Beneficial Reuse of Corrugated Paperboard in Civil Engineering Applications

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Abstract

Beneficial Reuse of Corrugated Paperboard in Civil Engineering Applications Gregory Michael Stone

An investigation was conducted to explore the potential for reuse of corrugated paperboard. Corrugated paperboard represents a large fraction of the municipal solid waste generated and discarded in the United States. Alternative applications for reuse can provide a significant benefit by reducing the volume of waste being disposed and by reducing the use of raw materials. Four civil engineering applications were examined for potential beneficial reuse of corrugated paperboard: slurry trench construction, vertical drilling, directional drilling, and controlled low strength materials (CLSM).

For the purpose of this project, corrugated paperboard was pulped and added to bentonite slurry or CLSM mixtures. Bentonite slurry mixtures were tested for viscosity, density, filtrate loss, and permeability. The behavior of the bentonite slurries was greatly influenced by interaction and interlocking of corrugate fibers; in general resulting in increased viscosity, filtrate loss, and permeability and decreased density. CLSM mixtures were tested for flow consistency, unit weight, air content, and compressive strength. CLSM mixtures prepared with corrugated paperboard showed an increased water demand due to high absorption of the corrugate. The higher water content was a significant factor contributing to decreased unit weight and compressive strength. CLSM mixtures containing corrugated paperboard also exhibited increased air contents, possibly due to entrapment of air within the corrugate pulp.

Corrugated paperboard was used to successfully replace up to 27% of bentonite for slurry trench applications, 60% of bentonite for vertical drilling applications, and 59% of bentonite for directional drilling applications while maintaining acceptable engineering properties. For CLSM mixtures up to 1% of fine aggregate was replaced with corrugated paperboard while maintaining satisfactory engineering properties.

Incorporation of corrugated paper board into bentonite slurry, CLSM, and drilling fluid applications provides a viable option for beneficial reuse.

Keywords: Bentonite Slurry, CLSM, Corrugated Paperboard, Waste Materials, Slurry Trench, Water Wells, CIDH Piles, Directional Drilling

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Chapter 1: Introduction

1.1 Background

Currently paper is the largest contributor to the waste stream for municipal solid waste (MSW) landfills in the United States, comprising 28.2% of all MSW generated, approximately 62.1 million tonnes. Corrugated paper board makes up the largest portion of paper wastes; with approximately 24.7 million tonnes of corrugated box generated in 2009 (United States Environmental Protection Agency 2010). Of this total, approximately 81.3% was recovered for recycling, leaving an estimated 4.6 million tonnes to be discarded in landfills, representing 3.7% of all waste discarded in MSW landfills (USEPA 2010). A portion of this discarded corrugate is currently unrecyclable products, such as wax coated corrugated boxes and corrugate contaminated with food waste. An alternative to disposal in landfills would significantly contribute to reducing waste.

Over the past century there has been an increasing trend in the use of industrial byproducts and post-consumer waste products in civil engineering. Fly ash, blast furnace slag, and silica fume are industrial byproducts used in concrete. Additionally, scrap tire rubber, recycled carpet fiber, and paper mill sludge have been used in various geotechnical engineering applications. However, use of corrugated paperboard in civil engineering has not been commonly reported in literature.

The large scale of many civil engineering projects makes them well suited for the beneficial reuse of waste products. This thesis presents the findings of an investigation related to the feasibility of reusing corrugated paper board in a variety of civil engineering applications. In selecting potential reuse applications, uses of high volumes of materials were favored. These applications allow for a significant quantity of corrugate

to be reused even at relatively low replacement or addition rates, when the entire project is considered. Specific project types investigated include: bentonite slurry for use in slurry trenches, drilling fluids for both vertical and directional drilling, and controlled low strength materials.

1.2 Significance of Research

Landfill space is becoming an ever scarcer and more expensive commodity promoting investigation into alternatives to the disposal of waste in landfills. There have been numerous previously demonstrated uses of waste materials in civil engineering applications. Use of waste products is a sustainable practice, providing a dual benefit of diverting materials from landfills and reducing the quantities of raw materials used by civil engineering projects. The reuse studies conducted for this research represent novel applications that have not been previously reported.

1.3 Organization of Contents

The structure of this thesis is organized as follows: Chapter 2 provides a review of relevant literature for the applications investigated as well as background on corrugated paperboard. The experimental test program, materials, and methods are detailed in Chapter 3. Experimental results and a discussion of the results including engineering significance are presented in Chapter 4. Chapter 5 presents the engineering significance of these results. Conclusions and recommendations for future work are provided in Chapter 6.

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Chapter 2: Literature Review

2.1 Introduction

A review of literature relevant to this investigation is presented in this chapter. The following topics are covered: bentonite slurries and their application to the construction of slurry trenches, vertical borings, and directional drilling, as well as controlled low strength materials, and corrugated paperboard.

Bentonite slurries are used in a variety of civil engineering applications, including: slurry trench construction, and as drilling fluids for vertical and directional drilling. The primary purposes of these slurries are to control fluid infiltration, stabilize the excavation, and suspend and remove cuttings during construction. This chapter provides an overview of the properties of bentonite pertinent to use in bentonite water slurries, such as the potential for swelling and the formation of a diffuse double layer. The engineering properties of bentonite water slurries, including rheological behavior, viscosity, density, pH, filtration, and permeability are presented. The effect of these properties on slurry performance in various civil engineering applications and the appropriate ranges of properties for each application are presented.

Controlled low strength materials (CLSM) are used in place of compacted earth fill in civil engineering applications. This chapter presents an overview of CLSM, the materials used, and important engineering properties. The engineering properties presented include: flowability, unit weight, air content, and compressive strength. In addition, previous uses of waste materials in CLSM are presented.

This chapter also presents the structure, composition, and classification of corrugated paperboard. In addition the magnitude of the contribution of paper, including

corrugated paperboard, to the MSW waste stream is presented. An examination of the paper waste generated, recycled, and discarded in the United States is provided.

2.2 Bentonite

Bentonite is the trade name given to commercially available clay products consisting primarily of montmorillonite. Montmorillonite is a member of the smectite mineral group. The chemical structure of montmorillonite consists of an octahedral sheet between two silica tetrahedral sheets. These layers are loosely connected by van der Waals bonds and by cations present in the interlayer space (Mitchell and Soga 2005). There are several different compositions of montmorillonite differentiated by the primary cation present in the inter-layer space. Sodium and calcium are the predominant cations present in montmorillonite; however heavy metals such as chromium can substitute in for these cations as well. The valence of the cations in the inter-layer space has an effect on the physical properties of the montmorillonite and resulting montmorillonite-water mixtures. When added to water, montmorillonite is highly colloidal and expansive (Mitchell and Soga 2005).

Bentonite used in hydraulic cutoff applications is generally sodium bentonite. The single valence of the sodium cations allows for a large diffuse double layer to form around each clay particle, as the low charge holds the bound water molecules more loosely than cations of higher valence. The diffuse double layer is formed around clay particles when the particles come into contact with water. Adsorbed water molecules, and loosely bound water molecules form the diffuse double layer. The thickness of the double layer can be approximated by the following equation (Mitchell and Soga 2005):

$$\frac{1}{K} = \left(\frac{\varepsilon_0 D k T}{2 n_0 e^2 v^2} \right)^{\frac{1}{2}} \quad (1)$$

1/K	=	double layer thickness
ε_0	=	permittivity of a vacuum
k	=	Boltzman's Constant
D	=	dielectric constant of the material
T	=	temperature
n_0	=	electrolyte concentration
e	=	electric charge
v	=	cation valence

An increased double layer size decreases the effective distance between particles and decreases the permeability of the clay-water solution, making bentonite slurries ideal for applications where low permeability is desired.

The single valence cations present in sodium bentonite make it more susceptible to cation exchange, meaning that single valence cations may be replaced by higher valence cations through substitution. As the valence of the absorbed cations increases, the double layer thickness decreases through an inverse square relationship as seen in Equation 1. This collapse in double layer thickness will result in increased permeability of the clay-water system. This is of particular concern in slurry wall applications for pollutant mitigation. When a pollutant containing cations of a valence greater than 1 comes into contact with bentonite slurry the pore water chemistry is changed, potentially causing a collapse of the double layer, and potentially increasing the permeability of the slurry wall beyond acceptable limits.

2.2.1 Bentonite Slurries

The swelling properties of bentonite-water slurries and the creation of a diffuse double layer make bentonite-water slurries useful in a variety of applications. Bentonite

slurries are thixotropic, shear thinning materials, after application of a shearing stress the shear strength and viscosity of the material decreases and upon removal of applied of shearing stress the bentonite will regain the initial shear strength over a period of time (Filz et al. 1997).

Bentonite-water slurries are non-Newtonian fluids; in that, the shear stress is not directly proportional to the shearing rate. These slurries are often modeled as Bingham plastic fluids, requiring an initial yield stress to be reached before flow begins (Filz et al. 1997). Figure 2.1 provides a graphical representation of the relationship of shear stress to shearing rate for Bingham plastic and Newtonian fluids.

Figure 2.1 Shear Stress-Shear Strain Rate Relationships (Filz et al. 1997)

The use of bentonite slurries began with oil well drilling in the petroleum industry (Xanathakos 1979). As such, testing for the engineering properties of bentonite slurries is conducted according to methods developed by the American Petroleum Institute (API),

specifically the API Recommended Practices 13B (API 2003). The applicable properties include drilling fluid density, viscosity, filtrate loss, and pH. These test methods were developed primarily for field testing and used for rapid indication of bentonite slurry properties, in lieu of more rigorous laboratory practices. Some tests (e.g., Marsh Funnel, Mud Balance density) are standardized by ASTM in addition to procedure outlined by API. These properties and associated test methods are described in the sections that follow.

Density

Bentonite slurry density is measured by a device known as a mud balance. The mud balance consists of a cup of calibrated volume that is attached to a single beam slide balance. As these slurries are used to counteract ground water pressure to stabilize excavations and borings, it is imperative that the density of the bentonite slurry exceed that of water (1.0 g/cm^3) to ensure that infiltrating water does not displace slurry from the excavation.

Viscosity

Provisions are included in API for the determination of viscosity using two devices, a Marsh funnel and a direct-indicating viscometer. The use of the Marsh funnel has a drawback in that it does not truly measure viscosity. Viscosity is measured and reported in terms of seconds-Marsh, the time taken for 946 mL (one quart) to flow through the funnel orifice. This value can be correlated to a viscosity value in typical units of centipoise (Pitt 2000). However, because the Marsh funnel operates at only one shearing rate and bentonite is a non-Newtonian fluid the full shear relationship cannot be developed.

Direct indicating viscometers allow for more accurate determination of the shear stress to shear strain relationship. By taking several readings at various shearing rates, the yield point and plastic viscosity can be calculated. The yield point is the initial stress that must be exceeded in order for flow to begin (Xanathakos 1979). Due to the relative ease of operation and speed, Marsh funnel viscosity is often used as an indicator of the other in-situ properties of the bentonite slurry.

