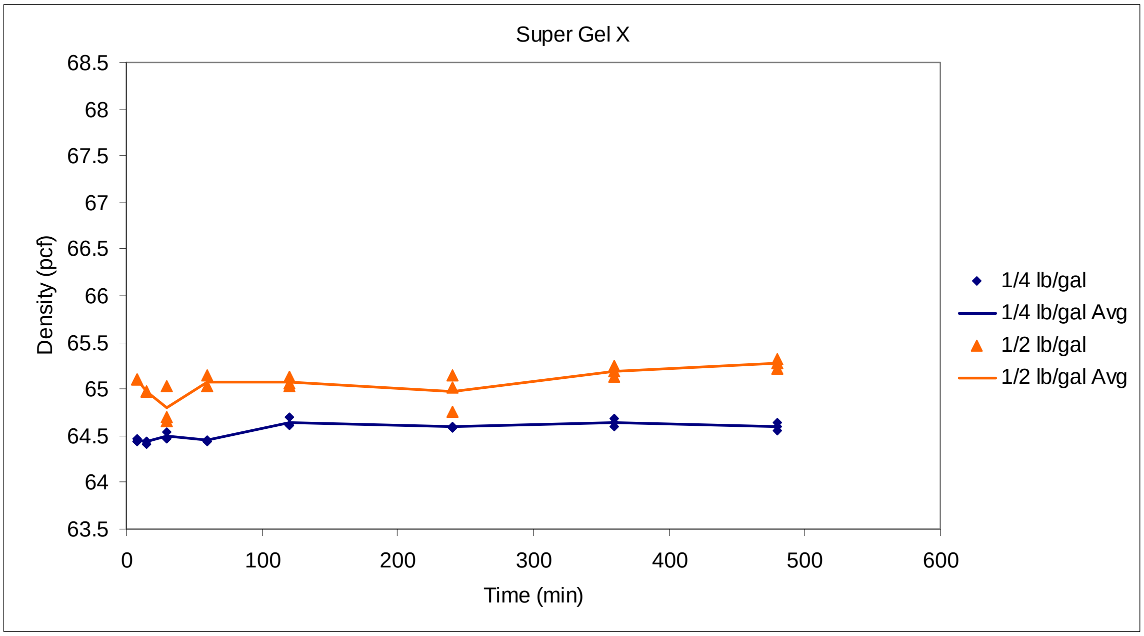


Figure 3.4. Density versus time for Super Gel X.

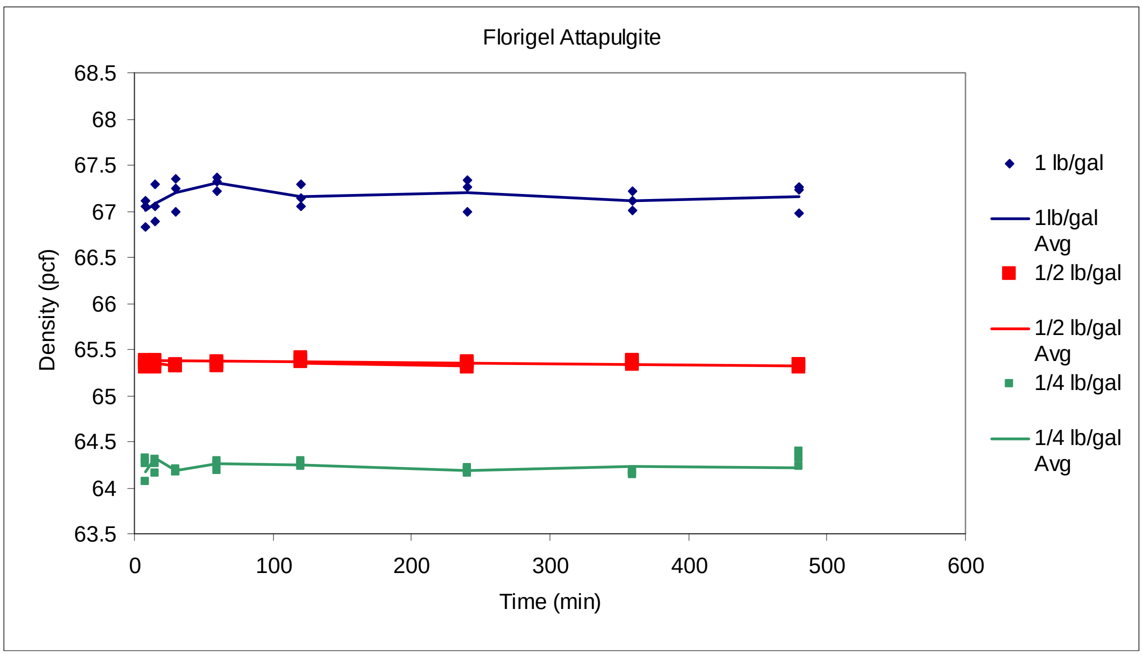


Figure 3.5. Density versus time for Florigel Attapulgite.

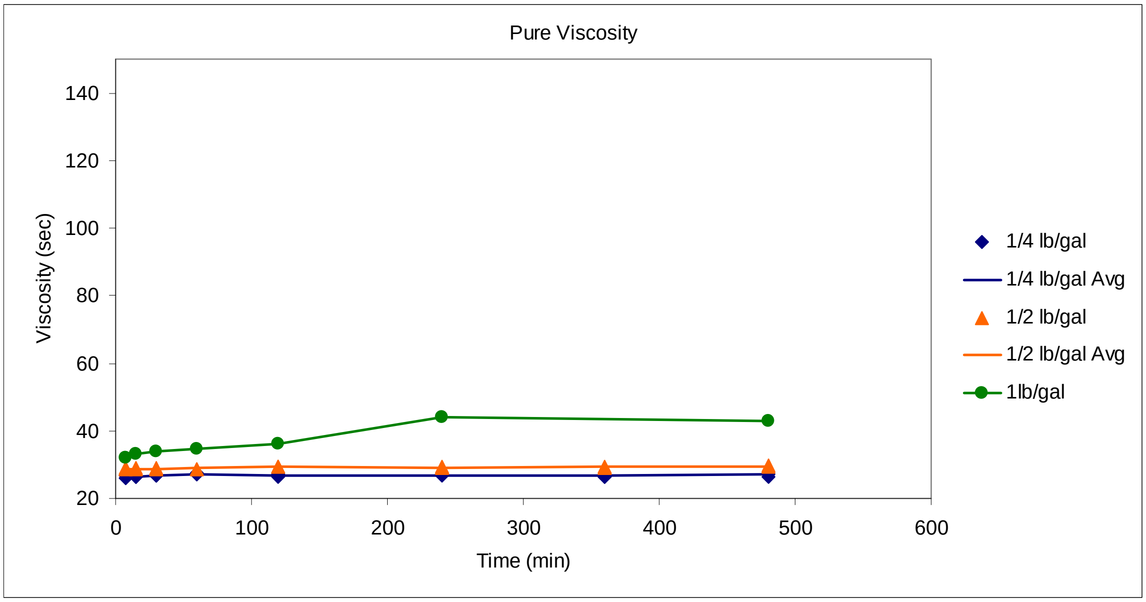


Figure 3.6. Viscosity versus time for Pure Gold.

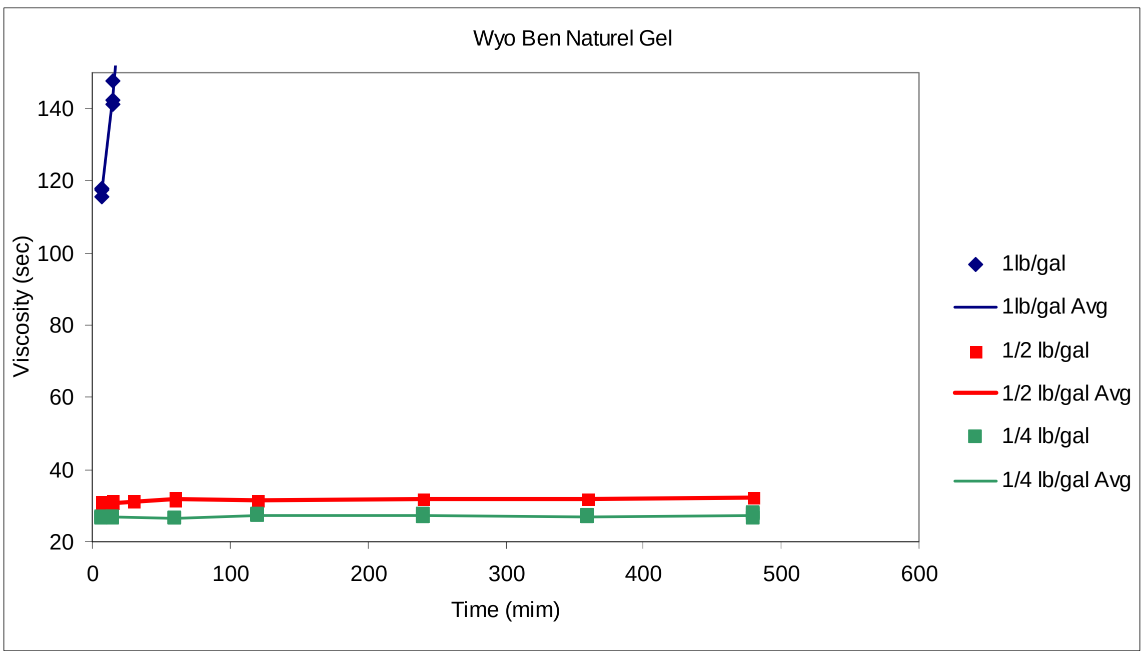


Figure 3.7. Viscosity versus time for Wyo Ben Natural.

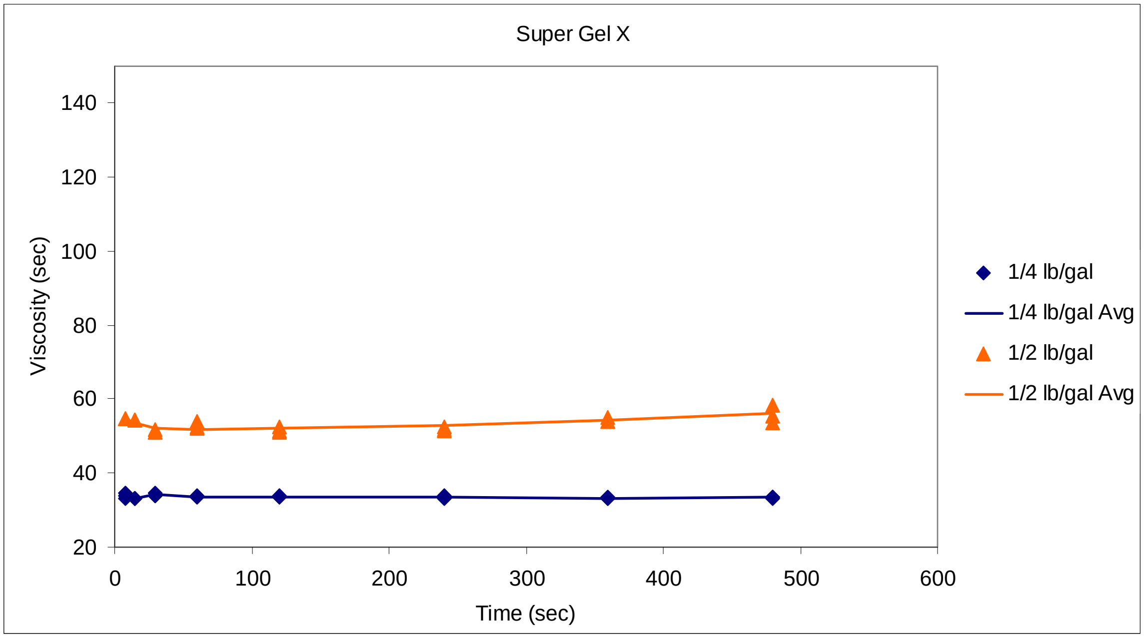


Figure 3.8. Viscosity versus time for Super Gel X.

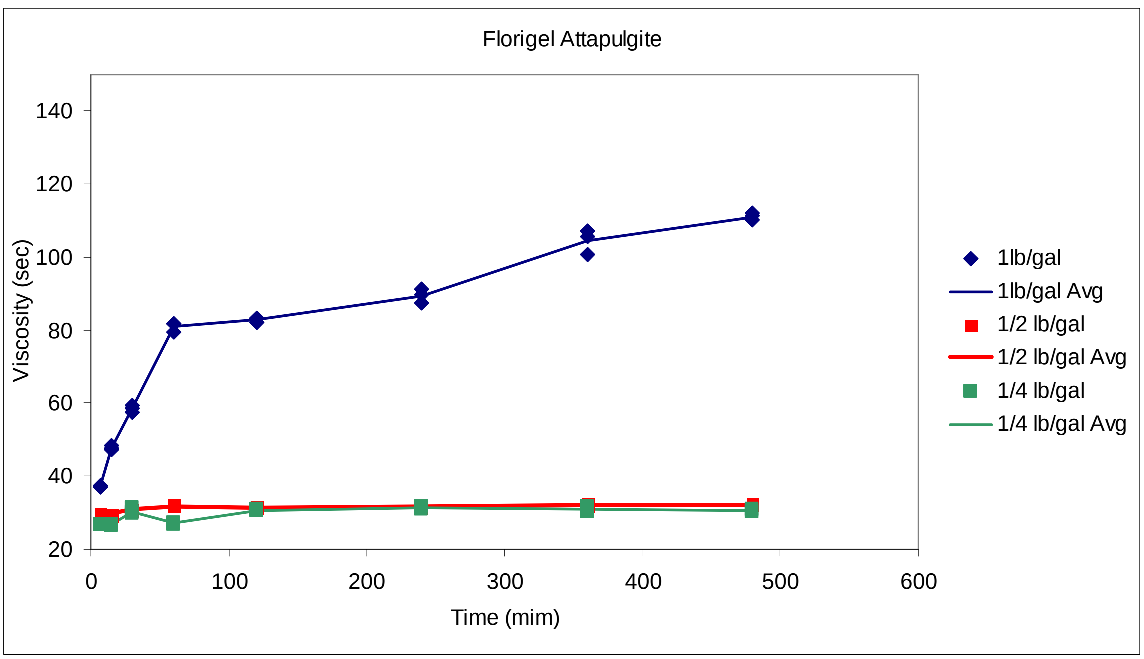
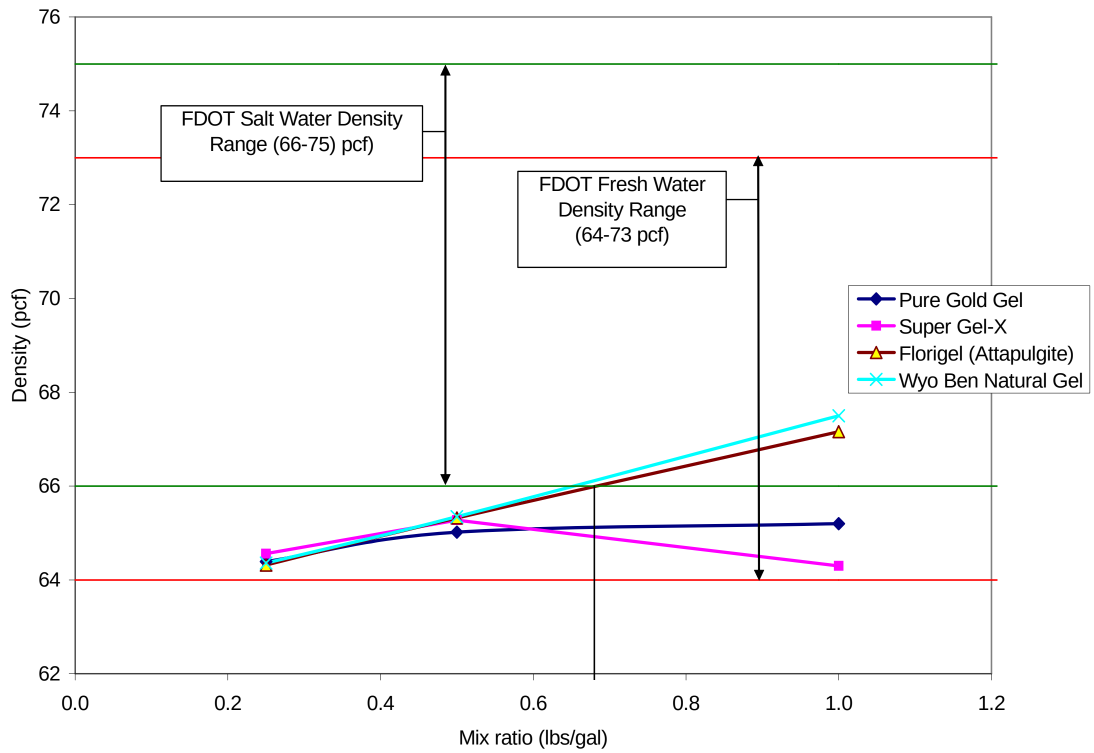