Filtration

Filtration, alternatively known as filtrate loss, refers to the amount of fluid lost to surrounding strata during formation of a filter cake, a thin relatively impermeable layer that accumulates on the walls of the excavation. The fluid lost to the formation is termed the filtrate. The filtrate loss test is used as a measure of filtration behavior and filter cake formation. There are two procedures used to measure the filtrate loss of bentonite, one for low temperature and low pressure (ambient temperature and 0.7 MPa) and one for high temperature and high pressure (200 °C and 4 to 8.9 MPa). Both methods are valid, and in fact necessary, for use of bentonite slurries in petroleum well drilling. However the low temperature and pressure method is more applicable to geotechnical field conditions.

The low pressure-low temperature test is conducted using a standard API filter press, a filtration cell with a compressed air inlet, and a spigot allowing the filtrate to leave the cell. A piece of hardened, low ash, 2.7 µm filter paper is placed at the bottom of the cell and the cell is filled with slurry. The cell is then pressurized to 690 kPa (100 psi) and the filtrate is collected for 30 minutes, to determine the amount of fluid loss. The filtrate loss is reported in mL for the 30 minute increment.

pH

The acidity or alkalinity of a solution is measured using pH, the negative logarithm of the hydrogen ion activity in a solution. The API recommended method of pH measurement is through the use of a glass electrode pH meter.

The pH of a solution affects dispersion of clay particles. As pH increases, positive surface charge of clay particles decreases drastically and negative surface charge increases somewhat, resulting in an increase in net negative charge (Chorom et al. 1994). This increased negative charge increases the repulsive forces between colloidal particles, leading to greater dispersion. Chorom et al. (1994) determined that above a threshold pH value of approximately 6 the positive charge reached zero for the clays examined. In addition, Chorom et al. (1994) indicated that the percentage of dispersible clay in water increased with increasing pH. Low values of pH can negatively affect the dispersion of clay in solution, however high values of pH can also have adverse effects on bentonite slurries. In slurries with pH of 11 or greater flocculation can occur (CETCO 2010). In order to control the pH of the slurry, it is recommended that the mixing water be treated with soda ash, Na_2CO_3 to promote removal of potentially deleterious calcium through precipitation as calcium carbonate. A pH between 8 and 9 is recommended for bentonite slurries by Baroid Industrial Drilling Products (2011).

The type of bentonite used can greatly influence the properties of the resulting slurry. Bentonite types are distinguished by both chemical attributes and physical properties such as yield. The yield of the bentonite is reported in barrels, and is the number of 0.16 m^3 (42 gallon) barrels of slurry at an apparent viscosity of 15 centipoise that can be prepared with 907 kg (2000 lbs) of bentonite (Driscoll 1986). Bentonite types include a standard 90 barrel yield bentonite, "natural" or "untreated" bentonite,

chemically resistant bentonite, and high yield (180 barrel yield) bentonite. High yield bentonite should not be used in slurry wall applications, as mixtures with acceptable rheologic properties tend to have a bentonite content that is too low to achieve other properties (i.e., permeability) (Ryan and Day 2003). High yield bentonite can be used in other slurry applications such as drilled shafts, water well drilling, and other vertical boring applications, while standard 90 barrel yield bentonite is the most common type used for slurry trench construction.

2.3 Bentonite Slurry Walls

Bentonite slurry walls are vertical barriers for the control of groundwater flow and curtailment of pollutant migration. Slurry walls can be designed to contain or divert the flow of groundwater and contaminants (Sharma and Lewis 1994). Bentonite slurry for construction of slurry walls is typically prepared using approximately 5% bentonite by total mix weight.

The bentonite contents recommended by various researchers for use in bentonite slurry trenches are provided in Table 2.1.

Table 2.1 Recommended Bentonite Contents

Recommended Bentonite Content	Reference
4 to 7%	US Environmental Protection Agency (1984)
5 to 6%	D'Appolonia and Ryan (1979)
6%	Filz et al. (1997)
4 to 8%	Rad et al. (1995)

The effectiveness of a slurry wall is influenced significantly by both the engineering properties of the slurry (viscosity, density, and filtration) and the alignment (vertical and horizontal) of the wall.

Marsh funnel viscosity is the most commonly specified property for bentonite slurries. A wide range of Marsh funnel viscosity values have been reported for use in bentonite slurry trench construction. A summary of recommended ranges for Marsh funnel viscosity is presented in Table 2.2.

Table 2.2 Summary of Recommended Marsh Funnel Viscosities

Recommended Marsh Funnel Viscosity (s)	Reference
40	D'Appolonia and Ryan (1979)
40 to 45*	Ryan (1976)
35 to 40	Rad et al.(1995)

*Ryan (1977) notes that values ranging from 35 to 80 s have been used without issue

Xanathakos (1979) recommended selecting Marsh funnel viscosity based on soil formation type. Recommendations for Marsh funnel viscosities for construction of slurry walls in various formations are presented in Table 2.3.

Table 2.3 Recommended Marsh Funnel Viscosities for Various Soil Types (Xanathakos 1979)

Soil Type	Recommended Marsh Funnel Viscosity (s)	
	Excavation in Dry Soil	Excavation with Groundwater
Clay	27-32	--
Silty Sand or Sandy Clay	29-35	--
Sand with Silt	32-37	38-43
Fine to Coarse Sand	38-43	41-47
Sand with Gravel	42-47	55-65
Gravel	46-52	60-70

Bentonite slurries for slurry trench construction should have a unit weight significantly lower than that of the material used to backfill the wall to ensure that the backfill entirely displaces the slurry and does not have pockets or inclusions (D'Appolonia and Ryan 1979). Rad et al. (1995) recommend a total unit weight of approximately 10 kN/m³. However, Ryan and Day (2003) and D'Appolonia and Ryan (1979) advised against specification of bentonite slurry based on density, as small variations in density can result in large variation in other slurry properties. In addition, the depth to the groundwater table is often more critical than slurry density.

The filtrate loss for slurries used in slurry trench construction is recommended to be less than 30 mL in a 30 minute period (Rad et al. 1995). D'Appolonia and Ryan (1979) reported that slurries exhibiting a high filtrate loss form thicker but more permeable filter cakes than those exhibiting low filtrate loss. In addition, it was observed that filtrate loss

has a limited influence on the ratio of filter cake permeability to filter cake thickness (D'Appolonia and Ryan 1979).

Horizontal wall alignments are classified as downgradient, upgradient, or circumferential. Downgradient walls are used in situations with limited upgradient flow, but may require pumping if the water table is raised. Upgradient walls are used to divert groundwater flow around a contaminated area. Circumferential slurry walls completely surround contaminated sites (Sharma and Lewis 1994). Various configurations for slurry walls are presented in Figure 2.2 to Figure 2.4. Circumferential Slurry Wall Configuration (USEPA 1984).

Vertical wall configurations can be grouped into two categories: keyed-in walls and hanging walls. Keyed-in slurry walls are used for the containment of contaminants that are miscible in water, or sink to the bottom of an aquifer such as with dense non-aqueous phase liquids (DNAPLs), or in situations with unknown contamination conditions. In contrast, hanging slurry walls are used when contaminants float on top of groundwater, such as light non-aqueous phase liquids (LNAPLs) (Sharma and Lewis 1994).

Figure 2.2 Downgradient Slurry Wall Configuration (USEPA 1984)

Figure 2.3 Upgradient Slurry Wall Configuration (USEPA 1984)

Figure 2.4 Circumferential Slurry Wall Configuration (USEPA 1984)

Slurry walls are constructed by excavating a trench through pervious soils to an appropriate depth. This excavation can continue into a relatively impermeable layer, referred to as an aquitard as is the case for keyed-in slurry walls or can be left at some height above the aquitard as with hanging slurry walls. During and after excavation, slurry consisting of bentonite and water is maintained in the trench, level with the existing ground surface.

The slurry serves two primary purposes in the construction process: formation of a filter cake and maintaining the stability of the excavation. A filter cake is a thin, low permeability layer that the slurry forms on the trench faces and prevents fluid loss to the surrounding soil. As slurry is introduced into the excavation, it permeates into the pores of the surrounding soil. The slurry will continue to penetrate into the surrounding strata until the bentonite particles accumulate and begin to clog the pores between soil particles.

Figure 2.5 Construction of a Bentonite Slurry Wall (Geosolutions 2011)

This filter cake layer can have a permeability as low as 10^{-9} cm/s. Initially, fluid is lost to surrounding soil at a high rate; after the filter cake is formed this rate decreases (USEPA 1984). Filter cake formation is illustrated in Figure 2.6. The second purpose of the slurry is to prevent collapse of the surrounding soils during construction. Excavation stability is achieved by the slurry exerting a hydrostatic pressure on the filter cake, which resists the lateral earth pressure.

Figure 2.6 Filter Cake Formation for Fine and Coarse Grained Materials (Filz et al. 1997)

In fine grained soils the void spaces between adjacent particles are small enough for bentonite particles to accumulate and fill the voids (Filz et al. 1997). The hydrostatic pressure forces the bentonite into the surrounding soil until the filter cake forms a seal. In coarse grained soils, the void spaces may be too large to retain the bentonite particles. In these circumstances, silt and fine sand present in the excavation are retained in the void spaces may aid in the retention of bentonite particles (Filz et al. 1997).

After excavation is completed, the excavated trenches filled with bentonite slurry are backfilled with one of several materials. In the soil-bentonite backfill method, bentonite slurry from the trench is mixed with the excavated in-situ soil or select imported material. Additional dry bentonite may be added in order to achieve the desired permeability of the backfill (D'Appolonia and Ryan 1979). Other wall types such as concrete backfill and soil-cement backfill can be used as well. In the United States the

most common backfill material is a soil-bentonite mixture. Backfilling with a cement-bentonite mixture is more prevalent in the United Kingdom (Opdyke and Evans 2005).

The permeability of a slurry wall depends on the permeability of both the filter cake and the soil backfill. D'Appolonia and Ryan (1979) presented the following equation for the horizontal permeability of a slurry wall:

$$k = \frac{t_s}{\left(\frac{t_s}{k_s}\right) + 2\left(\frac{t_c}{k_c}\right)} \quad (2)$$

where k , is hydraulic conductivity, t is thickness, and the subscripts s and c represent soil backfill and filter cake respectively. Sharma and Lewis (1994) presented a method of determining the value of k_c/t_c using a filter press. In this method, a filter cake is allowed to form according to the standard API (2003) filtration test. At the end of filter cake formation, excess slurry is decanted and replaced with water. A pressure head equal to the difference in slurry pressure and the surrounding pore fluid pressure is applied. The flow through the filtration area is then used to calculate the ratio of k_c/t_c .

The permeability of the soil backfill is influenced primarily by the grain size distribution of the soil and the amount of bentonite used in the mixture. The hydraulic conductivity is also influenced by the confining stress on the backfill. Determination of hydraulic conductivity of soil backfill in the laboratory can yield unconservative values, due to overestimation of the effective stress due to bridging of the backfill within the trench (Evans 1994).

2.4 Drilling Applications

Bentonite slurries are often used as drilling fluids in the construction of vertical and horizontal borings. Two applications of vertical borings are cast-in-drilled hole (CIDH) piles and water wells. One application of horizontal boring is bypassing obstacles using Horizontal Directional Drilling. The purposes of the bentonite slurry in these applications are similar to those for slurry wall construction (e.g., stabilize the excavation, prevent infiltration by water).

One key difference between slurry wall construction and drilling applications is the dependence of the filtration characteristics on the dynamic factors of slurry circulation. When the drilling fluid is circulated, the rates of filtrate loss and filter cake formation as well as the stability of the filter cake are dependent not only on slurry properties and hydrostatic pressure, but also on the circulation rate and circulation pressure. The permeation rate into a newly exposed formation is initially high and then the rate reduces to equilibrium conditions. The time needed to attain equilibrium, generally one to two hours, is dependent on circulation rate, differential pressure, drilling fluid composition, and temperature (Dewan and Chenevert 2001).

Dewan and Chenevert (2001) presented a numerical model for the formation of filter cake under dynamic conditions. The model was based on six parameters characterizing the filter cake: reference porosity, reference permeability, "pressure up" compressibility index, "pressure down" compressibility index, zero pressure shear strength, and erosion friction factor. The prediction of these properties based on drilling fluid composition has not been reported due to the large variability of drilling fluids. The formation of filter cake under dynamic conditions was determined to be controlled by

two mechanisms. The first is the progressive buildup of increasingly smaller particles. The second is the erosion of the filter cake, which only occurs when the thickness exceeds the dynamic equilibrium thickness. Therefore, filter cake developed under hydrostatic conditions tends not to erode, while an excess filter cake built up during drilling fluid circulation is more easily eroded.

2.4.1 Cast-in-Drilled Hole (CIDH) Piles

CIDH piles are vertical borings, generally 1 to 4 m (3 to 12 ft.) in diameter, used in the construction of cast in place, reinforced concrete foundation elements. These borings are constructed by excavating a shaft, placing a steel reinforcing cage, and backfilling with concrete. Excavation is typically completed using an auger system; however, cutting heads and core barrels can also be used. The three primary methods of drilled shaft construction include: the dry method, the casing method, and the wet method (FHWA 2010).

The dry method of construction is used in stable formations with little or no seepage of groundwater into the excavated hole. This method includes drilling a shaft to the desired tip elevation, removing loose debris from the base of the excavation, placing a reinforcing cage, and finally placing concrete into the excavation. Drilling fluid is not used in this method of shaft construction. The dry method of CIDH pile construction is generally not suitable if more than 75 mm (3 in.) of groundwater is accumulated at the bottom of the shaft. In the event that this seepage limit is exceeded, the construction is completed using either the casing or wet method of construction.

The casing method is used in cavable formations or when an excavation is made wholly or partially through permeable strata. A casing typically made of steel is advanced through the caving or permeable strata to the full depth of the excavation. This is accomplished using one of three methods: the dry method, advancing a casing through a slurry filled starter hole, and excavation using full length casing. The dry method of construction does not use drilling fluid and is suitable only for excavations with little to no seepage, a casing is used only to stabilize the borehole during construction. The latter two methods (Figure 2.7 and Figure 2.8) use drilling fluid for either a portion or the entirety of the excavation. For construction with a full length casing, the drilling fluid is used solely to prevent groundwater infiltration. For shafts constructed using a slurry filled starter hole, the drilling fluid serves to stabilize the excavation as well.

Figure 2.7 CIDH Pile Construction Using Casing Through Filled Starter Hole Process (FHWA 2010)

Figure 2.8 CIDH Pile Construction Using Full Length Casing Process (FHWA 2010)

The wet method of construction is used for excavations through permeable strata where dewatering is not feasible. This method is similar to the manner in which slurry walls are created. A shaft is excavated and bentonite slurry is pumped in. The level of the bentonite is maintained above the level of the piezometric surface. According to the Federal Highway Administration (FHWA 2010), the level of the slurry should be maintained at least 1.5 m (5 ft) above the ground water surface. Depending on site conditions and in the case of confined aquifers, it may be necessary to have a slurry level above ground level, requiring the use of a casing extending above the ground surface. After the shaft is excavated to the desired tip elevation the reinforcing cage is inserted and concrete is placed using a tremie pipe. The tremie pipe is inserted to the bottom of the excavation and concrete is placed from the bottom of the shaft upwards maintaining the tremie pipe below the level of the fresh concrete surface so as to not allow mixing of bentonite slurry and the concrete. FHWA (2010) recommends the tremie pipe be kept 3 m (10 ft) below the concrete surface. The concrete will displace the bentonite and expel it

from the top of the excavation. The wet method of construction is illustrated in Figure 2.9.

Figure 2.9 CIDH Pile Construction Using the Wet Method of Construction (FHWA 2010)

CIDH piles can also be constructed using the wet method with a cutting head and reverse circulation drilling (Figure 2.10). In this method, bentonite slurry is pumped into the annular space of the excavation around a central tube and the cuttings are carried away from the bottom through this central tube. The name reverse circulation refers to the process being the opposite of that used in water well drilling, in which fresh slurry is pumped down the central tube and spent slurry and spoils travel around the cutting head in the upward direction in the annular space and out of the excavation.

Figure 2.10 Schematic of Reverse Circulation Drilling Equipment (FHWA 2010)

Bentonite for CIDH Piles

Bentonite slurries are used in both the casing and wet method of CIDH pile construction in cavable and permeable soils. Maintaining the required properties of the bentonite slurry is important for a successful excavation, and casting of a CIDH pile. Due to the short term nature of CIDH excavations, filter cake formation and stability are more important than long term low permeability. Slurry density and viscosity are additional design parameters that should be considered.

As the main concern with CIDH pile construction is borehole stability, the formation of a filter cake on which hydrostatic pressure can be exerted is important. FHWA (2010) recommended that filter cake resulting from a standard API low pressure-low temperature filter cell test be no more than 3.2 mm (0.125 in.) in thickness. Higher values of cake thickness may indicate that a substantial filter cake layer may remain after concrete is placed. This remaining filter cake may attach to the reinforcing cage and interfere with the bond between concrete and reinforcing steel (FHWA 2010).

Filtrate loss is a significant concern on an economic basis, as it is a measure of the fluid loss to the surrounding soil during filter cake formation. Higher values of filtrate loss indicate that more slurry will be needed to offset the amount lost to the soil, resulting in increased cost to the contractor. From an engineering perspective, the filtrate loss is not a critical factor as long as the borehole remains stable. FHWA (2010) recommends a filtrate loss value of less than 10 mL in 30 minutes of API filtration test.

A slurry density higher than that of water is necessary in order to maintain net outward hydrostatic pressure on the filter cake and the walls of the borehole. FHWA (2010) recommends a density ranging from 1.03 g/cm³ to 1.06 g/cm³.

The proper viscosity of the bentonite slurry depends on the intended application. Generally for CIDH pile construction, the slurry is intended only to maintain borehole stability and does not need to lift a significant amount of cuttings as they are removed mechanically. For this purpose lower viscosity slurries may be used. In the case of reverse circulation drilling, the slurry is the primary transport mechanism for cuttings leaving the borehole. The suspension of cuttings requires higher viscosity slurry. FHWA (2010) recommends a Marsh funnel viscosity of 28 to 50 seconds.

2.4.2 Water Wells

Drilling fluids are also used in the construction of vertical borings for water wells. Shafts are drilled into an aquifer to enable water extraction. The subsurface can be drilled using several methods including: the cable tool method, direct rotary drilling, and reverse circulation drilling. Among these methods, direct rotary drilling and reverse circulation drilling utilize drilling fluids (Driscoll 1986).

In direct rotary drilling, the borehole is advanced by a rotating cutting bit attached to the drilling pipe. The cuttings are removed through continuous circulation of drilling fluid. Drilling fluid is pumped through the drill pipe and is expelled through ports or jets in the cutting bit. The drilling fluid then carries the cuttings up through the annular space between the drill pipe and the walls of the boring. The drilling fluid then flows into a settling pit where the cuttings settle out of suspension. The fluid is then drawn out of the pit and recirculated into the well shaft.

Reverse circulation drilling can also be used to construct water wells. This method is typically used in boring larger diameter wells with a diameter greater than 600 mm (24 in.) [Driscoll 1986].

Drilling fluids for use in water well drilling can consist of air or water combined with one of several components. Water based drilling fluids consist of water mixed with a colloidal phase, such as native clay, bentonite, or polymeric additives. Drilling fluids for use in water well applications serve to stabilize the well and remove cuttings during excavation. In addition drilling fluids serve to lubricate and cool the cutting bit, bearings, drill pipe, and mud pump (Driscoll 1986).

The stability of a water well requires that the hydrostatic pressure exerted by the drilling fluid be greater than the hydrostatic pressure exerted by the ground water plus any additional pressure in confined aquifers. It is recommended that an excess pressure of 34.5 kPa (5 psi) be maintained for proper well stability (Driscoll 1986).

The viscosity of water based drilling fluids is primarily dependent on particle size. A typical bentonite clay particle is smaller than 4 μm , while a particle of the natural polymer formed from guar seeds can be as small as 0.0001 μm (Driscoll 1986). To obtain viscosity equivalent to bentonitic drilling fluids, less polymeric particles are needed than clay particles. In addition, the particle shape and electric charge will affect the viscosity (Driscoll 1986). Table 2.4 provides recommended viscosities for construction of water wells in various soil types.

Table 2.4 Recommended Marsh Funnel Viscosities for Various Formation Types (Driscoll 1986)

Soil Formation Type	Recommended Marsh Funnel Viscosity Range (s)
Fine Sand	35 to 45
Medium Sand	45 to 55
Coarse Sand	55 to 65
Gravel	65 to 75
Coarse Gravel	75 to 85

2.4.3 Directional Drilling

Horizontal Directional drilling (HDD) is a technique used for a variety of applications including: drilling holes in orientations other than vertically in order to navigate under or around roadways, railways, rivers, and other obstacles. Drilling is

conducted by first drilling a pilot hole using a cutting bit and circulating drilling fluid. The cutting head is steerable and relays its position to an operator allowing for a specific course to be followed. Drilling continues until the drill bit exits the surface on the opposite side of the obstacle. The pilot hole is then reamed until the desired diameter is obtained. The conduit is attached to the reamer and drill pipe and pulled through the reamed hole (Horizontal Drilling International 1999).