Figure 3.9. Viscosity versus time for Florigel Attapulgite.



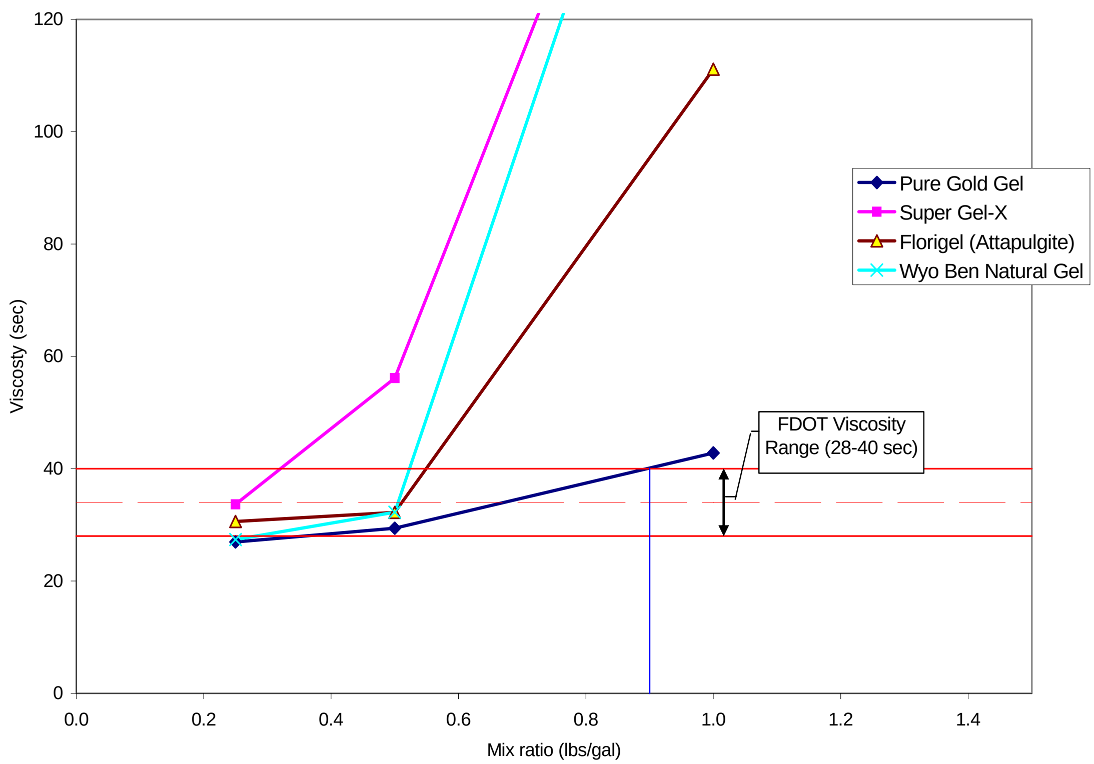


Figure 3.10. Density and viscosity as function of mix ratio for all products.

Table 3.1. Suggested mix ratios from both testing and manufacturer recommendations.

Product	Mix Ratio			Mixing Time (minutes)
	Viscosity	Density	Manufacturer	
	(lb/gal)	(lb/gal)	Suggested	
Pure Gold Gel	0.25 - 0.9	0.15 (min)	none	30
Wyo Ben Natural Gel	0.2 - 0.5	0.15 (min)	none	15
Super Gel X	0.15 - 0.3	0.15 - 1.0	0.17	7.5 - 10
Florigel (attapulgite)	0.25 - 0.55	0.65 (max)	none	7.5 - 10
Extra High Yield Gel			0.15 - 0.25	

3.2 Verification Testing

Further testing to corroborate and better define the slurry properties was also conducted. Wyo Ben Extra High Yield product was added to the test matrix for this series. Each mix started with 100 gallons of potable water with increasing mix ratios of 10%. The slurry was allowed to recirculation for 30 minutes at a pumping rate of 60 GPM. After 30 minutes of mixing, the slurry was tested for viscosity and density. Figures 3.11 - 3.15 show the results of the testing compared to the previous testing.

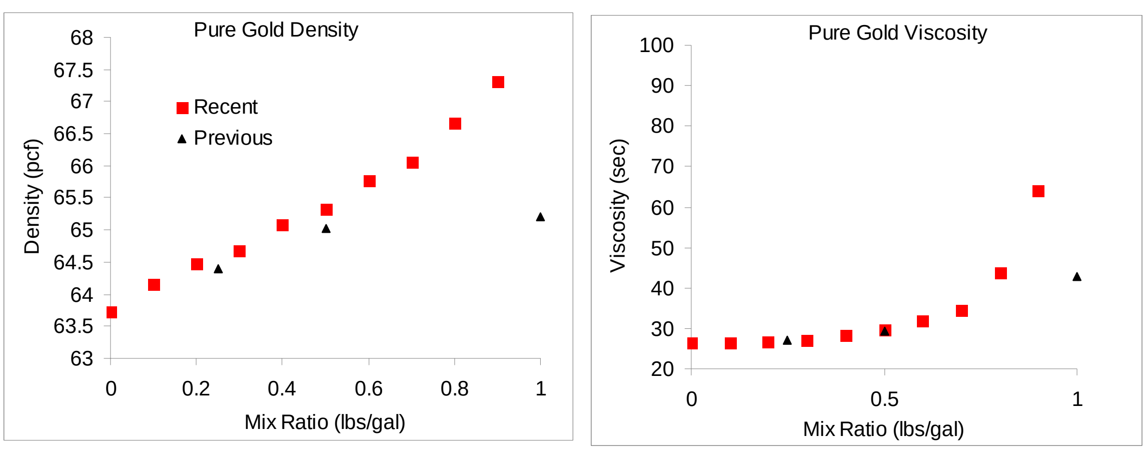


Figure 3.11. Pure Gold testing results.

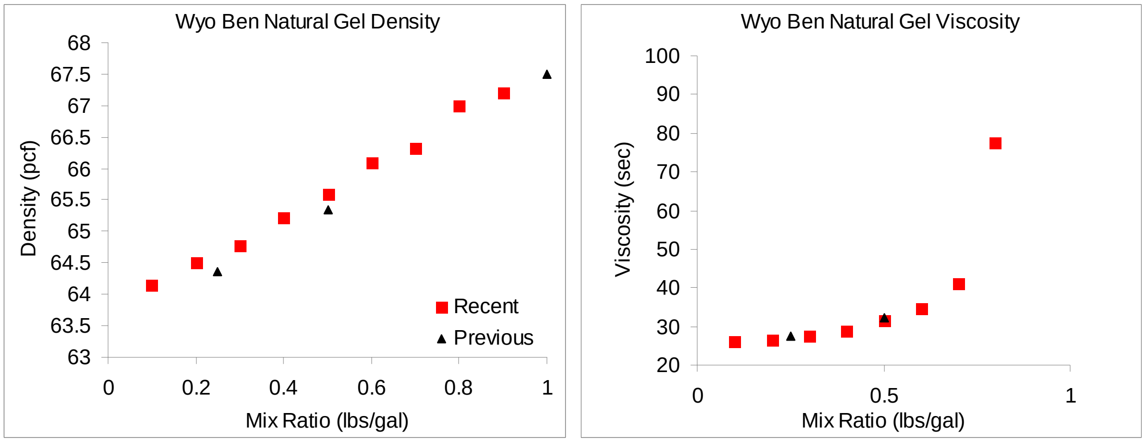


Figure 3.12. Wyo Ben Natural testing results.

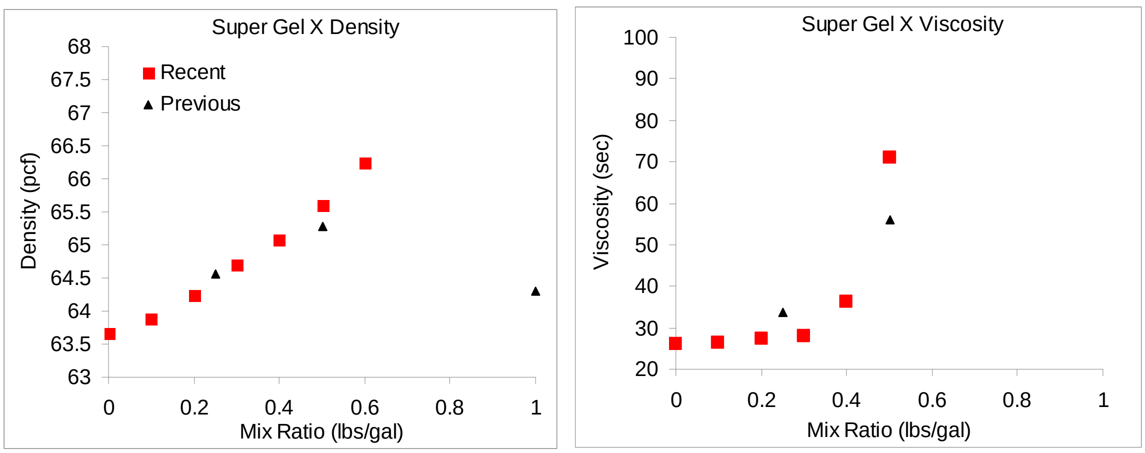


Figure 3.13. Super Gel X testing results.

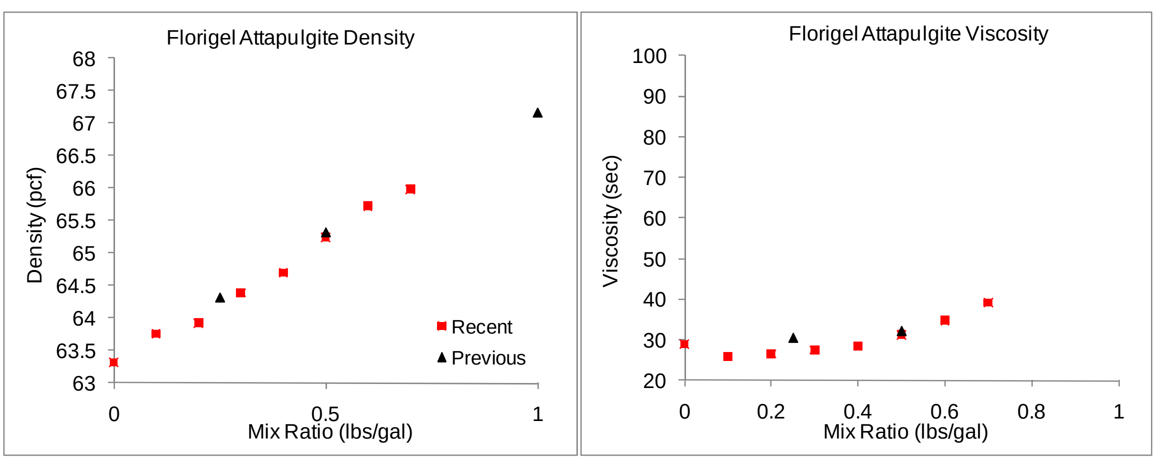


Figure 3.14. Florigel Attapulgite testing results.

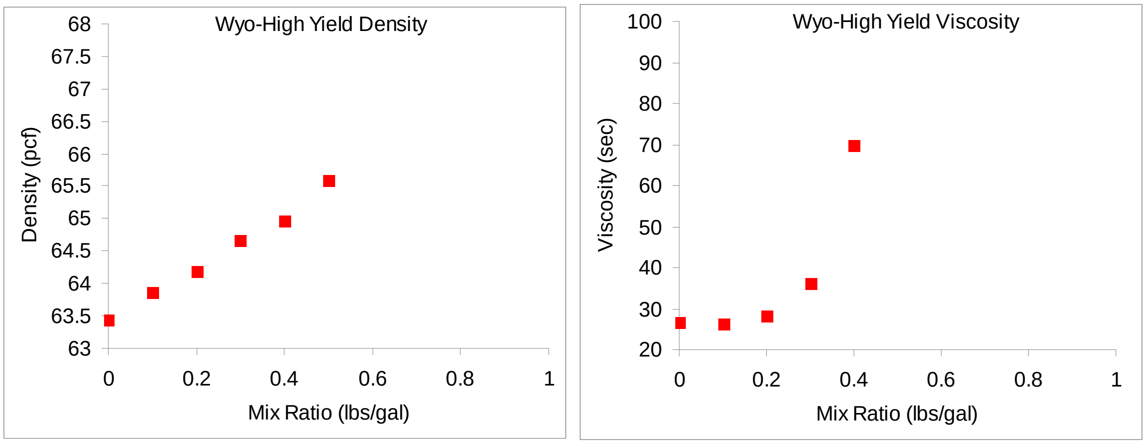


Figure 3.15. Wyo Ben High Yield testing results.

In an effort to automate slurry testing, the inflow pressure and flow rate were monitored via computerized data collection. Figures 3.16 - 3.20 show the pressure versus flow rate curve for each product tested at varying mix ratios. The flow rate measurements used an inline flow meter (paddle-wheel type) which does not compensate for varied fluid density or viscosity. As a result the reported flow rates are over-predicted with higher mix ratios.

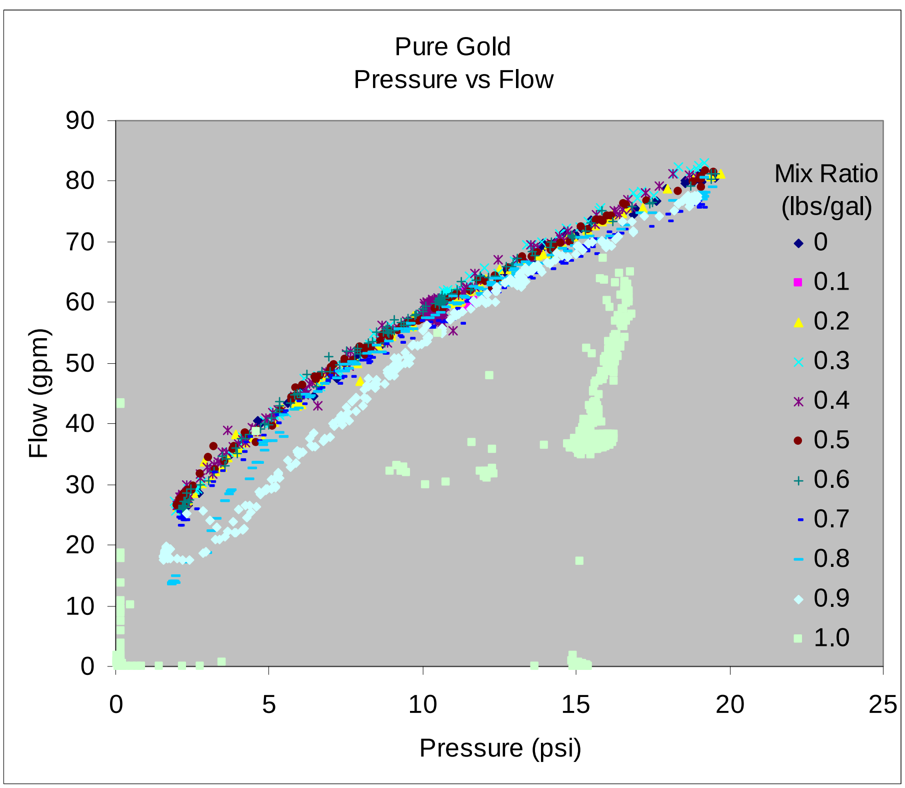


Figure 3.16. Pure Gold pressure versus flow testing results.

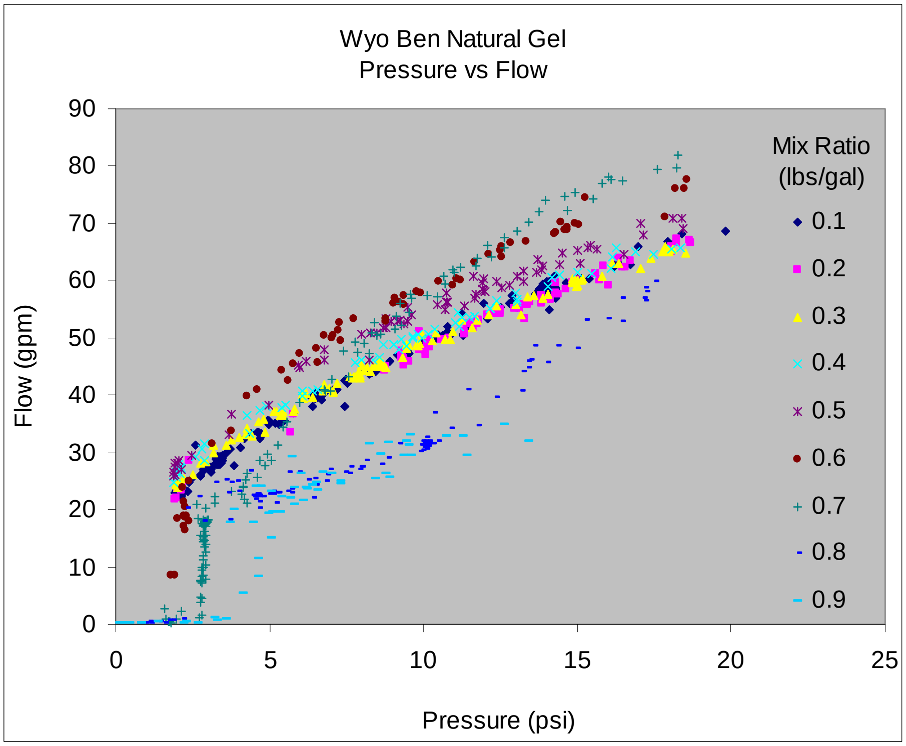


Figure 3.17. Wyo Ben Natural Gel pressure versus flow testing results.

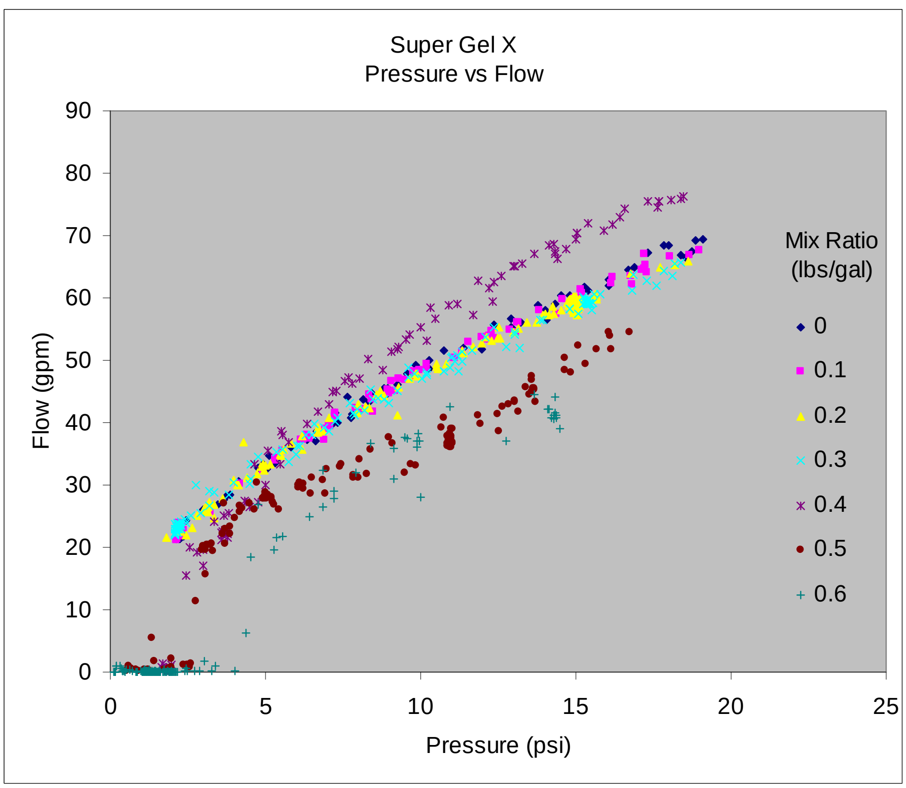


Figure 3.18. Super Gel X pressure versus flow testing results.

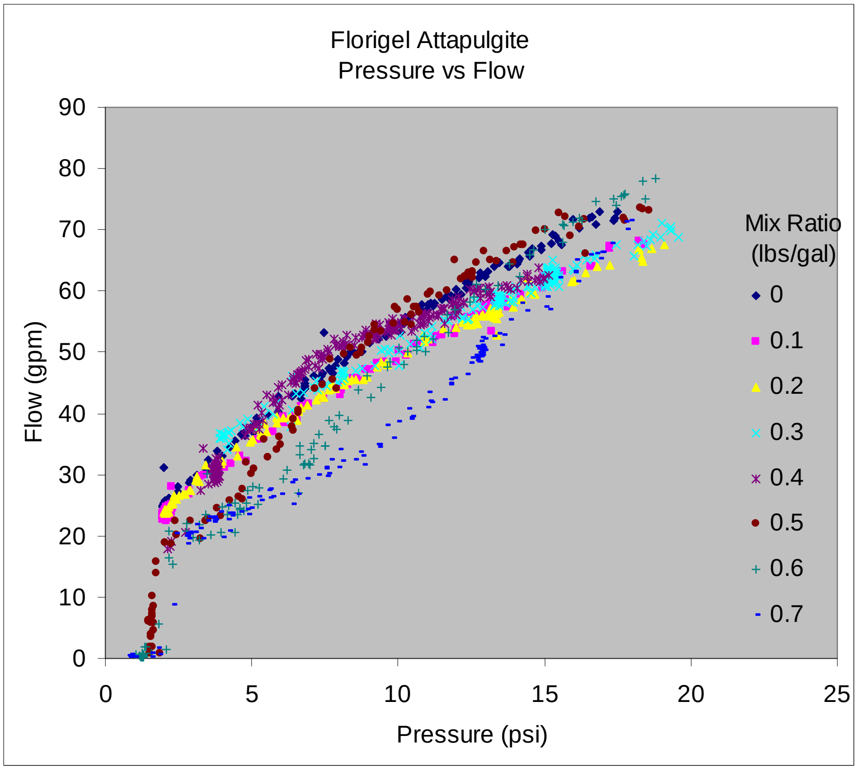


Figure 3.19. Florigel Attapulgite pressure versus flow testing results.

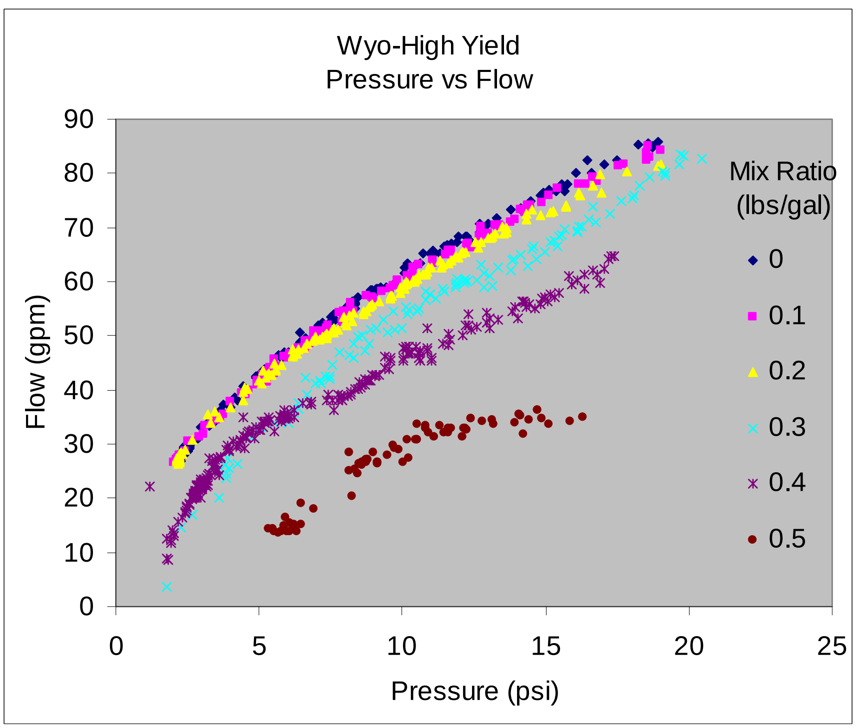


Figure 3.20. Wyo-High Yield pressure versus flow testing results.

3.3 Automatic Viscosity Measurements

Although not practical (at present) for field applications, equipment capable of making automated viscosity measurements are available, but quite expensive. These machines generally spin a shaft of known torsional characteristics in a fluid and record the drag in the form of torque and rotational velocity. One such device was trialed for this project which yielded limited success. The pitfall with this device was its sensitivity to vibration and wind. This is not unexpected given the minute amounts of torque required to discern a large range in viscosity. Figure 3.21 shows both the automated and manual measurements used for viscosity in this study.

Figure 3.21 Manual (left) and automatic (right) viscosity measurements used in the study.

3.4 Low Shear Slurry Mixing

The initial mineral slurry mixing was performed with a high shear centrifugal pump. A comparative study was also conducted to show the role of pump type (e.g. high shear versus low shear) on slurry mixing efficiency. The low shear system incorporated a 3 inch diaphragm pump with a maximum flow rate of 5100 GPH (Figure 3.22). The diaphragm pump was initially setup to flow through the venturi hopper (as used in previous tests) which required the feed line to be reduced from 3 inches to 2 inches.

Figure 3.23 shows the low shear mixing system initially setup. Internal to the venturi hopper is a further reduction to ¾ inch I.D to produce vacuum / venturi action. As diaphragm pumps are positive displacement, the resulting high line pressure resulted in an enormous diaphragm force. The pump was not designed for these pressure levels and would periodically stall during operation.

As a result of the pumps limitations, the venturi hopper was removed, as well as the 3 inch to 2 inch reduction. The system was then plumbed, as shown in Figure 3.24, to recirculate in a 130 gallon funnel-bottom tank. The dry slurry powder was introduced to the system by pouring the powder directly into the tank (Figure 3.25). The system was then allowed to recirculate for 30 minutes and viscosity and density measurements were taken from the time of initial powder introduction up to 8 hours afterwards. Figure 3.26 shows the comparison of the low shear mixing versus high shear mixing of Pure Gold mineral slurry. Table 3.2 shows the results after 30 minutes of mixing with a low shear and high shear pump.

Figure 3.22. Low shear 3 inch diaphragm pump.

Figure 3.23. Initial plumbing of diaphragm pump and venturi hopper.

Figure 3.24. Low shear mixing setup.

Figure 3.25. Introduction of Pure Gold.