The circulating drilling fluid absorbs the heat generated from the friction of the drill pipe and drill bit on the walls of the borehole. In addition, the cuttings are carried away from the bit and to the surface. The fluid also allows for temporary suspension of cuttings when drilling is stopped. For cuttings to be removed from the hole, the annular mud circulation velocity must exceed the settling velocity. In addition to sealing the borehole and preventing fluid loss, the filter cake formed in HDD helps to lubricate the borehole when the conduit is pulled through. Sand and other solids should be removed from the slurry before recirculation to prevent wear and abrasion of pumps and drilling equipment. The cuttings removed from the slurry can be used to obtain information about the formation. The slurry also helps to transmit hydraulic power through the use of jets at the cutting bit, which expel slurry and advance the bit through the boring. Finally, the drilling fluid helps to support the weight of the drill pipes and conduit (Horizontal Drilling International 1999).

For a drilling fluid to be effective for HDD, the fluid must have several characteristics. First, the viscosity must be high enough such that the cuttings remain suspended until transport to the surface is complete. The density of the slurry should be

high enough to provide sufficient buoyant force on the pipe while not causing excessive weight to be dragged by the conduit or drill pipe (Horizontal Drilling International 1999).

The capacity of the drilling fluid to carry cuttings is dependent not only on the drilling fluid properties, density and viscosity, but also the circulation characteristics of the drilling fluid, flow volume and flow velocity (Baumert et al. 2005, Okrajni and Azar 1986). The use of aerated drilling fluids may also increase the cutting carrying capacity (Naganawa et al. 2002). Okrajni and Azar (1986) determined that the flow characteristics (turbulent or laminar flow), well bore inclination, and mud rheological properties were the main factors influencing cutting carrying capacity. The rheological properties considered were yield point and plastic viscosity. The recommended properties of drilling mud and circulation characteristics vary with the angle of inclination from vertical of the well bore. Recommended properties were provided for three ranges; 0 to 45 degrees, 45 to 55 degrees, and 55 to 90 degrees (Okrajni and Azar 1986).

For well bores inclined from 0 to 45 degrees from vertical, a laminar flow is recommended. In addition the yield point should be high (typical value of approximately 9.6 Pa (20 lbs/100 ft²). Similarly the ratio of yield point to plastic viscosity should be high (typical value of approximately 2). For well bores inclined 45 to 55 degrees either turbulent or laminar flow can be used. From an economic standpoint turbulent flow is preferred because less bentonite can be used as drilling fluid rheological properties typically do not affect cutting removal during turbulent flow. However, if the static drilling fluid requirements are such that turbulent flow cannot be obtained, the recommendations for the 0 to 45 degrees are applicable. For well bores with an inclination of 55 to 90 degrees; (i.e., approaching horizontal orientation) turbulent flow is

preferred. If turbulent flow cannot be obtained, laminar flow must be considered. The yield point is not a critical factor in the 55 to 90 degree orientation region. However, the ratio of yield point to plastic viscosity must be maintained as high as possible. The use of high viscosity drilling fluids is only advantageous in shallow angle wells (Okrajni and Azar 1986).

Boreholes with inclinations in the 0 to 45 degree region are primarily vertically aligned; therefore drilling fluid recommendations appropriate for vertical borings, such as those outlined by Driscoll (1986) and FHWA (2010) are also applicable. Boreholes with inclinations in the 45 to 55 degree and 55 to 90 degree regions have a primarily horizontal alignment. The effectiveness of these boreholes is governed less by the rheological properties of the drilling fluid than the flow characteristics, as turbulent flow is desirable.

Characterization of fluid flow as turbulent or laminar is done using the Reynolds Number. The Reynolds Number (Re) is a dimensionless parameter that provides a measure of the ratio of inertial forces to viscous forces. Re is calculated using Eq. 3 (Fox et al. 2006).

$$Re = \frac{Q D_H}{\nu A} \quad (3)$$

$$\begin{aligned} Q &= \text{Volumetric Flow Rate} \\ D_H &= \text{Hydraulic Diameter} \\ \nu &= \text{Kinematic Viscosity} \\ A &= \text{Cross Sectional Area of Pipe} \end{aligned}$$

Flow is considered laminar if Re is less than 2300 and turbulent if Re is greater than 4000, with intermediate values falling in a transition region (Fox et al. 2006). The

kinematic viscosity is a ratio of the dynamic viscosity divided by the density. For flow in an annular region, as is applicable to directional drilling the hydraulic diameter is the difference in the outer and inner annulus diameter. To obtain turbulent flow with a given borehole geometry (i.e., fixed D_H and A), the volumetric flow rate must be increased or the kinematic viscosity must be decreased. The kinematic viscosity can be decreased by increasing the density or by decreasing the dynamic viscosity (Fox et al. 2006).

2.5 Controlled Low Strength Material

Controlled low strength material (CLSM) is a self-leveling, self-compacting cementitious material primarily used in place of compacted soil backfill (Figure 2.11). A variety of alternative names are used for CLSM including: flowable fill, unshrinkable fill, and controlled density fill. ACI 229 defines CLSM as a cementitious material that is fluid at placement and one which results in a compressive strength of 8.3 MPa (1200 psi) or less. However, to allow for future excavation an unconfined compressive strength of less than 2.1 MPa (300 psi) is required, and an unconfined compressive strength below 0.7 MPa (100 psi) is required for hand excavation (ACI 2011).

Due to the variety of properties that can be obtained with CLSM, it is well suited for a range of potential applications. Mixtures with compressive strengths near the upper limit (8.3 MPa) are suited for use as structural fills beneath buildings, used to distribute the structural load over a larger area (ACI 2011). Additional uses for CLSM include backfill behind retaining walls, pavement bases, conduit bedding, void filling, and bridge reclamation.

Figure 2.11 CLSM being placed in a trench (FHWA 2012)

CLSM mixtures are subject to few requirements and specifications, typically focusing on the compressive strength of the mixture. Riggs and Keck (1998) conducted a survey of the specifications for CLSM by six state transportation agencies. For all six states surveyed, the only mechanical property specified was the unconfined compressive strength. Additional restraints were placed on the materials and mixture proportions (e.g., cement type and allowable pozzolans). However, substitute mixtures are permitted to be presented for approval. Several of the states surveyed waived the gradation requirements on aggregates, with one state allowing the use of coal bottom ash, an ash that is unfit for use in conventional concrete, as a fine aggregate.

2.5.1 Materials in CLSM

CLSM is generally composed of portland cement, fly ash, aggregates, and water. The low level of requirements for CLSM offers a wide range of variability in the mixture

proportions and materials used. CLSM mixtures are produced with materials similar to conventional concrete (cement, fly ash, fine aggregate, water) as well as a variety of industrial byproducts.

Portland Cement

According to ACI Committee 229 (2010), the cement used in CLSM is typically Type I or II portland cement conforming to ASTM C150. Other cements, such as blended cements conforming to ASTM C595, can be used if indicated by successful testing results.

Fly Ash

Fly ash is a pozzolanic material generated as a byproduct of coal combustion for energy production. Pozzolans react in a secondary cementitious reaction with the products of portland cement hydration. In this reaction, silica from the pozzolan combines with calcium hydroxide from cement hydration to form calcium silicate hydrate (Hewlett 2004).

Fly ash is broadly classified into three classes: Class F, Class C, and those not meeting either requirement. The first two classes are distinguished based on chemical composition (ASTM C618). Class F fly ashes have a sum of iron oxide, alumina, and silica contents greater than 70% of the material weight, Class C fly ashes have a sum of iron oxide, alumina, and silica between 50 and 70% based on the results of an X-ray Fluorescence (XRF) oxide analysis; the remainder of the chemical composition is taken up by calcium oxide and relatively minor amounts of other compounds. Class F fly ashes are termed low-lime and Class C fly ashes are termed high-lime due to the difference in

Calcium Oxide content. Typical chemical compositions of Class C and Class F fly ashes are provided in Table 2.5 (Hewlett 2004).

Table 2.5 Compositions of Fly Ashes (adapted from Hewlett 2004)

Fly Ash Type	SiO₂	Al₂O₃	Fe₂O₃	CaO	MgO	Na₂O	K₂O	SO₃
High Lime Fly Ash (Class C)	32.8	22.9	5.1	27.4	4.82	1.56*	---	2.21
Low Lime Fly Ash (Class F)	52.24	19.01	15.71	4.48	0.89	0.82	2.05	1.34

Values provided are in percent by mass, not all minor constituents are shown

*Na₂O Equivalent

Due to the high calcium oxide content, Class C fly ash exhibits some self cementing reaction. This calcium is present in the form of dicalcium silicate, which reacts relatively slowly results in long term strength gain. This long-term strength gain may make Class C fly ash unacceptable for use in CLSM, due to compressive strengths above 2.1 MPa at later ages when re-excavation is likely to occur (Turler 2005).

Fly ash for use in CLSM does not need to conform to either Class F or Class C as defined in ASTM C 618. This allows for the use of substandard products such as ponded ash or basin ash that are generally stockpiled or discarded. These products generally have a high carbon content making them undesirable for conventional concrete mixtures. Fly ashes with carbon contents of up to 22% have been successfully used in CLSM mixtures (ACI 2011).

Aggregates

The aggregate types used in the production of CLSM vary widely. Mixtures may contain fine aggregate, coarse aggregate, a combination of both, or no aggregate at all (ACI 2011). Aggregates used in CLSM generally conform to the requirements of ASTM

C33 because ready mix concrete suppliers have these materials on hand. However, aggregates of lower quality than those used in concrete production may also be used as an alternative.

Various alternative aggregates have been shown to produce satisfactory CLSM, including high fines (greater than 20%) silty sands and on-site soils. Soils with high clay contents should be avoided as they can have deleterious effects on the mixture properties such as increased water demand, increased shrinkage, and mixture heterogeneity from incomplete mixing of the clay (ACI 2011).

2.5.2 Waste Materials in CLSM

CLSM is subject to minimal requirements. Flexible specifications allow for the use of a variety industrial byproducts and wastes that are typically discarded. Waste products have been used to replace both cementitious materials and aggregates in CLSM mix designs. As aggregates account for the largest portion of the CLSM mixture, their replacement provides a large impact. Products such as crushed glass, reclaimed concrete, and scrap tire rubber have produced acceptable CLSM mixes as a partial or total replacement of the aggregate. A summary of materials reported to have been incorporated into CLSM is presented in Table 2.6.

The addition of waste materials often requires the adjustment of mixture proportions to alleviate or minimize certain detrimental impacts. One common impact observed was an excess of bleed water (Naik and Singh 1997, Tikalsky et al. 1998, Pierce and Blackwell 2003, Cheung et al. 2007, Deng and Tikalsky 2007).