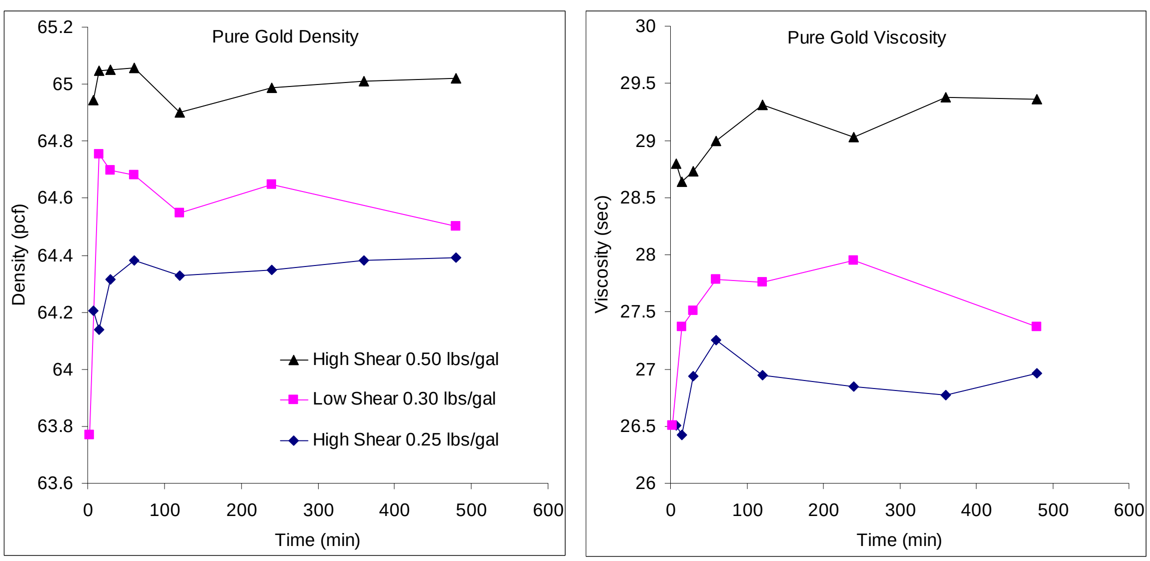


Figure 3.26. Comparative results from low shear and high shear mixing.

Table 3.2. Pure Gold Mixing Results

Pure Gold Test Results at 30 minutes			
	High Shear (0.25 lb/gal)	Low Shear (0.3 lb/gal)	High Shear (0. 5 lb/gal)
Viscosity (sec)	26.94	27.51	28.73
Density (pcf)	64.31	64.70	65.05

Results of these tests were somewhat unexpected whereby no apparent effect of pump type was observed. Rather, the low shear pump results fell in line with previous test results based on mix ratio alone (Figure 3.26 and Table 3.2). This was likely the result of alterations in the setup based on logistics. The flow rate and line forces from the surging diaphragm pump were so severe that the plastic tank and fittings used earlier with the steady-state centrifugal pumps were not robust enough. Consequently, the low shear pump was plumbed into the 130 gal steel tank (constructed for another application discussed later) capable of providing the necessary restraint. Figure 3.27 shows both mixing system tanks.

Simultaneous mixing and viscosity measurements were performed side-by-side to compare each system. During testing, the low shear system performed better than the high shear system (more rapid increase in viscosity). The mixing systems were operated for 2 hours then dismantled to determine the cause. Investigation of the two tanks showed that the flat-bottom tank (high shear system) would accumulate unmixed slurry at the bottom while the funnel-bottom tank (low shear system) reduced accumulation and forced the unmixed slurry to continue moving through the pump to be more completely mixed. Figure 3.28 shows the accumulation in both tanks. The funnel-bottom tank had less than 1 quart of unmixed slurry clumps while the flat-bottom tank had approximately 5 gallons of unmixed slurry. The net effect of this accumulation was reduced mix ratio.

To remove the effect of this variable (tank bottom design), the high shear system with venturi hopper powder introduction was setup and recirculated through the funnel-bottom tank (Figure 3.29). The results from all three tests are shown in Figure 3.30.

In summary, dry powder bentonite mixing occurs relatively quickly (less than one hour) despite the type of pump used when recirculated in sediment-reducing (funnel-bottom or similar effect) holding tanks regardless of the method of introducing the powder. In the cases demonstrated, both venturi hopper systems and bulk dump provided similar results if no accumulation was allowed to sit unrecirculated at the bottom of a holding tank. This is in keeping with field mixing approaches discussed in Chapter 2 whereby contractors have found ways of reducing sediment accumulation in their mixing tanks to increase slurry mixing efficiency. In this case, the design of the mixing tank bottom either promoted suspension or eliminated sediment accumulation.

Figure 3.27. Low shear tank system (left) and high shear tank system (right) setups.

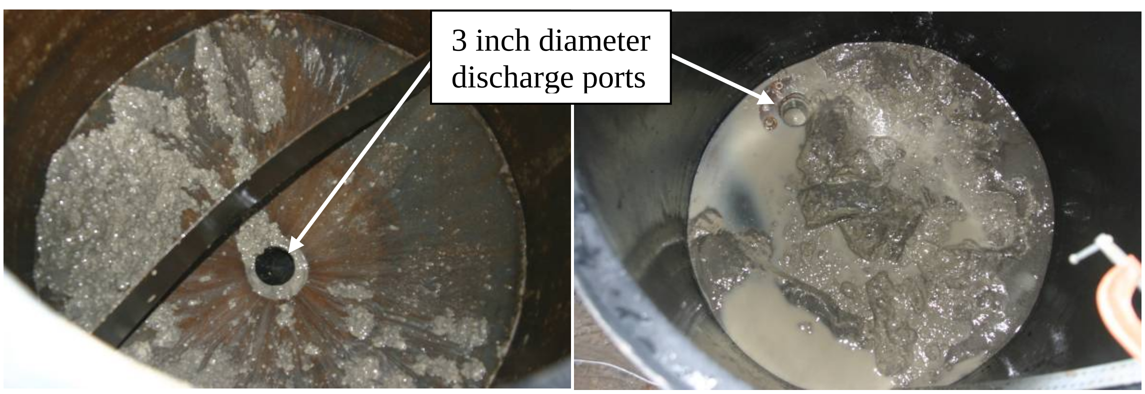


Figure 3.28. Unmixed slurry accumulation in conical-bottom tank (left) and flat-bottom tank (right); both tanks approximately 30 inches in diameter.

Figure 3.29. High shear pump with venturi hopper plumbed into funnel-bottom recirculating tank.

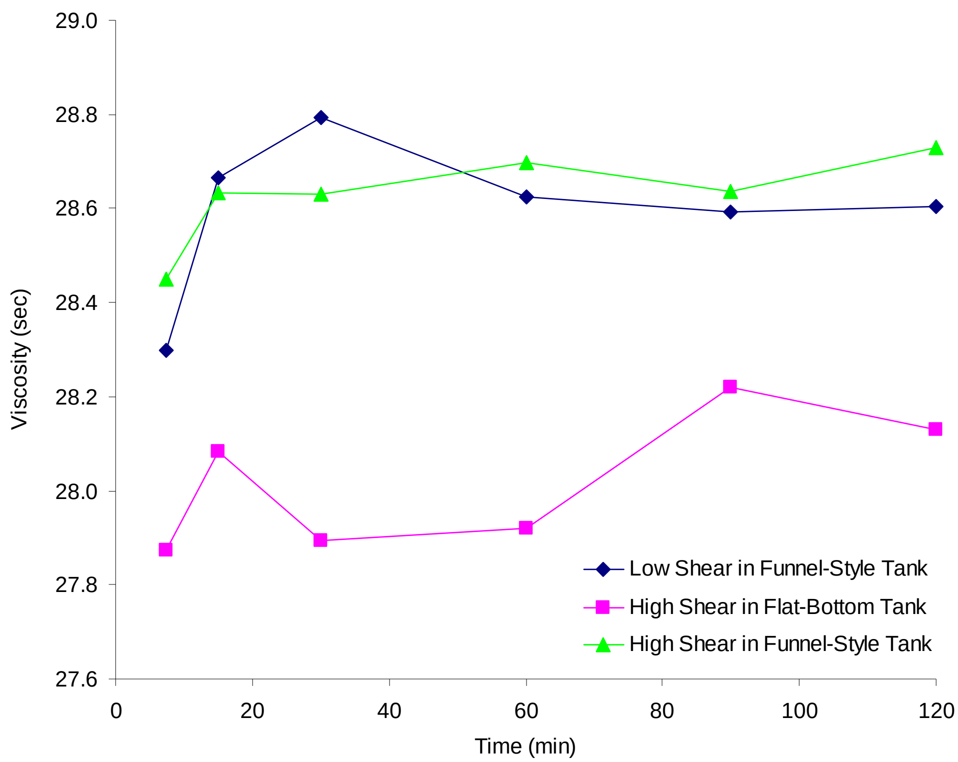


Figure 3.30. Viscosity results from different mixing systems.

To both increase the introduction rate of the mineral powder as well as eliminate hopper clogging/clumping, a new system was assembled using non-clog, Teflon-lined eductors, widely known as the "Hootonanny". These off-the-shelf units are inexpensive and can easily be adapted to different configurations based on supply line flow rates and pressures. This chapter provides an overview of the testing of these units and the development of a field-ready slurry mixing system.

4.1 Individual Eductor Testing

Individual eductors were tested as-received to determine their performance. The testing monitored the in-flow rate, pressure, and pick-up vacuum (Figure 4.1). Results of these tests are shown in Figures 4.2 and 4.3.

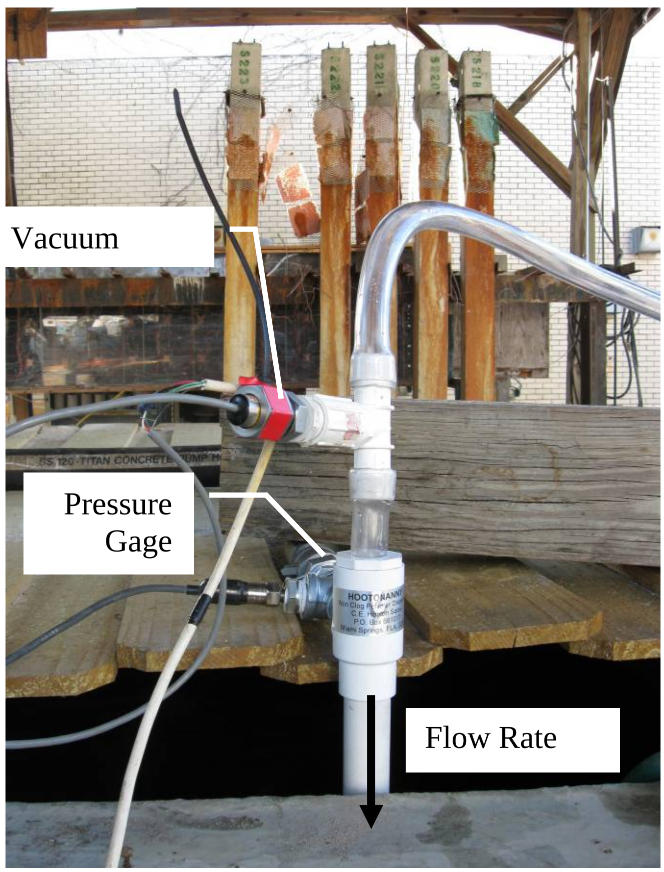


Figure 4.1. Inflow pressure and vacuum gages plumbed into eductor unit.

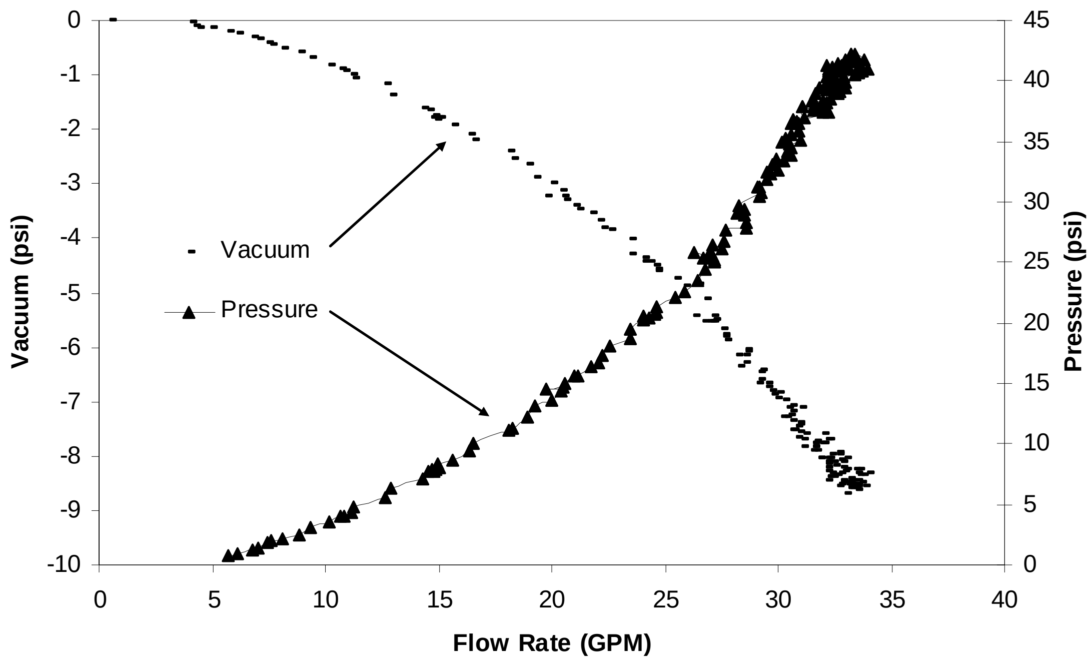


Figure 4.2. Eductor system performance per flow rate.

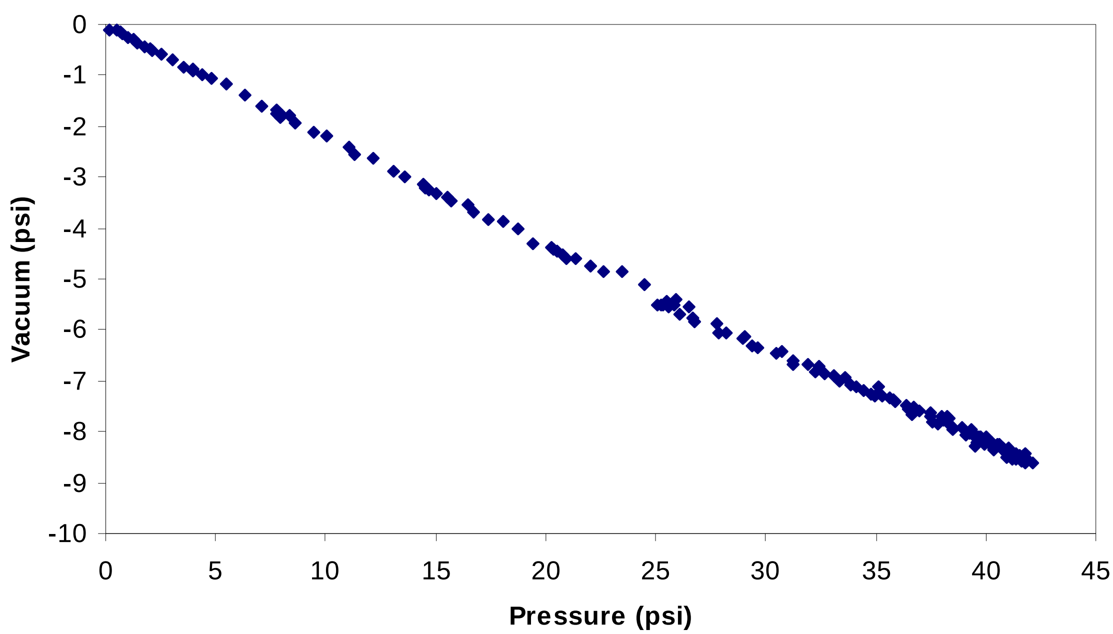


Figure 4.3. Eductor system vacuum versus inflow pressure.

Some suppliers of the eductors offer optional components (e.g. large capacity funnels/hoppers and mounting hardware) to be used in concert with the devices. To that end, preliminary screening for the applicability of these components was investigated. A flow table was used to evaluate the best method for powder introduction; vacuum pick-up or gravity / hopper fed. Pressure, vacuum, fluid flow rate, and mass flow rate were recorded to assess the performance. Mass flow rate was determined by monitoring the weight of powder extracted from a bin as a function of time. The results from the testing are shown in Table 4.1. The vacuum fed testing resulted in material pickup ranging from 0.19 to 0.32 lbs/gal. The vacuum fed testing was more subject to the user, although various vacuum hose tips used at the end of the pick-up hose also had a slight effect. The gravity fed system had material pickup rates varying from 0.29 to 2.19 lbs/gal and was dependant on the relative density of the powder in the hopper. At the loosest states of powder in the hopper, mass flow rates were highest. Interestingly, the powder in the hopper was sensitive to densification caused by vacuum compaction within the hopper. Attempts to use some form of shaker or sifting action led to increased densification and were abandoned. Figures 4.4 - 4.13 show the individual testing results.

Table 4.1. Flow Table Results for Powder Introduction

Pressure (psi)	Flow Rate (GPM)	Mix Ratio (lbs/gal)	Material	Test Type
25.25	21.08	0.43	Wyo-Ben	Gravity Fed – Loose
43.46	30.79	2.19	Wyo-Ben	Gravity Fed – Loose
44.74	29.70	0.32	Super Gel X	Vacuum – Wide Opening
46.14	29.13	0.79	Super Gel X	Gravity Fed – Loose
22.88	25.29	0.26	Super Gel X	Vacuum – Standard Opening
34.01	30.64	0.19	Super Gel X	Vacuum – Standard Opening
40.33	33.41	0.23	Super Gel X	Vacuum – Standard Opening
18.89	23.16	0.38	Super Gel X	Gravity Fed – Standard
30.92	29.83	0.29	Super Gel X	Gravity Fed – Standard
39.20	34.00	0.83	Super Gel X	Gravity Fed – Standard

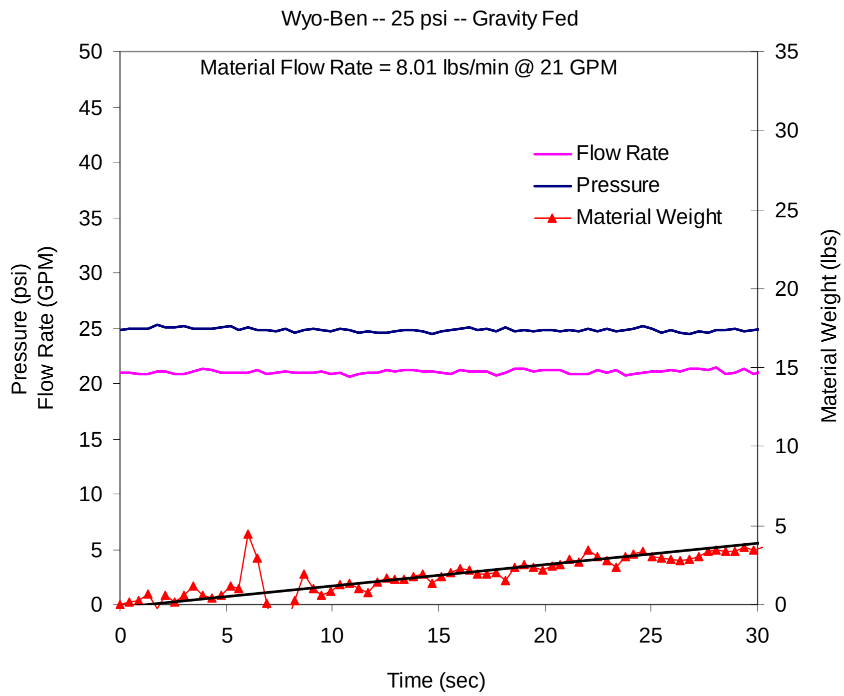


Figure 4.4. Gravity fed Wyo-Ben loose in the hopper at 21 GPM.

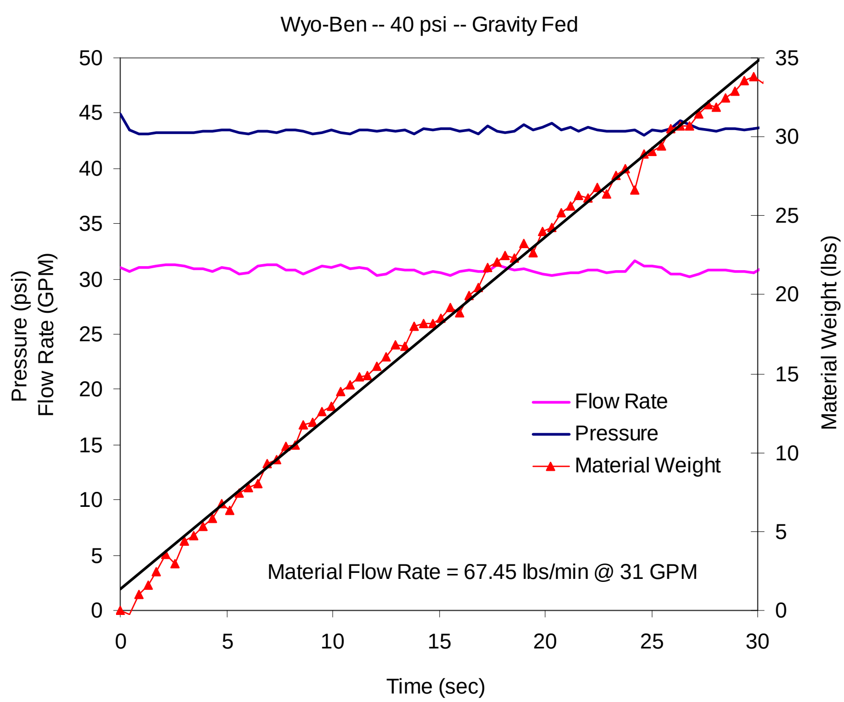


Figure 4.5. Gravity fed Wyo-Ben loose in the hopper at 31 GPM.

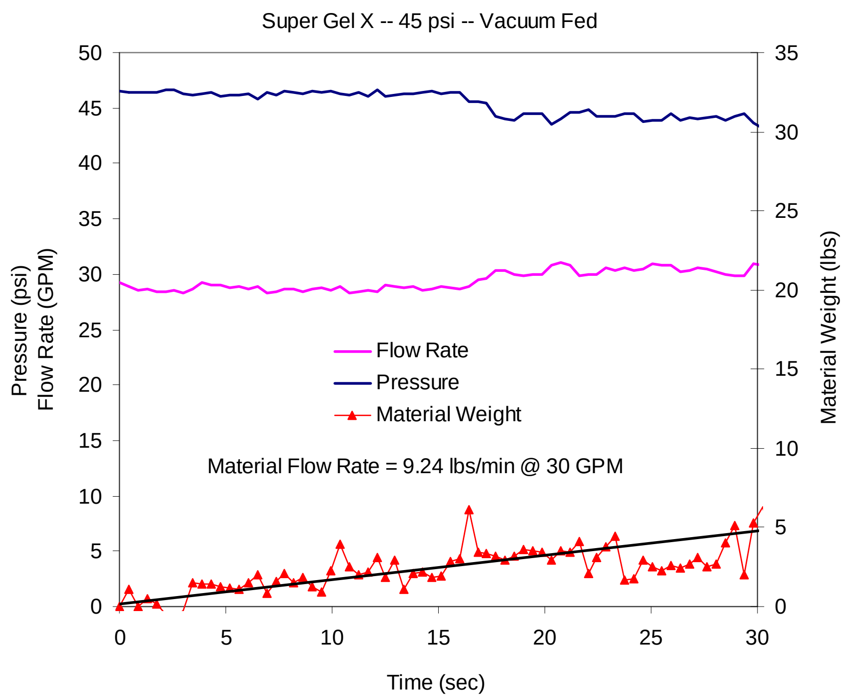


Figure 4.6. Vacuum fed Super Gel X with a wide opening at 30 GPM.

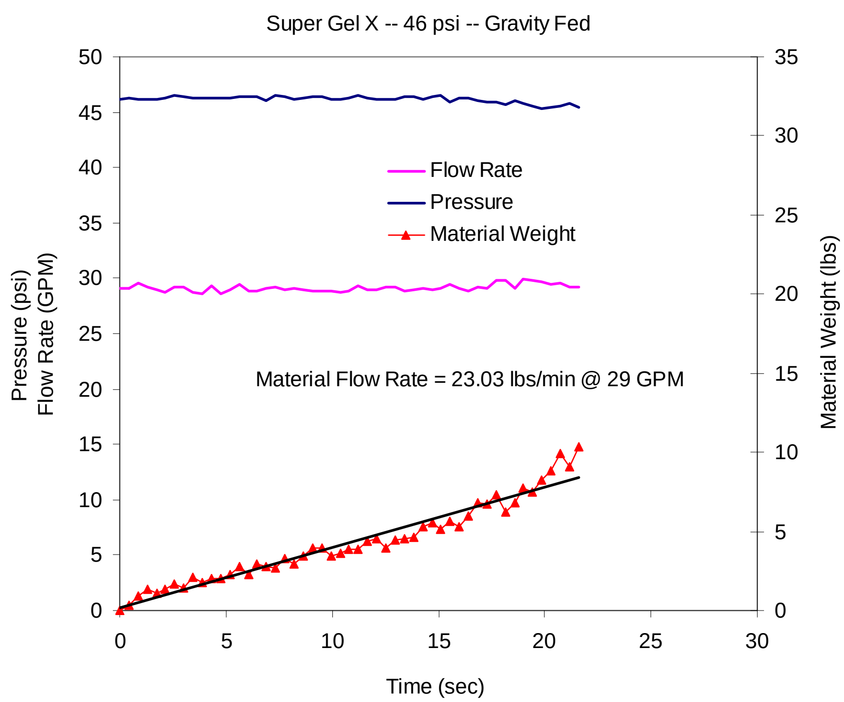


Figure 4.7. Gravity fed Super Gel X loose in the hopper at 29 GPM.

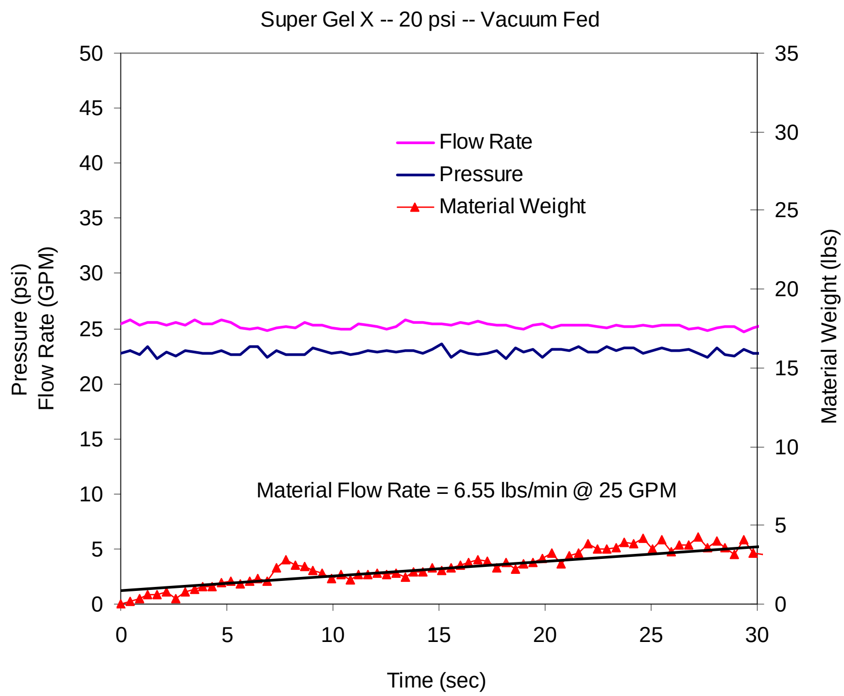


Figure 4.8. Vacuum fed Super Gel X with a standard opening at 25 GPM.

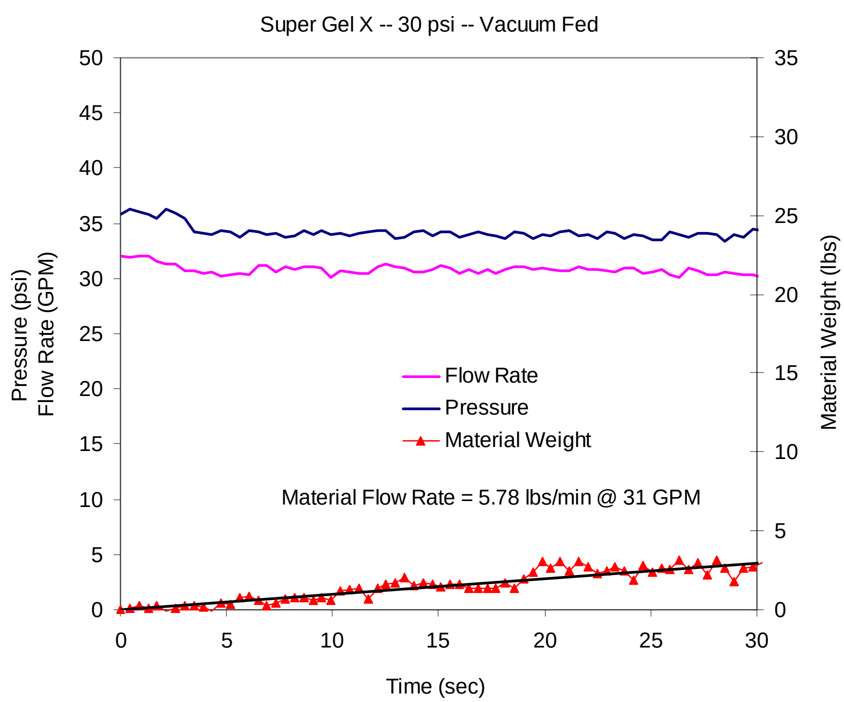


Figure 4.9. Vacuum fed Super Gel X with a standard opening at 31 GPM.