Table 2.6 Summary of Waste Materials Used as a Full or Partial Aggregate Substitute in CLSM

Material Used	Material Replaced	Replacement Rate	Reference
Spent Foundry Sand	Fly Ash	30-85%	Naik and Singh (1997)
Spent Foundry Sand	Aggregate	100%	Deng and Tikalsky (2008)
Spent Foundry Sand	Aggregate	100%	Abichou et al. (2004)
Recycled Glass	Aggregate	10%-30%	Wang (2009)
Scrap Tire Rubber	Aggregate	Varied by researcher (15-50%)	Pierce and Blackwell (2003), Cheung (2007)
Coal Combustion Products	Aggregate	5%-31%	Won et al.(2004)

2.5.3 Low-Density CLSM

Low-density CLSM (LD-CLSM) is a specialty type of CLSM used to decrease overburden on weak underlying soil or used as an insulating and isolating fill. Also, the cellular air void structure can provide thermal insulation and can provide some shock mitigation. ACI 229 provides a classification system based on the in-service density and typical minimum compressive strengths (ACI 2011) (Table 2.7).

Table 2.7 LD-CLSM Classification by Density and Compressive Strength (ACI 2011)

Class	In-service Density kg/m³ (pcf)	Minimum Compressive Strength MPa (psi)
I	290 to 380 (18 to 24)	0.1 (10)
II	380 to 480 (24 to 30)	0.3 (40)
III	480 to 580 (30 to 36)	0.6 (80)
IV	580 to 670 (36 to 42)	0.8(120)
V	670 to 800 (42to 50)	1.1 (160)
VI	800 to 1300 (50 to 80)	2.2(320)
VII	1300 to 1900 (80 to120)	3.4 (500)

A description of production of LD-CLSM using preformed foam concentrates or gas-forming chemicals mixed with cement paste or mortar is provided in ACI 229 (ACI 2011). These foams are generally the volume producing agents in LD-CLSM mixtures. Pierce and Blackwell (2003) produced a lightweight CLSM with densities ranging from 1200 to 1600 kg/m³ (73 to 98 pcf) using crumb rubber. These LD-CLSM mixtures produced excavatable 28-day compressive strengths ranging from 269 to 1194 kPa (39 to 173 psi) spanning several LD-CLSM categories.

2.5.4 Properties of CLSM

CLSM mixtures must be able to fill a desired void or space without the need for any manual placement effort. Additional properties of both fresh and hardened CLSM are based on the required field performance. These properties include; flowability, bleeding, unit weight, and unconfined compressive strength.

Flowability

Flowability refers to the ability of CLSM to self compact and readily fill voids. This property is one of the major advantages of CLSM in that it enables rapid placement of material without the need for conventional compaction equipment or labor. Flowability is measured using the flow consistency test (ASTM D6103). The test consists of filling an open ended cylinder with CLSM, lifting the cylinder vertically, and then measuring the resulting radial spread. ACI 229 states that good flowability, in regards to the flow consistency test, is obtained at a spread of 200 mm (8 in.) with no visible segregation (ACI 2011).

Bleeding

Bleeding is measured by observation of the bleed water on the surface of a CLSM mixture. Bleed water migrates out of the mixture, and as such is indicative of subsidence. Due to this subsidence, it may be necessary to increase the volume of material placed for a project to ensure the desired finish surface elevation is obtained.

Unit Weight

The unit weight of a CLSM mixture is dependent on the specific gravity and proportions of the components, and on the entrapment of air during mixing. CLSM can be used for a variety of applications, some of which require mixtures with different unit weights (e.g., LD-CLSM). Determining and maintaining consistent unit weight is important when CLSM is placed around structures and conduit or as backfill for retaining walls to properly account for loads during design of the wall. Unit weight is measured by filling a container of known volume with CLSM and recording the weight.

Unconfined Compressive Strength

Unconfined compressive strength is the most commonly specified requirement for CLSM mixtures. Factors that can influence the specified compressive strength include: the application, the likelihood of future excavation, and the magnitude of expected service loads. For a given project a minimum strength, maximum strength, or both may be specified.

2.5.5 Scale of CLSM Projects

The scale of CLSM projects can vary from small volume utility repair work to large scale installation of new utility lines. Several case studies were presented by

Kaneshiro et al. (2004) that demonstrate the variable scale of CLSM projects (Table 2.8).

Table 2.8 Scale of Selected CLSM Projects

Agency	Project Description	Project Size
U.S. Bureau of Reclamation	Reinforced Concrete Pipe Installation	518 km of pipeline
Massachusetts Department of Transportation	Boston Harbor Tunnel and Central Artery Project	2.3 million m ³
Denver Airport	Pipeline Installation	53,500 m ³

2.6 Corrugated Paperboard

Corrugated paperboard consists of two main components: the flat facing called the linerboard and the corrugated (or fluted) interior known as the medium. The liner board and medium are attached with an adhesive. Paper board is cut and folded into a wide variety of corrugate box shapes and styles. Corrugate boxes can be constructed from various combinations of linerboard and medium to achieve the desired properties (Fibre Box Handbook 1999).

Each corrugated paperboard box has a marking containing information about the particular box. This marking is known as the box manufacturer's certificate, and contains information regarding the structural configuration and strength of the particular corrugate used to create the box. An example of a typical certificate is presented in Figure 2.12.

Figure 2.12 Typical Box Manufacturer's Certificate (Shaanxi University 2011)

The structural classification of corrugated paperboard involves characterization of the size of the fluted medium into one of six lettered classifications (A, B, C, D, E, F), and the board style, a description of the number of linerboard and fluted medium sheets used in the construction of the corrugated paperboard. Typical board styles include single face, single wall, double wall, and triple wall (Figure 2.13). Other properties such as the basis weight or grammage, a measure of the weight per area of the corrugate, also are used to classify the corrugated box.

The strength of a corrugate box is dependent on the direction of loading and is characterized using two distinct test methods. The bursting strength measures the strength perpendicular to the plane of the corrugated paperboard sheet and the edge crush strength measures the strength along the axis of the paperboard sheet in the direction of the fluted medium.

Single Face: One medium is glued to one flat sheet of linerboard.

Single Wall: The medium is between two sheets of linerboard. Also known as Double Face.

Double Wall: Threesheets of linerboard with two mediums in between.

Triple Wall: Four sheets of linerboard with three mediums in between.

Figure 2.13 Common Corrugate Paperboard Styles (Fibre Box Association 1999)

2.6.1 Corrugated Paperboard in the MSW Stream

Paper is the largest single contributor to the MSW stream in terms of weight of material generated (USEPA 2010). The composition of the MSW stream generated in 2009 is presented in Figure 2.14.

Figure 2.14 Composition of MSW Stream Generated in 2009 (USEPA 2010)

Within the paper category, corrugated boxes represent the greatest proportion of the generated waste, nearly 40%. A summary of generation, recovery, and disposal quantities for paper products is presented in Figure 2.15.

While corrugated board has a high rate of recovery, it is still the largest contributor to the discarded waste stream for paper and paperboard products. Corrugated board contributes approximately 4.6 million tonnes (5.1 million tons) of waste to the total waste discarded to MSW landfills, which is approximately 3.9% of the total waste discarded in 2009 (USEPA 2010).

Figure 2.15 Summary of Generation, Recovery, and Disposal of Paper and Paperboard Products in 2009 (adapted from USEPA 2010)

Chapter 3: Experimental Test Program

This chapter provides an overview of the materials and testing methods used and the mixtures prepared for each portion of this project. Materials include: corrugated paperboard, bentonite, portland cement, and fly ash. The testing methods, mixture preparation procedures, and mixture summary are separated, and presented according to application.

3.1 Corrugate

Various corrugate box types were considered for use in this project including: standard corrugated boxes, pizza boxes, and waxed agricultural boxes. The standard corrugated box consisted of single walled construction with the common C-flute sized medium. The standard corrugated box was tested in both the virgin (new) condition and after a simulated use cycle. The pizza boxes were tested in new condition and used condition. The pizza boxes were not put through the simulated use cycle because a source of similarly used boxes from a single company was identified. Various waxed corrugate types were tested only in a used state because a source for virgin boxes could not be located. The waxed corrugate was not used in the test program due to difficulty in fiberizing, even though initial material characterization was conducted.

The nomenclature for use conditions is as follows; "new" refers to virgin C-flute corrugate or unused pizza boxes, while "used" refers to post consumer pizza boxes or C-flute corrugated boxes that have been subjected to a simulated use cycle based on the International Safe Transit Association Preshipment Testing Procedures (ISTA 2001).

The simulated use cycle was used to produce C-flute corrugate that had undergone consistent wear and handling. In this cycle, boxes were loaded with a mass of 9.07 kg (20 lbs) to simulate the contents of the package. The loaded box was then dropped from a height of 0.76 m (30 in.) first on a corner, then onto the longest face edge radiating from that corner, followed by dropping on the bottom face, a small side face, and finally on a large side face. Following the drop test, the box was subjected to a random vibration table. The box was set on the bottom face and vibrated for 30 minutes, followed by 10 minutes each on the small side face, large side face, and top face. This was followed by a second drop sequence identical to the first.

The corrugate used was characterized according to Technical Association of the Pulp and Paper Industry (TAPPI) standards. Each box was structurally classified based on flute shape and size as well as the wall structure (single, double, or triple walled container). The results of this classification are summarized in Table 3.1. In addition, several tests were conducted to assess the strength of the boxes in both the virgin and post-consumer state. These tests include the edge crush (TAPPI T839) and burst (TAPPI T810) tests. Additional testing was used to characterize the box basis weight (TAPPI T410) and water absorption (Cobb test, TAPPI T441). The devices used in these tests are presented in Figure 3.1. The average results of each test are presented in Table 3.1, the results for waxed corrugate represent an average of all waxed corrugate types due to the relatively small sample size for individual waxed corrugate types.

Table 3.1 Summary of Corrugate Classification Results

Corrugate Type	Use Condition	Structural Classification	ECT (kN/m)	Burst (kPa)	Water Absorption (g/m ²)		Basis Weigh (g/ m ²)
					Inside Face	Outside Face	
Pizza Box	New	Single Wall E-Flute	6.1	1040	99	90	148.9
	Used	Single Wall E-Flute	6.5	897	82	116	164.5
C-Flute	New	Single Wall E-Flute	6.4	1353	73	83	192.8
	Used	Single Wall E-Flute	5.7	1136	79	99	195.9
Waxed (average)	Used	Varies	13.4	1912	8	8	362.9

a) ACCUCUT II Sample Cutter (2 in.)

b) TMI Monitor/Burst Tester

c) TMI 17-11-49 ECT Test Fixture

d) Messmer Buchel Crush Tester

e) TMI Cobb Test Fixture

Figure 3.1 Corrugate Testing Apparatus

3.1.1 Edge Crush Test

The edge crush test (ECT) is a measure of the compressive strength of the wall of a corrugated board parallel to the fluted medium. The load is reported in units of load per unit length. This test was performed on a representative sample of each corrugate type in accordance with TAPPI T 839. To perform this test a 50.8 mm x 50.8 mm (2 in. x 2 in.) coupon was cut from a sample using a specialized apparatus. These coupons were then inserted into a clamping mechanism (Figure 3.1c) to avoid localized edge failure; a load was then applied parallel to the fluted medium at a rate of 111 ± 22 N/s (25 ± 5 lbs/s) using the apparatus in Figure 3.1 d until a maximum was obtained. Histograms of the data for ECT for all corrugate types are presented in Figure 3.2.