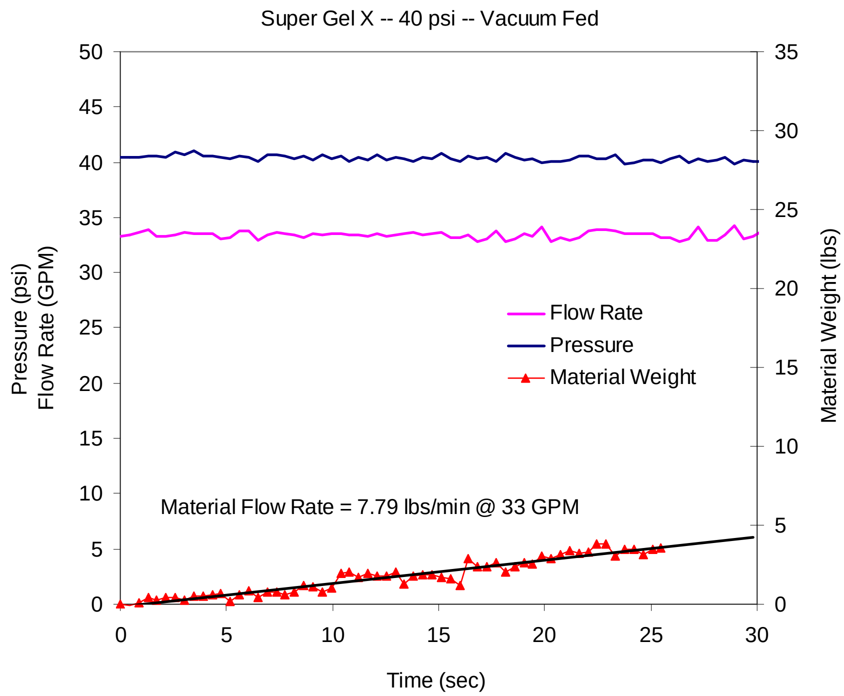


Figure 4.10. Vacuum fed Super Gel X with a standard opening at 33 GPM.

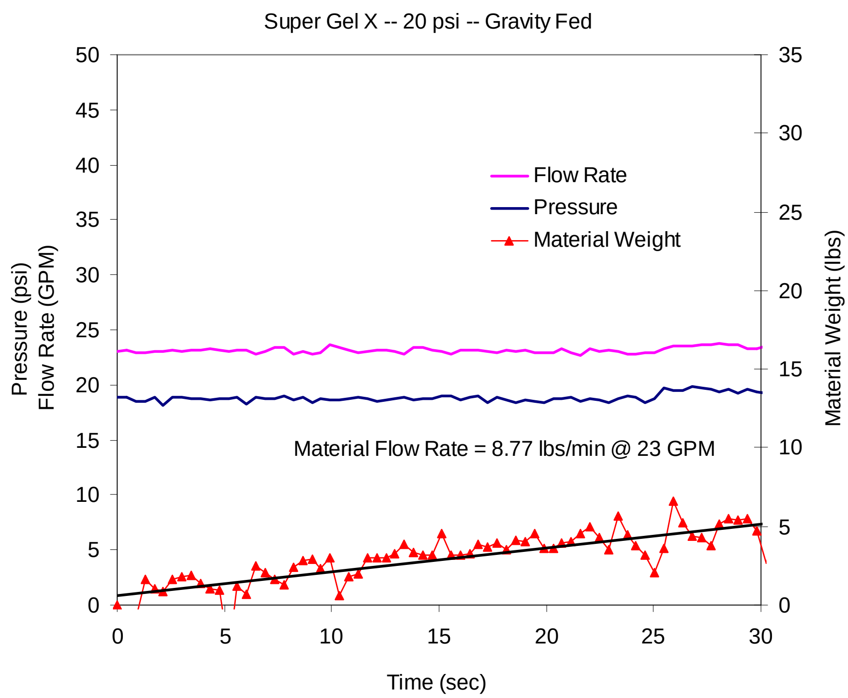


Figure 4.11. Gravity fed Super Gel X standard density in the hopper at 23 GPM.

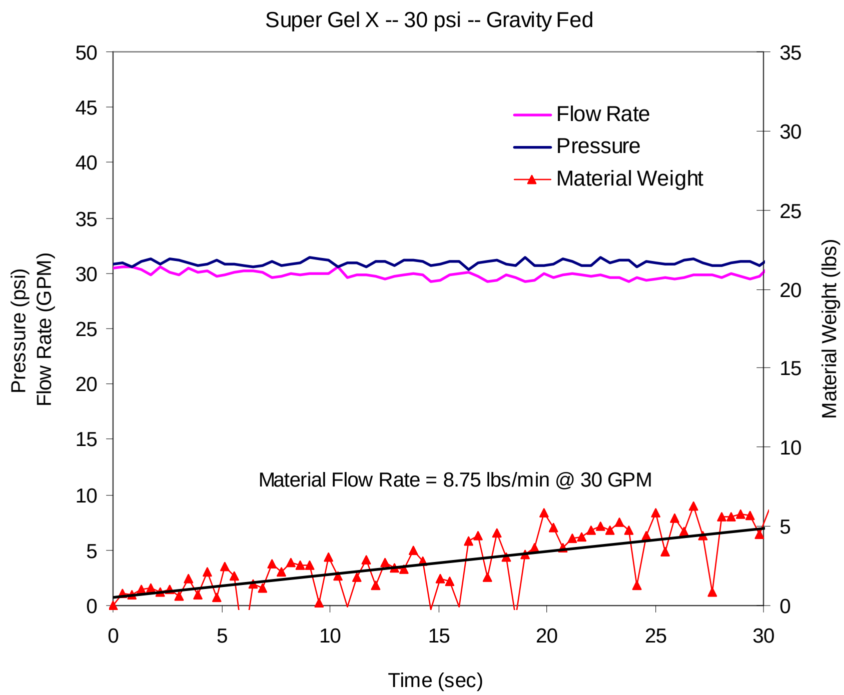


Figure 4.12. Gravity fed Super Gel X standard density in the hopper at 30 GPM.

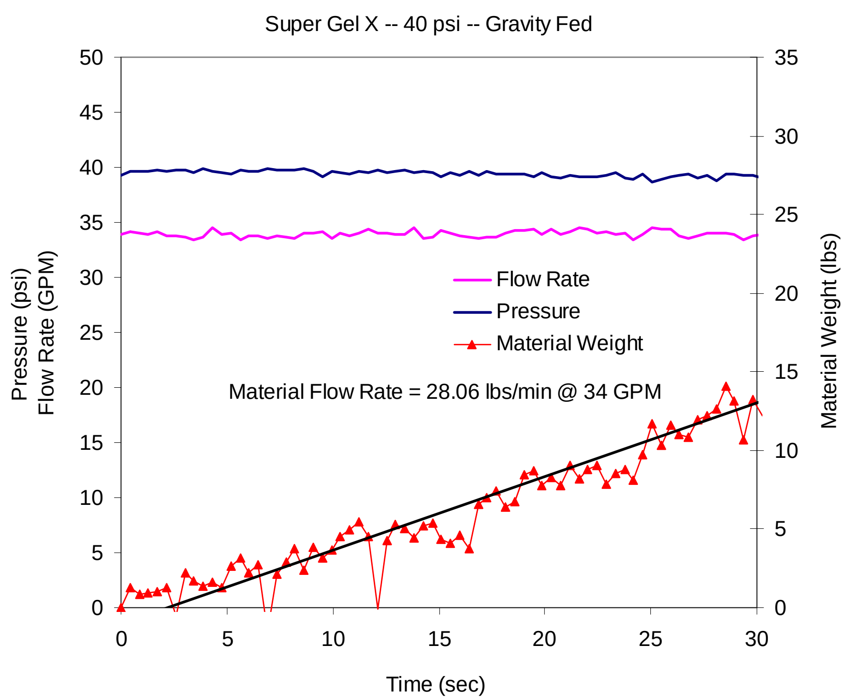


Figure 4.13. Gravity fed Super Gel X standard density in the hopper at 34 GPM.

4.2 Eductor System for Mineral Slurry Mixing

As received, the devices mix slurry perfectly - without the aid of high shear re-circulating pumps - but at a slow rate (5-8 lbs/min, vacuum fed with standard opening). If it is assumed that 2-2.5 lbs of powder per cubic feet of slurry are required, then a single unit would take up to 3 hours to process a target volume of 2000 gallons. As the time required to hydrate the slowest of the tested products (30 minutes) resulted from using the PureGold Gel, the new system testing used that material.

The required flow rate of the individual devices is 30 GPM at an operating pressure of 35 psi in order to develop 0.5 atm (15 in-Hg) of vacuum pickup. During the preliminary testing, mineral pickup rates ranged from 5 to 80 lbs per minute with the 30 GPM flow rate which resulted in mix ratios of 0.15 to 2.7 lbs/gal. The wide range of variation in the pickup rate resulted from whether the unit was gravity fed (highest) or vacuum fed (lowest). A target minimum mix ratio of 0.3 – 0.4 lbs/gal was adopted based on previous testing wherein the initial viscosity meets the low end of FDOT standards. By targeting the low end for the initial viscosity (and associated mix ratio), the ultimate viscosity after prolonged use and/or mixing results in a matured (fully hydrated) viscosity still within specifications.

Additional design considerations for the mixing system were to mix slurry as rapidly as possible using reasonably available equipment and mix a typical 2000 gallon batch of slurry in less than 15 minutes (half the longest hydration time requirement). With these parameters, a pump capable supplying 600 GPM (at zero pressure) was used which could develop 240 GPM while operating at 30 psi. This allowed 8 individual eductor units to be ganged in parallel with a combined pickup rate up to 200 lbs/min (vacuum fed). Figure 4.14 shows the concept drawings of multi-gang eductor units. At 240 GPM the system has more than enough flow rate to satisfy the 15 minute window.

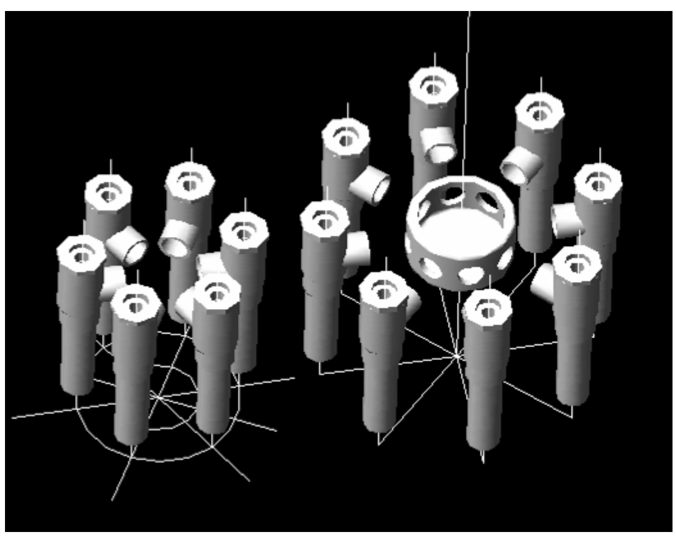


Figure 4.14. Concept drawings for multi-ganged eductor systems.

Along with the fabrication of the 8 gang eductor unit, a slurry mixing station was also built, as shown in Figure 4.15. The slurry mixing station consisted of a dry powder hopper for vacuum introduction, a 4 inch water main with the 8 eductor nozzles, a 130 gallon mixing tank, and a 3 inch pump to transfer the slurry from the mixing tank to a holding tank or directly to the excavation.

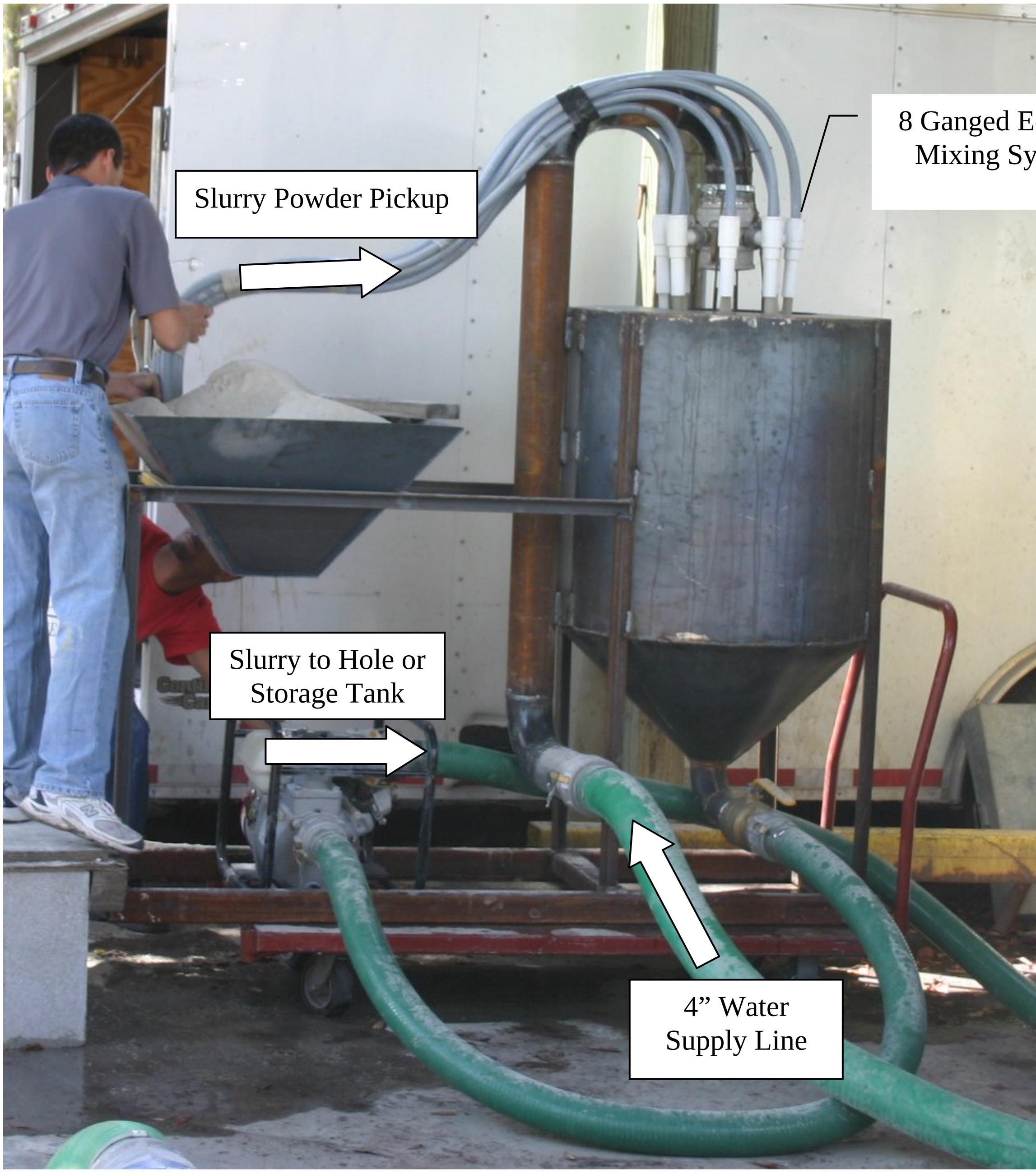


Figure 4.15. Multi-gang eductor system.