3.1.2 Burst Test

The burst test is a measure of the resistance of corrugated paperboard to rupture under an applied pressure, and is representative of the strength of the corrugated board perpendicular to the direction of the fluted medium. The bursting strength was determined according to TAPPI T810. The test was conducted by positioning a section of a corrugated board over a diaphragm (figure 3.1 b). The diaphragm is then inflated to a pressure ranging from 690 to 4825 kPa (100 to 700 psi) and the pressure at which the board ruptures was recorded. Histograms of the burst strength for each corrugate type are presented in Figure 3.3.

a) Used C-Flute

b) New C-Flute

c) New Pizza Box

d) Used Pizza Box

e) Waxed Corrugate

Figure 3.2 Histograms of Corrugate Edge Crush Strength

a) Used Pizza Box

b) New Pizza Box

c) New C-Flute

d) Used C-Flute

e) Waxed Corrugate

Figure 3.3 Histogram of Corrugate Burst Strength

3.1.3 Grammage

The grammage of a corrugated board provides an indication of the mass of the corrugate per unit area. The basis weight was determined for each corrugate type according to TAPPI T410. The test was carried out by delaminating the linerboard from the medium, environmentally conditioning the components, and then determining the mass of each component. The resulting sum of the mass of the components is then divided by the area of the liner board. The value was reported as the mass per m² (10.75ft²) of corrugate. To assist in the delamination process, waxed corrugate was soaked in warm water to break down some of the adhesive. However, this may have had an effect on the basis weight as some wax may have been removed. The determined values are provided in Table 3.1.

3.1.4 Water Absorption

The water absorption characteristics of the corrugated board were determined according to TAPPI T441, also known as the Cobb Test. This test is used to determine the mass of water absorbed by a section of corrugate covered by 1 ± 0.1 cm of water in a 120 s period. After the 120 s period, the excess water is blotted from the surface. This value does not represent the maximum absorption of the corrugated board. The value of water absorptiveness, or Cobb value, is reported in units of grams of water absorbed per m² within the specified time period.

Several methods were used to strip the wax from the corrugate in an attempt to determine the water absorption as well as enable fiberization of the waxed corrugate. Both chemical and mechanical means were used, in the form of solvents and sand abrasion.

3.2 Bentonite

Three bentonite products manufactured by Baroid Industrial Drilling Products for three distinct applications (slurry walls, directional drilling, and vertical drilling) were used in this project. Characterization of the bentonite included Atterberg limits testing (determined according to ASTM D4318), specific gravity (values obtained from the manufacturer), and free swell testing (conducted according to ASTM D5890). These results are summarized in Table 3.2.

Table 3.2 Properties of Bentonite Materials Used in Testing

Product Name	Engineering Application	Specific Gravity	Liquid Limit	Plastic Limit	Swell Index
Aquagel	Slurry Walls	2.65	539	82	30
Boregel	Directional Drilling	2.50	836	44	43
Quikgel	Vertical Drilling	2.60	709	40	40

3.2.1 Bentonite Slurry Preparation Procedure

All materials were weighed in the dry state prior to mixing in a Waring Blender (Model CB15). Bentonite was stored in sealed buckets to ensure that the bentonite remained in a dry condition. Corrugate was cut into small coupons (1 to 4 in²) to facilitate addition to the blender for pulping. The mixing water was weighed and then conditioned to a pH of approximately 8.5 by adding soda ash. The pH measured with a digital glass electrode pH probe (Mettler Toledo Model MP220).

To prepare the mixtures, water was first added to the blender followed by the corrugate. The blender was run at low speed for two minutes to pulp the corrugate prior to addition of the bentonite. The bentonite was then added and the blender was run on

low setting for an additional 2 minutes in the case of slurry wall applications and 15 minutes in the case of horizontal directional drilling and vertical drilling applications. For select mixtures an additional 3 minutes of blending time was used, beyond the initial pulping and mixing, to determine the effect of extended pulping on the engineering properties of corrugate-bentonite slurry mixtures.

3.2.2 Bentonite Slurry Mixture Proportioning

Slurry mixtures were proportioned to obtain specific baseline values of Marsh funnel viscosity (ASTM D6910) as a primary indicator of slurry performance. Mixtures were prepared at various bentonite contents until the bentonite contents required for a desired viscosity were identified. For slurry wall applications, a Marsh funnel viscosity of 40 seconds was used based on recommendations in the literature. This viscosity was obtained at a bentonite content of 5.5% (by mass) corresponding to 94.5% water. The 5.5% solids content was used as constant solids content throughout this testing program. A summary of the mixtures prepared for this series is presented in Table 3.3.

Table 3.3 Summary of Mixtures Prepared for Slurry Wall Applications Using C-Flute Corrugate

Use Condition	Bentonite (%)	Corrugate (%)	Water (%)
N/A	5	0	95
N/A	5.5	0	94.5
N/A	6	0	94
New	5	0.5	94.5
New	4.5	1	94.5
New	4	1.5	94.5
New	3.5	2	94.5
New	3	2.5	94.5
New	2.5	3	94.5
New	2	3.5	94.5
Used	5	0.5	94.5
Used	4.5	1	94.5
Used	4	1.5	94.5
Used	3.5	2	94.5
Used	3	2.5	94.5
Used	2.5	3	94.5
Used	2	3.5	94.5
Used (extended mix)	5	0.5	94.5
Used (extended mix)	4.5	1	94.5
Used (extended mix)	4	1.5	94.5
Used (extended mix)	3.5	2	94.5
Used (extended mix)	3	2.5	94.5

Mixtures were prepared using Aquagel bentonite. All percentages are on a by mass basis.

Table 3.4 Summary of Mixtures Prepared for Slurry Wall Applications Using Pizza Box Corrugate

Use Condition	Bentonite (%)	Corrugate (%)	Water (%)
New	5	0.5	94.5
New	4.5	1	94.5
New	4	1.5	94.5
New	3.5	2	94.5
New	3	2.5	94.5
New	2.5	3	94.5
New	1.5	4	94.5
Used	5	0.5	94.5
Used	4.5	1	94.5
Used	4	1.5	94.5
Used	3.5	2	94.5
Used	3	2.5	94.5
Used	2.5	3	94.5
Used	1.5	4	94.5
Used	0.5	5	94.5
Used (extended mix)	5	0.5	94.5
Used (extended mix)	4.5	1	94.5
Used (extended mix)	4	1.5	94.5
Used (extended mix)	3.5	2	94.5
Used (extended mix)	3	2.5	94.5

Mixtures were prepared using Aquagel bentonite. All percentages are on a by mass basis.

In testing for directional and vertical drilling, a range of slurry viscosities was targeted based on the recommendations provided in Driscoll (1986) for drilling in various soil types. To determine the required bentonite contents for each target viscosity, a series of mixtures at varying bentonite contents were prepared. The marsh funnel viscosities were then plotted, and the bentonite content at each viscosity was approximated based on observation of the range of behavior demonstrated by all the data (i.e. average of range). The values were rounded to the nearest 0.1%, with the exception of one baseline value, 4.25% bentonite, because a mixture prepared at that solids content provided the desired

viscosity. The graphs for both directional and vertical drilling (Boregel and Quikgel respectively) are presented in Figure 3.4 and 3.5, with vertical lines representing the extrapolated solids contents at which the target viscosities were obtained.

Figure 3.4 Boregel Viscosity as a Function of Bentonite Content for Establishment of Baseline

Figure 3.5 Quikgel Viscosity as a Function of Bentonite Content For Establishment of Baseline

The baseline bentonite contents determined for each desired viscosity were used as total solids contents for the directional and vertical drilling testing programs. Based on these solids contents, mixtures were prepared by incrementally replacing 0.5% of the bentonite by total weight with corrugate. This replacement continued until a mixture was failing the Marsh funnel test either due to clogging or excessively high Marsh funnel viscosity. This was repeated for each of the baseline solids contents and for both directional drilling and vertical drilling applications. A summary of the bentonite mixtures prepared for directional drilling and vertical drilling is presented in Table 3.5.

Table 3.5 Summary of Mixes Prepared for Directional Drilling Applications

	% Bentonite	% Corrugate	Mass Bentonite (g)	Mass Corrugate (g)	Mass Water (g)
4.25% Solids	4.25	0	85	0	1915
	3.75	0.5	75	10	1915
	3.25	1	65	20	1915
	2.75	1.5	55	30	1915
	2.25	2	45	40	1915
	1.75	2.5	35	50	1915
	1.25	3	25	60	1915
4.4% Solids	4.4	0	88	0	1912
	3.9	0.5	78	10	1912
	3.4	1	68	20	1912
	2.9	1.5	58	30	1912
	2.4	2	48	40	1912
	1.9	2.5	38	50	1912
	1.4	3	28	60	1912
4.6% Solids	4.6	0	92	0	1908
	4.1	0.5	82	10	1908
	3.6	1	72	20	1908
	3.1	1.5	62	30	1908
	2.6	2	52	40	1908
4.8% Solids	4.8	0	96	0	1904
	4.3	0.5	86	10	1904
	3.8	1	76	20	1904
	3.3	1.5	66	30	1904
	2.8	2	56	40	1904
	2.3	2.5	46	50	1904
4.9% Solids	4.9	0	98	0	1902
	4.4	0.5	88	10	1902
	3.9	1	78	20	1902
	3.4	1.5	68	30	1902
	2.9	2	58	40	1902
	2.4	2.5	48	50	1902
	1.9	3	38	60	1902

Mixtures were prepared using Boregel bentonite, and used C-flute corrugate. All percentages are on a by mass basis.

Table 3.5 Summary of Mixes Prepared for Vertical Drilling Applications

	% Bentonite	% Corrugate	Mass Bentonite (g)	Mass Corrugate (g)	Mass Water (g)
2.6% Solids	2.6	0	52	0	1948
	2.1	0.5	42	10	1948
	1.6	1	32	20	1948
	1.1	1.5	22	30	1948
	0.6	2	12	40	1948
3.0% Solids	3	0	60	0	1940
	2.5	0.5	50	10	1940
	2	1	40	20	1940
	1.5	1.5	30	30	1940
	1	2	20	40	1940
3.2% Solids	3.2	0	64	0	1936
	2.7	0.5	54	10	1936
	2.2	1	44	20	1936
	1.7	1.5	34	30	1936
3.3% Solids	3.3	0	66	0	1934
	2.8	0.5	56	10	1934
	2.3	1	46	20	1934
	1.8	1.5	36	30	1934
	1.3	2	26	40	1934
	0.8	2.5	16	50	1934
3.4% Solids	3.4	0	68	0	1932
	2.9	0.5	58	10	1932
	2.4	1	48	20	1932
	1.9	1.5	38	30	1932
	1.4	2	28	40	1932

Mixtures were prepared using Quikgel bentonite, and used C-flute corrugate. All percentages are on a by mass basis.