The 130 gallon mixing tank is not intended to be filled, but rather serves as a catch basin for slurry sediment that is not immediately suspended. At the mid-height within the mixing tank is an impact plate on which the eductors discharge tubes are directed. This causes additional turbulence that might be absorbed if permitted to spray directly into a slurry filled container. Figure 4.16 shows the turbulence caused by the eductor discharge on the impact plate while mixing slurry and running plain water. The conical base aids in directing sediment out the bottom of the tank into a 3 inch diameter line which then passed through an additional centrifugal pump and was sent to a holding tank (or excavation).

4.2.1 Multi-ganged Eductor System Results

The multi-ganged eductor system was used to mix target 1000 gallon slurry batches in the laboratory. The mixing used Pure Gold Natural Gel mineral product with a minimum target of 300 lbs of material per 1000 gallons of fluid. After each mix, viscosity and density was measured and recorded. Table 4.2 shows the results of both mixes.

Table 4.2. Multi-ganged eductor system mixing results.

Mixing Time (min)	Fluid Volume (gal)	Mix Ratio (lbs/gal)	Viscosity (sec)	Density (lbs/ft^3)	pH
2.72	593.73	0.51	30.0	65.49	8
3.05	673.2	0.45	29.8	65.47	N/A

The actual mix ratio was somewhat higher than targeted (0.45 – 0.51 lbs/gal rather than 0.3) which is dependent on the user. A more moderate vacuuming action produces 0.3 lbs/gal whereas the user for these tests was instructed to be more aggressive. In general, though, each eductor introduced 0.05 – 0.06 lbs per total gallon of system water (lbs/gal/eductor).

Although the immediate viscosity coming out of the eductor outflow is within specifications, additional recirculation, mixing, or tool agitation of the initially dispersed mineral powder is advantageous. As a result, the slurry produced by the multi-gang system meets drilling standards (at lower end of the state viscosity specification) immediately and continues to mature with time and usage. Results from Chapter 3 indicate that occurs between 20 to 30 minutes depending on the mineral powder product used.

These tests provide a usable range for the system as one or more of the eductor vacuum lines can be disconnected. The values shown in Table 4.2 represent an upper range (aggressive vacuuming) while a lower limit can be obtained at 0.3 lb/gal divided by eight when only one eductor is permitted to vacuum. This would correspond to 0.0375 lbs/gal at a system flow rate of 240 GPM. The lowest mix ratio observed that would be reasonable is 0.1 to 0.15 lbs/gal when using polymer fortified / high yield products. Therefore, by using only 3 or 4 of the eductors to provide vacuum (while all 8 eductors still provide water flow), a satisfactory high yield slurry product can be produced.

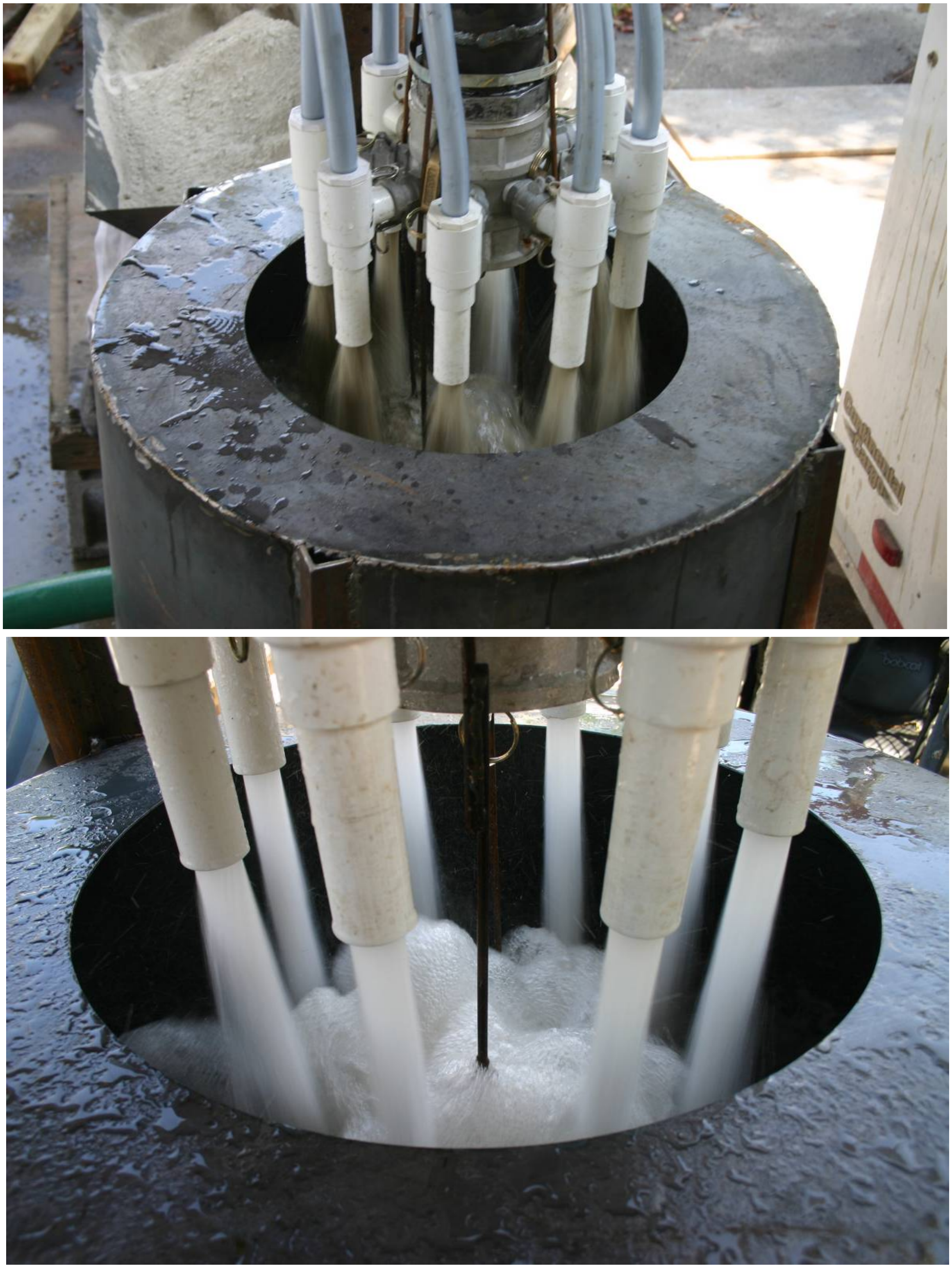


Figure 4.16. Turbulence inside mixing tank from eductor spraying on impact plate (slurry, top; plain water, bottom).

4.3 Field Implementation

Two forms of field implementation were undertaken: small scale slurry mixing for drill rigs used for soil borings and full scale use for drilled shaft construction.

4.3.1 Small Scale Slurry Mixing

The standard procedure for drill rigs performing exploratory borings begins with a drilling pan full of water on to which a thin layer of bentonite powder is sprinkled with the intent of minimizing large clumps of bentonite powder. A predetermined amount of powder is added which is usually between ½ and ¾ of a bag (25 – 37 lbs). The powder general "floats" on the water (due to surface tension) until the layer becomes heavy-enough, folds in on itself, and submerges. The driller then tracks down all of the slurry clumps with the intake hose to facilitate the slurry mixing process. After discussing the procedure commonly used by the FDOT District 1 drill crew, they agreed to try a single eductor unit equipped with a simple clamp mount for the side of the drilling pan. Figure 4.17 shows the clamping assembly as well as the unit in use.

The procedure used is similar to that proposed for the multi-gang system wherein the pan was filled through the eductor supply line while simultaneously introducing the bentonite powder. By the time the pan was filled, sufficient material had been drawn in by the vacuum line directly from the product bag.

Figure 4.17. Single eductor unit mounted to drill rig slurry pan.

4.3.2 Full Scale Slurry Mixing

The multi-gang eductor system was sent for field implementation at the time of this final report. However, only onsite field demonstration mixing and training of the system has been completed due to project delays. A discussion of the project, training, and how it was tailored for their use are discussed below.

The project selected for full scale verification was a Progress Energy project in Orange County, Florida named the "Boggy Marsh/Four Corners-Gifford 69/115kV Line." The project consisted of 44 single shaft foundations ranging from 26 to 51 ft deep. Of the 44 shafts, seven were 60 inch diameter, thirty were 72 inch diameter, and seven were 84 inch diameter. The drilled shaft contractor R.W. Harris, Inc. of Clearwater, Florida was interested in expediting slurry production because small slurry tanks are more practical for wide spread sites to minimize equipment movement. Figure 4.18 shows the multi-gang slurry mixing system prior to shipping out.

Figure 4.18. Multi-gang eductor mixing system sent for field implementation.

The multi-ganged eductor system was setup in Clearwater, FL at the R.W. Harris yard for training purposes. The contractor provided a water truck, 1600 gallon slurry holding tank (shown in Figure 2.10), and a drill rig with a 72 inch diameter auger. Figures 4.19 – 4.28 show the setup and training of R.W. Harris personnel with the eductor system.

Problems were encountered during the training period with the quality of the supply water. The eductor system requires the supply water to be free from debris. Debris larger than 0.1 inches will clog the eductors and hinder their performance. In this case, the water truck was full of 3/8 to 1/2 inch gravel that periodically became dislodged from the truck tank and deposited in the eductor bodies. Figure 4.22 shows the cleaning process for a single eductor. Water quality was similarly a problem during laboratory testing. As a result, the laboratory "clean" water holding tank was equipped with a screened filter box that removed incidental leaves and debris that would clog the eductors. This filter box was also brought to the field training session for such a scenario. The water truck source was abandoned for the remainder of the demonstration / training and a nearby pond was used in conjunction with the screened filter box (Figure 4.23). Slurry preparation continued using the new clean water source.

Figure 4.19. Overview of setup at R.W. Harris yard with water truck, 1600 gallon holding tank, and multi-gang eductor system.

Figure 4.20. R.W. Harris personnel mixing drilling slurry with the multi-gang eductor system.


Figure 4.21. Slurry moved to 1600 gallon recirculating tank.

(a) (b)

(c)

Figure 4.22. Training on how to clean a clogged educator; (a) remove set screw, (b) remove Teflon nozzle, and (c) clean Teflon body.


Figure 4.23. Water supply pump drawing from pond with filter box.

The mineral slurry product selected for the project was a high yield / polymer fortified bentonite (Figure 4.24) that required less powder per gallon (0.1 – 0.15 lb/gal) than pure bentonite (0.3 lb/gal) as demonstrated in Chapter 3. Figure 4.25 shows the slurry produced using all eight eductors. By inspection, the slurry was too viscous and was not tested for properties. As a result, the crew was instructed to disconnect the intake feed of half the eductors during slurry preparation, thus cutting the mix ratio in half. This allowed the water inflow rate to remain the same (240 GPM) while the powder introduction rate is reduced. Further, the field superintendent recognized the ease at which he could adjust slurry properties after an initial slurry batch had been prepared.

Upon correcting the mix ratio for the high yield mineral slurry, a more appropriate slurry was prepared and tested (Figures 4.26 – 4.27). Some recirculation was provided by the holding tank although minimal in comparison to the cross sectional area of the tank. In such cases, the flow rate and in tank velocity is too low to re-suspend unmixed particles/sediment. However, the slurry properties provided at the onset were sufficient (29 sec/qt Marsh Funnel) to be used directly. This slurry was then redirected to the excavation where a 72 inch diameter excavation was commencing (Figure 4.28).

Figure 4.24. Halliburton Quick-Gel product used by R.W. Harris.

Figure 4.25. Initial slurry mixture with 8 eductors.

Figure 4.26. Viscosity testing directly after mixing with mulit-gang educator system.

Figure 4.27. Viscosity testing at excavation.

Figure 4.28. Mixed slurry in excavation.

Although drilling and slurry production were interrupted periodically for training and strategic discussions, the observed slurry production rate was considered suitable to accommodate the normal, uninterrupted excavation rate.

Recommendations for field use at the upcoming project were discussed amongst the crew and USF researchers. From these discussions the following conclusions were drawn:

- Water source cannot be trusted to be clean unless sourced from a hydrant directly. Even then, a large surface area inline filter screen system should` be incorporated.

- When using a reduced number of eductors, the “off-line” eductors serve as back-ups that can be reintroduced without stopping the process should one or more of the eductors become clogged with water source debris. This is evident through the clear vacuum tubing and the presence or lack of moving slurry powder.

- Slurry quality can be tailored to meet desired viscosity with an initial pilot volume from which the correct number of eductors can be put on-line (vacuum lines connected).

- Present system uses a 4 inch pump that provides clean water which is periodically started and stopped as needed. This could be provided by intermittent operation of the water truck onboard pump or by continuously running and recirculating back to source via valves to eliminate start/stop of the pump motor. The 3 inch pump used to transport slurry from the system tank to the excavation would still require periodic start/stops as it runs only when slurry is being produced.

- Holding tank may not be required especially when sufficient surface casing volume is provided to store additional slurry over and above that required to maintain sufficient head differential with the existing water table.

Chapter Five: Conclusions and Recommendations.

Given the relatively high water table in most regions of the state of Florida, most drilled shaft excavations use a slurry stabilized approach. This is particularly true for smaller projects that can not justify the expense of large equipment capable of setting full-length temporary casing (i.e. shafts for miscellaneous structures, etc). The most widely accepted and perhaps the most effective slurry type is bentonite mineral slurry formed by mixing dry bentonite powder with water. Attapulgite powder is used in place of bentonite when saline conditions are present. Regardless of mineral type, slurries require adequate mixing to ensure the desired fluid properties that result from the fully hydrated minerals. Whereas some states specify a minimum hydration time without regard to the mineral or equipment employed, the state of Florida has performance-driven specifications for drilled shaft slurry. Therein, any means of producing mineral slurry capable of meeting these specifications (Table 2.1) is acceptable.