3.3 Bentonite Slurry Testing

Bentonite slurries were tested directly for viscosity and density. In addition, filtrate loss, filter cake formation, and permeability through the filter cake were determined. Some tests (e.g., Marsh Funnel, mud balance density) have procedures in both API (2003) and in ASTM (2010), in these circumstances the ASTM procedures were used as the primary reference.

3.3.1 Viscosity

The viscosity of each test batch was determined using a Marsh funnel according to ASTM D6910 (Figure 3.6). To conduct this test, the Marsh funnel was filled to a known capacity line of 1500 ml and the time for 946 ml (one quart) to drain from the orifice was determined. The test was run three times and the viscosity measurements were averaged.

Test procedures deviated from the ASTM standard, in that the slurries were not poured through the attached funnel screen and were instead poured directly into the funnel. This was done to ensure that corrugate fibers remained in the slurry throughout testing, and were not removed or segregated due to the presence of the funnel screen.

Figure 3.6 Marsh Funnel

3.3.2 Density

The density of each bentonite slurry mix was determined using a mud balance according to ASTM D4380 (Figure 3.7). The mud balance consists of a cup attached to a balance with a sliding counterweight. The cup is filled by pouring the bentonite slurry from the storage vessel, inserting the lid, and then wiping off any excess slurry. The counterweight is then moved until the system is balanced as indicated by the attached bubble level. The device directly indicates a density for the slurry in several units, for the purpose of this research the selected unit was g/cm^3 . The test was conducted using freshly mixed slurry, tested within 10 minutes of mixing.

Figure 3.7 Mud Balance for Measuring Bentonite Slurry Density

3.3.3 Filtrate Loss

The filtrate loss test was conducted according to testing procedures in API RP 13 B (2003) in a low pressure, low temperature filter cell (Figure 3.8). The device consisted of a filter cell, filter paper, and graduated cylinder. A head of 0.69 MPa (100 psi) was applied to the slurry using compressed air and the volume of effluent passing through the filter cell over 30 minutes was measured. The filtration apparatus with stand, graduated cylinder for collection, and compressed air hook up is presented in Figure 3.9.

Figure 3.8 Exploded View of Low Pressure Low Temperature API Filter Cell

Figure 3.9 Low Pressure Low Temperature Filtration Cell

3.3.4 Filter Cake Permeability

The permeability of the filter cake was determined using the same filtration cell used for determining filtrate loss. After determining the filtrate loss, excess slurry was decanted from the cell leaving the filter cake and filter paper intact at the bottom. The cell (Figure 3.9) was then refilled with water and a pressure difference of 0.14 MPa (20 psi) was applied across the filter cake specimen. The volume of effluent was then recorded over a 30 minute period.

The filter cake permeability was calculated using Equation 4.

$$k_c = \frac{t_c}{hA} \left(\frac{dq}{dt} \right) \quad (4)$$

In this equation k_c is the filter cake permeability, t_c is the filter cake thickness, dq/dt is the mass flow rate, h is the pressure head, and A is the area of filtration.

3.3.5 Filter Cake Thickness

The thickness of the filter cake was measured using digital calipers. After permeability testing the filter cake and filter paper were removed from the filter cell and placed on a sheet of glass prior to thickness measurement. Measurements of the filter cake, glass and filter paper combined, as well as just the filter paper and glass were then taken. Three measurements were taken at various locations around the filter cake. The average of the 3 measurements was used to calculate thickness of filter cake. A concentric ring of thicker filter cake formed around the perimeter of the filter cell was observed for most of the tests. In these instances, an average cake thickness along the a line radiating from the center to the edge of the filter cake was approximated visually and the measurement was taken at this location.

3.4 CLSM Materials

CLSM typically consists of cement, fly ash, fine aggregate, and water. High replacements of portland cement with fly ash are commonly used. In this test program, mixtures were prepared at various cement to cementitious materials ratios. In addition, corrugate was used to replace various percentages of the fine aggregate.

3.4.1 Cement

Type II/V Portland cement was used in all CLSM mixtures. Type II/V cement was chosen as it is typical for use in California due to its sulfate resistance. The specific gravity of cement was assumed to be 3.15 (Kosmatka et al. 2002).

3.4.2 Fly Ash

A class F fly ash from the Escalante Fly Ash facility of the Salt River Materials Group was used in this test program. The specific gravity was determined to be 2.19 according to ASTM C188. A summary of the oxide analysis provided by the manufacturer is presented in Table 3.6.

Table 3.6 X-Ray Fluorescence Oxide Analysis of Fly Ash (adapted from Salt River Materials Group mill report)

Oxide	Weight %
Silicon Dioxide, SiO ₂	61.73
Aluminum Oxide, Al ₂ O ₃	24.62
Ferric Oxide, Fe ₂ O ₃	4.36
SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃	90.71
Calcium Oxide, CaO	3.83
Magnesium Oxide, MgO	0.95
Sulfur Trioxide, SO ₃	0.21
Loss on Ignition	0.22
Sodium Oxide, Na ₂ O	0.61
Potassium Oxide, K ₂ O	1.21

3.4.3 Fine Aggregate

The fine aggregate used in CLSM testing was Sisquoc sand acquired from Hanson Aggregate. The specific gravity of the fine aggregate was determined to be 2.56 and the absorption was determined to be 2.1% according to ASTM C128. A sieve analysis was performed according to ASTM C136; the gradation curve is presented in Figure 3.10.

The fine aggregate gradation generally conformed to ASTM C33 requirements; however, there was a slight excess in material passing the #50 sieve (3 mm). Fine aggregate for CLSM generally conformed to ASTM C33 due to availability from ready mix concrete suppliers, but strict conformance are not required according to ACI 229 (2011).

Figure 3.10 Fine Aggregate Gradation Curve

3.5 CLSM Mixture Proportioning

The baseline mixture was based on a mix design specified by the Ohio Department of Transportation (ACI 2011). The cementitious materials content was identical to the Ohio DOT mix design and the fine aggregate content was adjusted to yield 1.0 m³ (1.32 yd³). An air content of 3% was assumed for proportioning the mixtures

based on ACI 211 recommendations (ACI 2011). Adjustments were made to water content based on aggregate absorption and moisture content. Fine aggregate was replaced by corrugate on a weight basis, increasing the mixture yield as the corrugate had a lower specific gravity than the fine aggregate.

To ensure comparability between mixtures with and without corrugate, a minimum water content equal to that of the baseline mix was used. Additional water was made available to obtain a flowability equivalent to that of the baseline. Any additional water demand was recorded to determine actual batched proportions. This is similar to the acceptance criteria for mortar mixtures based on ASTM C109, as well as previous CLSM research conducted by Cheung et al. (2007). For this test program, 21 mixes were prepared. A first round of testing consisted of batches designed to be approximately 0.057 m^3 (2.0 ft^3) in volume, these were termed full scale batches. Additional batches were designed to be approximately 0.014 m^3 (0.5 ft^3) in volume, and were termed small scale batches. Actual batch sizes varied due to the decreased specific gravity of the corrugate. The variations in procedure between each mixture type is described in further detail in section 3.6.1. The CLSM mixtures prepared for the test program are presented in Table 3.7, the values are the "as-prepared" quantities, accounting for differences in unit weight and yield between batches. The mixtures were assigned designations for ease of reference. The number preceding the letter C is the percentage of fine aggregate replaced by corrugate. The number following the hyphen is the cement to cementitious materials ratio expressed as a percentage. For example, mixture 0.5C-65, had 0.5% of the fine aggregate replaced with corrugate and 65% of the cementitious materials was cement (i.e., the remaining 35% was fly ash).

Table 3.7 Summary of CLSM Mixtures Prepared

Mix Designation	Batch Size	Mixture Components in SSD State, kg/m ³ (lbs/yd ³)									
		Cement		Fly Ash		Fine Aggregate		Water		Corrugate	
0C-100	Small Scale	206	(347)	0	(0)	1553	(2613)	295	(497)	0	(0)
0.25C-100	Small Scale	209	(352)	0	(0)	1555	(2616)	223	(376)	4	(7)
0.5C-100	Small Scale	176	(296)	0	(0)	1307	(2199)	376	(632)	6	(11)
1.0C-100	Small Scale	154	(260)	0	(0)	1141	(1919)	432	(727)	11	(19)
2.0C-100	Small Scale	133	(223)	0	(0)	969	(1631)	528	(889)	20	(33)
4.0C-100	Small Scale	99	(166)	0	(0)	717	(1207)	568	(955)	29	(49)
6.0C-100	Small Scale	67	(113)	0	(0)	485	(816)	720	(1211)	30	(50)
0.0C-65	Small Scale	135	(227)	74	(125)	1536	(2584)	312	(525)	0	(0)
0.25C-65	Small Scale	116	(195)	63	(107)	1329	(2235)	194	(326)	3	(6)
0.5C-65	Small Scale	124	(209)	68	(114)	1394	(2346)	271	(456)	7	(12)
1.0C-65	Small Scale	116	(195)	63	(107)	1288	(2167)	302	(508)	13	(22)
2.0C-65	Small Scale	83	(140)	45	(76)	922	(1552)	550	(926)	19	(33)
4.0C-65	Small Scale	67	(113)	37	(62)	731	(1229)	702	(1180)	30	(51)
6.0C-65	Small Scale	51	(86)	27	(46)	547	(920)	812	(1366)	35	(58)
0C-29	Full Scale	58	(98)	145	(244)	1473	(2478)	291	(489)	0	(0)
0.25C-29	Small Scale	64	(108)	156	(262)	1628	(2739)	152	(256)	4	(7)
0.5C-29	Small Scale	61	(103)	148	(248)	1489	(2506)	225	(379)	8	(13)
1.0C-29	Small Scale	52	(87)	125	(211)	1252	(2107)	348	(586)	13	(22)
2.0C-29	Full Scale	45	(75)	111	(187)	1106	(1861)	267	(449)	22	(38)
4.0C-29	Full Scale	36	(60)	88	(149)	861	(1448)	283	(476)	36	(61)
6.0C-29	Full Scale	38	(64)	95	(160)	908	(1527)	341	(574)	58	(97)

SSD is the saturated surface dry state

3.6 CLSM Testing and Preparation Procedures

This section outline the procedures followed for preparing and testing CLSM mixtures. Mixtures were tested in the plastic state for flowability, unit weight, air content, and in the hardened state for compressive strength. Compressive strength specimens were tested at 28 days for all mixtures and at 7, 14, and 28 days for select mixtures.