Five slurry products were tested in this study: two were pure bentonite powders that fall within the state description for an acceptable drilled shaft slurry material, one a high yield attapulgite, and the remaining two were polymer-modified bentonite products. These polymer-modified products, called High Yield Bentonite, are often used in present practice but are not technically in keeping with the state specification of pure bentonite. When preparing pure bentonite slurries, no manufacturer information is provided on the packaging; testing (Chapter 3) showed that the minimum viscosity and density could be met using a mix ratio of 0.2 to 0.25 lbs dry powder per gallon of water (Table 5.1). In cases of high yield (polymer fortified) products, suggested values of mix ratio and pH are clearly provided by the manufacturer. When powder was introduced in a controlled fashion (with no excessive clumping) viable slurry could be achieved using conventional centrifugal pumps in 15 to 30 minutes. Extended testing of these slurry mixes up to eight hours afterward showed little to no change in slurry properties.

Table 5.1 Minimum mix ratio and mixing time for pure bentonite or attapulgite.

Product	**Mix Ratio**			**Minimum Mixing Time (minutes)**
	Viscosity	**Density**	**Manufacturer**	
	(lb/gal)	**(lb/gal)**	**Suggested**	
Pure Gold Gel	**0.25 - 0.9**	**0.15 (min)**	**none**	**30**
Wyo Ben Natural Gel	**0.2 - 0.5**	**0.15 (min)**	**none**	**15**
Florigel (attapulgite)	**0.25 - 0.55**	**0.65 (min)**	**none**	**7.5 - 10**

In practice, the controlled inflow of bentonite into a venturi hopper as performed by this study (Figure 5.1) is not realistic. Rather, these values represent best case scenarios; the hopper is generally filled to the top most of the time agitated as necessary to facilitate the powder introduction. Furthermore, the required amount of mineral could not be introduced while initially filling in most cases. As a result, the target volume of slurry was reached and then re-circulated through the venturi hopper until the desired weight of powder could be introduced.

Figure 5.1 Efficient / controlled mixing impractical for field application.

One solution that is both cost effective and feasible is the use of non-clog, Teflon-lined eductors capable of drawing in 0.2 – 0.5 lbs of dry mineral per gallon of incoming water. Based on the findings in Table 5.1, the required 0.2 to 0.25 lbs/gal was quite reasonable to achieve as the water was filling a mixing tank (without recirculation to introduce more powder).

Two trial batches targeting 300 lbs in 1000 gallon were prepared using the new slurry mixing system. These resulted in mix ratios of 0.45 to 0.51 lbs/gal corresponding to viscosities of 29.8 and 30 seconds and densities of 65.47 and 65.49 pcf, respectively. Recall FDOT specifications are 28 – 40 seconds and 64 – 73 pcf, again respectively, putting the trial 1000 gallon batches comfortably above the minimum required immediately after mixing. The time required to prepare these slurry batches correspond to mixing rates of 220 gallons of slurry per minute.

The initial contact between the water and dry powder while using these eductors produces very little sediment and no clumping. The overall system developed by the study further processes residual sediment that remains by first impacting against a steel plate and then by circulating it through a discharge pump as it is piped to either the excavation or a holding tank.

For convenience, Table 5.2 shows recommended configurations for various sizes of supply lines and flow rates. In general, each unit optimally performs at flow rates between 20 and 35 GPM which roughly corresponds to inlet pressures of 15 to 40 psi. The maximum rated pressure for SCH 40 PVC bodies is much higher, but the units should not be run in excess of 45 psi given that not all the components are glued as is customary for conventional PVC fittings. The configuration shown in Figure 5.2 has eight eductors run in parallel supplied by a 4 inch diameter supply line and a flow rate of 220 GPM.

Figure 5.2. Eductors equipped with quick-connect fittings for easy reconfiguration (shown 220 GPM total ; 27.5 GPM per eductor).

Although the assembly shown is outfitted with a 4 inch diameter supply manifold and eight eductor ports, each port is equipped with quick-connecting cam lock fittings which enable one or more of the ports to be capped as need to adapt to various supply line flow rates / sizes (Table 5.2).

Table 5.2. Recommended eductor configurations for various supply lines.

Nominal Supply Line Diameter (in)	Flow Rate (GPM)*	Number of Eductors
1	20 - 40	1
2	40 - 80	1 - 2
3	70 - 230	3 - 6
4	220 - 400	6 - 8

*Assumes relatively short supply lines (less than 30ft); extended lengths will reduce flow rate.

A secondary configuration option (in lieu of capping of ports based on pump capacity) is to simply disconnect the vacuum feed lines to one or more of the eductors while allowing all eductors to continue flowing water. As a result, the powder introduction rate can be tailored to meet a target mix ratio less than the fully functioning / optimal eductor pickup rate. Table 5.3 provides various eductor usage configurations based on provided flow rate (number of active ports) and the number of vacuum lines in use.

Table 5.3 Eductor / vacuum tube configurations for the multi-gang system.

Mix Ratio (lbs/gal)									
No. Active Ports	Flow Rate (GPM)	Number of Vacuum Lines Used							
		1	2	3	4	5	6	7	8
1	30	0.50	NA	NA	NA	NA	NA	NA	NA
2	60	0.25	0.50	NA	NA	NA	NA	NA	NA
3	90	0.17	0.33	0.50	NA	NA	NA	NA	NA
4	120	0.13	0.25	0.38	0.50	NA	NA	NA	NA
5	150	0.10	0.20	0.30	0.40	0.50	NA	NA	NA
6	180	0.08	0.17	0.25	0.33	0.42	0.50	NA	NA
7	210	0.07	0.14	0.21	0.29	0.36	0.43	0.50	NA
8	240	0.06	0.13	0.19	0.25	0.31	0.38	0.44	0.50

Conclusions

The present state specifications provide leeway for contractors to mix slurry in any means that satisfactorily produces the required slurry viscosity and density. The viscosity range is pertinent with regards to slurry preparation and first introduction into an excavation while the density criterion is intended to assure adequate displacement potential during concreting. Many contractors have developed innovative methods and mechanisms to mix slurry, but a key component to these systems is sediment recirculation. The study showed that regardless of pump type, mixing tanks that provide effective recirculation of un-hydrated mineral sediment (funnel-bottom) performed more efficiently than those that did not. Typical field practice is to fill a slurry holding tank through some sort of venturi hopper (often built in-house) until the tank is full and then to continue recirculating the tank contents until enough mineral powder is introduced and the slurry has mixed sufficiently to meet the target viscosity. The time of recirculation varies dependant on the efficiency of the sediment suspension method.

Commercially available, Teflon-lined eductors were shown to be effective at mixing slurry at rates commensurate with the slurry introduction rate of standard drilled shaft excavations (in this case 240 GPM). Furthermore, the system assembled for this project mixed mineral slurry (using pure bentonite) that immediately met state mineral slurry specifications without the need for holding tanks or additional recirculation. In practice, however, an intermediate tank (or oversized surface casing) may be more reasonable to reduce the number of start/stop cycles of the slurry mixing system. High yield or polymer fortified bentonite slurries were easier to prepare as the target mix ratio tended to be lower.

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Appendix A: State Specifications

Table A.1. Alabama Slurry Specifications (ALDOT, 2002).

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 % by Volume	N/A	N/A	N/A

Table A.2. Alaska Slurry Specifications (AlaskaDOT, 2009)

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 % by Volume			

Table A.3. Arizona Slurry Specifications (AZDOT, 2008).

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 % 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.

Table A.4. Arkansas Slurry Specifications (Ellis 2010).

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 % by Volume	N/A	N/A	N/A

a. Range of results at 60°F (20°C).

Table A.5. California Slurry Specifications (Caltrans, 2008).

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 % 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.

Table A.6. Colorado Slurry Specifications (CDOT, 2006).

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 % by Volume	Less than 5%	Less than 5%	Screen

Table A.7. Connecticut Slurry Specifications (ConnDOT, 2009).

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 % by Volume	N/A	N/A	N/A

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

Table A.8. Delaware Slurry Specifications (DELDOT, 2009).

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 % by Volume	1 MAX	4 MAX	200 Sieve Retain

Table A.9. Florida Slurry Specifications (FDOT, 2010).

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 % by Volume	4% MAX	N/A	FM 8-RP13B-3

* Fresh water @ 68°F (20°C)
** Salt water @ 68°F (20°C)

Table A.10. Georgia Slurry Specifications (GDOT,2006).

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 Cone
pH	8 – 11	N/A	N/A
Sand Content % 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.

Table A.11. Hawaii Slurry Specifications (HDOT, 2005).

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 % by Volume			

Table A.12. Idaho Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	1030 – 1200	N/A	Mud Weight API 13B-1 Section 1
Viscosity Seconds/L	27.5 – 53	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 % by Volume	N/A	4.0 MAX	Sand API 13B-1 Section 5

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

Table A.13. Illinois Slurry Specifications (IDOT, 2007).

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 % by Volume			

Table A.14. Indiana 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 % by Volume			

Table A.15. Iowa Slurry Specifications (Iowa DOT, 2008).

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 % by Volume			

Table A.16. Kansas 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 % by Volume			

Table A.17. Kentucky Slurry Specifications (KYTC, 2009).

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 % by Volume			

Table A.18. Louisiana Slurry Specifications (LaDOT, 2002).

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 % 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.

Table A.19. Maine Slurry Specifications (MDOT, 2009).

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 % by Volume			

Table A.20. Maryland Slurry Specifications (MDOT, 2008).

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 % by Volume			

Table A.21. Massachusetts Slurry Specifications (MDH, 2003).

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 $\{kg/m^3\}$	64 – 75 {1030 – 1200}	N/A	Mud Density API 13B-1 Section 1
Viscosity Seconds/qt {Seconds/L}	26 – 50 {27.5 – 53}	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 % by Volume	4.0 MAX	4.0 MAX	Sand Content API 13B-1 Section 5

Table A.22. Michigan Slurry Specifications (MDOT, 2008).

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 % 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.

Table A.23. Minnesota Slurry Specifications (MnDOT, 2007).

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 % by Volume	N/A	N/A	N/A

Table A.24. Mississippi Slurry Specifications (MDOT, 2007).

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 % 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.

Table A.25. Missouri Slurry Specifications (MODOT, 2007).

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 % 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.

Table A.26. Montana 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 % by Volume			

Table A.27. Nebraska 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 D4380
Viscosity Seconds/qt	28– 45	28– 45	Marsh Funnel and Cup API 13B Section 2
pH	8 – 11	8 – 11	pH paper, Glass electrode
Sand Content % by Volume	N/A	N/A	N/A

Table A.28. Nevada Slurry Specifications (NDOT, 2001).

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 $\{kN/m^3\}$	64.0 – 68.8 {10.1 – 10.8}	64.0 – 74.6 {10.1 – 11.8}	Mud Balance API 13B-1 Section 1
Viscosity* Seconds/qt	28 – 45	28 – 45	Marsh Funnel and Cup API 13B-1 Section 2.2
pH	8 – 11	8 – 11	pH paper, Glass Electrode
Sand Content % by Volume	N/A	N/A	N/A

* 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.

Table A.29. New Hampshire Slurry Specifications (NHDOT, 2006).

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 % 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.

Table A.30. New Jersey Slurry Specifications (NJDOT, 2009).

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 % by Volume	N/A	N/A	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.

Table A.31. New Mexico Slurry Specifications (NMDOT, 2007).

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 % 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."

Table A.32. New York Slurry Specifications (NYSDOT, 2010).

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 % by Volume	N/A	N/A	N/A

Table A.33. North Carolina Slurry Specifications (NCDOT, 2010).

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}	Mud Weight API 13B-1 Section 1
Viscosity Seconds/qt {Seconds/0.95L}	28 – 45	28 – 45	Marsh Funnel and Cup API 13B-1 Section 2.2
pH	8 – 11	8 – 11	pH paper, Glass Electrode
Sand Content % by Volume	Vol≤4	Vol≤2	Sand API 13B-1 Section 5

a. Perform tests when the slurry is above 40°F (4.4°C).
b. Increase density by 2 lb/ft^3 (32 kg/m^3) in saltwater.

Table A.34. North Dakota Slurry Specifications (NDDOT,2010).

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 % by Volume			

Table A.35. Ohio Slurry Specifications (ODOT, 2010).

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 % by Volume	N/A	N/A	N/A

a. Range of values for 68°F.

Table A.36. Oklahoma Slurry Specifications (ODOT, 2009).

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 % by Volume	N/A	N/A	N/A

Table A.37. Oregon Slurry Specifications (ODOT, 2008).

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 % by Volume	4 MAX	4 MAX	Sand API 13B-1 Section 5

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

Table A.38. Pennsylvania Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3 {kg/m^3}	Unable to obtain specifications from State.		
Viscosity Seconds/qt {Seconds/L}			
pH			
Sand Content % by Volume			

Table A.39. Rhode Island Slurry Specifications

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density lb/ft^3	65 – 80	65 – 70	
Viscosity Seconds/qt	60 – 50		
pH	7 – 11	7 – 11	
Sand Content % by Volume	N/A	Vol≤4	

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

Table A.40. South Carolina 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 % by Volume	N/A	N/A	N/A

Table A.41. South Dakota 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 % by Volume			

Table A.42. Tennessee Slurry Specifications (TDOT, 2006).

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 % by Volume	Vol<4	Vol<10	API Sand Content Kit
Maximum Contact Time Hours	N/A	N/A	N/A

Table A.43. Texas Slurry Specifications **(**TxDOT, 2004).

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 % by Volume	Vol≤1	Vol≤6	

Table A.44. Utah 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 % by Volume			

Table A.45. Vermont Slurry Specifications (AOT, 2009).

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 {1030 – 1201}	Density Balance
Viscosity {Seconds/L}	{48 min}	{48 min}	Marsh Cone
pH	7 – 11	7 – 11	pH paper, pH meter
Sand Content % by Volume	N/A	N/A	N/A

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

Table A.46. Virginia Slurry Specifications (VDOT, 2010).

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 % 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.

Table A.47. Washington Slurry Specifications (WSDOT, 2009).

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 % 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.

Table A.48. West Virginia Slurry Specifications (WVDOT, 2000).

Property (Units)	At Time of Slurry Introduction	In Hole at Time of Concreting	Test Method
Density kg/m^3	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.		
Viscosity Seconds/L			
pH			
Sand Content % by Volume			

Table A.49. Wisconsin 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 % by Volume			

Table A.50. Wyoming 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 % by Volume			

Table A.51. Federal Highway Administration 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 % by Volume	4 MAX	4 MAX	API 13B-1