3.6.1 CLSM Preparation

Initially, all materials were weighed and sealed in buckets to ensure that the moisture content of the materials was kept constant. Corrugate was prepared for addition to mixtures by pulping in the Waring blender (Model CB15) in a similar manner to that used for bentonite slurry testing (Figure 3.11 Waring Blender). The corrugate was allowed to drain by gravity over a fabric mesh to remove some of the excess water. The mass of corrugate and total pulp mass were recorded to determine the effective water content of the pulp. It was expected that some, but not all, of this water became available as free water in the concrete mix. All corrugate was prepared for mixtures less than 48 hours ahead of mixing to minimize the potential for biological degradation.

Figure 3.11 Waring Blender

Materials were prepared in a 0.17 m³ (6 ft³) capacity Multiquip rotary drum mixer (Model MC64PE) for full scale batches and in a Kol Mixal portable mixer (Model M-61-BM) for small scale batches (Figure 3.12). Materials were added in general agreement with the order presented in ACI 229. First, approximately half of the aggregate and approximately 75% of the mix water was added. After mixing for several revolutions, the cementitious materials were added, followed by the remaining aggregates and the balance of the mixing water. In mixtures with corrugate as a partial fine aggregate replacement, the water content of the corrugate was close to, if not in excess of, the baseline water content as a result of the pulping procedure. For these mixtures the corrugate-water mix was added at intervals where water additions are noted in the above procedure. Water was then added to obtain the desired flowability of the CLSM mixture.

Figure 3.12 Mixers Used in Production of CLSM Batches. Rotary Drum Mixer (Left) and Portable Mixer (Right)

3.6.2 Flowability

Flowability of the CLSM mixtures was measured according to ASTM D6103 test method for determining the flow consistency. This test was performed by filling a 75 x 150 mm (3 x 6 in.) cylindrical mold (Figure 3.13) with CLSM and lifting the cylinder vertically, allowing the material to flow out of the bottom of the mold.

The radial spread of the mixture was then measured across two perpendicular diameters. The flowability was reported as the average of the two measurements. For the purpose of this research, a flow consistency of 200 mm (8 in.) was established as the threshold for acceptance based on good flowability as defined in ACI 229. An important attribute of mixtures with good flowability as defined by ACI 229 is that no segregation occurs in the mix. Mixtures were tested for flowability and additional mix water was added to reach the desired flowability as needed. In cases where excessive bleed water (i.e., segregation) was observed to run out from the flow consistency mold, no further

mix water is added and the cylinders were cast. A graphical representation of these criteria is presented in Figure 3.14.

Figure 3.13 Flow Consistency Mold with Bleed Water Exiting Bottom

Figure 3.14 Schematic of Acceptance Criteria for CLSM

3.6.3 Bleeding

Bleeding was observed and evaluated qualitatively after the procedure used by Cheung (2007). Bleeding was considered excessive if substantial bleed water was observed during or immediately following placement. Severe bleeding refers to substantial bleed water observed in the 20 minutes following placement. Moderate or minor bleeding refers to small amounts of bleeding that is not likely to affect the properties of the CLSM.

3.6.4 Air Content

The air content was determined using a pressure meter according to ASTM C231. This method was chosen because the uncertainty in the amount of water absorbed by the

corrugate prevented an accurate gravimetric determination of air content. The pressure meter is presented in Figure 3.15. The device consists of a 7.1 L (0.25 ft³) measure, an air tight lid, a hand operated pump, and a pressure gage.

Figure 3.15 Pressure Meter Components

3.6.5 Unit Weight

The unit weight of each test batch was determined according to ASTM D6023. The mass of concrete required to fill a measure of known volume was determined. The measure used was the same container used for determination of the air content as described above.

3.6.6 Compressive Strength

After preparing CLSM mixtures and conducting tests on the fresh properties of the mixtures, 300 x 600 mm (6 x 12 in.) cylinders were prepared in general accordance with ASTM D4832. Duplicate specimens were prepared for testing at 7, 14, and 28 day ages for each full scale batch. For small scale batches cylinders were prepared for testing at only 28 days. Cylinders were demolded by cutting the mold away from the specimen. Some specimens were not tested because they were weak and experienced damage during the demolding process; no compressive strength test results are available for these specimens.

Following removal from the molds, the specimens were capped with Hydrostone plaster cast against a plate of glass to provide a smooth bearing surface (Figure 3.16). Once the plaster hardened the specimens were rotated and a cap was created on the other end. Plaster was selected as the capping material to avoid damaging specimens, as can occur when using a sulfur capping compound with very weak specimens.

Compression tests were conducted in general agreement with ASTM C39, on a Satec universal testing frame (Model UTC 300HVL). The samples were loaded at a rate of 104 kPa/s (15 psi/s).

Figure 3.16 Capping Cylinders with Hydrostone Plaster

Chapter 4: Results and Discussion

The results of the experimental test program are presented in this chapter. Analyses were conducted to investigate engineering properties, effects of variable corrugate replacement rates, and economic implications.

The testing programs for each of the bentonite applications were conducted in a similar manner. Bentonite slurry mixtures with corrugate replacements were compared to baseline mixtures. The properties determined for bentonite slurry mixtures were Marsh funnel viscosity, density, filtrate loss, filter cake permeability, and filter cake thickness.

The CLSM mixtures were tested for flow consistency, unit weight, air content, and compressive strength. The results from mixtures containing corrugate are compared to baseline mixtures. The unit cost of each mixture is also presented.

4.1 Slurry Cut-Off Walls

Results for Marsh funnel viscosity, density, filtrate loss, filter cake permeability, and filter cake thickness tests are presented in Table 4.1 for C- flute corrugate and in Table 4.2 for corrugated pizza box.

Mixtures are designated by the following nomenclature. The first letter is designates the use condition of the corrugate the letter N signifies the use of corrugate in the new condition and U signifies corrugate in the used condition. The number represents the corrugate content in percent by mass. The second letter designates the corrugate type, C denotes C-flute corrugate, P denotes corrugated pizza box. B denotes a 100% bentonite baseline mixture, the number for baseline mixtures represents the bentonite content. The symbol “(+)” denotes extended mixing time. NM indicates that a value was not obtained.

Table 4.1 Summary of Test Results for Slurry Wall Application Using C-Flute Corrugate

Mixture Designation	Marsh Funnel Viscosity (s)	Density (kg/m³)	Filtrate Loss (mL)	Cake Thickness (mm)	Hydraulic Conductivity ÷ Thickness (s⁻¹)	Hydraulic Conductivity (cm/s)
B5.0	38	1030	19	2.4	4.68E-08	1.12E-08
B5.5	40	1030	16	2.7	4.89E-08	1.33E-08
B6.0	49	1035	14	1.8	3.24E-08	5.93E-09
N0.5-C	42	1025	19	3.8	4.20E-08	1.58E-08
N1.0-C	42	1010	17	3.1	4.74E-08	1.46E-08
N1.5-C	47	1010	22.8	3.2	4.30E-08	1.36E-08
N2.0-C	57	1010	26.3	4.8	5.14E-08	2.48E-08
N2.5-C	NM	1015	32.8	8.3	4.71E-08	3.91E-08
N3.0-C	NM	1010	39.8	10.8	6.92E-08	7.48E-08
U0.5-C	47	1025	20.6	3.2	3.80E-08	1.22E-08
U1.0-C	50	1020	20.1	3.5	4.38E-08	1.53E-08
U1.5-C	53	1010	21.6	3.6	3.72E-08	1.36E-08
U2.0-C	58	1010	26.2	4.2	5.02E-08	2.09E-08
U2.5-C	NM	1015	32.1	9.1	6.53E-08	5.92E-08
U3.0-C	NM	1015	36	11.0	8.00E-08	8.83E-08
U0.5-C(+)	46	1025	19	4.0	3.75E-08	1.49E-08
U1.0-C(+)	49	1015	20.7	3.0	4.08E-08	1.23E-08
U1.5-C(+)	49	1010	19.6	3.7	3.41E-08	1.26E-08
U2.0-C(+)	57	1010	25	5.5	4.25E-08	2.33E-08
U2.5-C(+)	79	1010	27.8	5.1	3.42E-08	1.74E-08
U3.0-C(+)	NM	1005	32.9	11.4	4.90E-08	5.58E-08

Table 4.2 Summary of Test Results for Slurry Wall Application Using Corrugated Pizza Box

Mixture Designation	Marsh Funnel Viscosity (s)	Density (kg/m³)	Filtrate Loss (mL)	Cake Thickness (mm)	Hydraulic Conductivity ÷ Thickness (s⁻¹)	Hydraulic Conductivity (cm/s)
B5.0	38	1030	19	2.4	4.68E-08	1.12E-08
B5.5	40	1030	16	2.7	4.89E-08	1.33E-08
B6.0	49	1035	14	1.8	3.24E-08	5.93E-09
N0.5-P	44	1025	18.8	3.2	4.27E-08	1.35E-08
N1.0-P	48	1020	20.1	4.0	4.07E-08	1.62E-08
N1.5-P	49	1015	22.6	4.1	4.38E-08	1.80E-08
N2.0-P	56	1010	24.6	5.7	4.80E-08	2.73E-08
N2.5-P	NM	1010	31	8.0	6.19E-08	4.89E-08
N3.0-P	NM	1010	33.6	10.5	7.48E-08	7.83E-08
U0.5-P	46	1025	20.1	3.1	4.13E-08	1.27E-08
U1.0-P	47	1020	21.1	3.4	4.02E-08	1.35E-08
U1.5-P	52	1010	23.2	4.4	4.61E-08	2.03E-08
U2.0-P	55	1010	24.6	6.2	3.22E-08	1.98E-08
U2.5-P	70	1015	28.7	8.2	4.37E-08	3.58E-08
U3.0-P	NM	1015	34.3	6.2	4.83E-08	3.00E-08
U0.5-P(+)	39	1025	16.8	2.2	3.44E-08	7.60E-09
U1.0-P(+)	39	1020	17.5	1.5	3.55E-08	5.23E-09
U1.5-P(+)	41	1010	18.8	2.7	3.65E-08	9.91E-09
U2.0-P(+)	48	1000	24	4.0	4.82E-08	1.93E-08
U2.5-P(+)	65	1015	30.2	8.0	6.96E-08	5.54E-08
U3.0-P(+)	NM	1015	31	10.7	7.66E-08	8.17E-08

4.1.1 Marsh Funnel Viscosity

The effects of corrugate type and corrugate content on the Marsh funnel viscosity were measured throughout the testing program. In general, as corrugate content increased, Marsh funnel viscosity increased as presented in Table 4.1 and 4.2. This was attributed to an interlocking of corrugate fibers, resulting in increased viscosity and eventually bridging or clogging of the funnel orifice at higher corrugate contents.

Effect of Corrugate Type

No significant difference was observed between the performances of C-flute or pizza box corrugate. Slurry mixtures prepared with corrugate with a given use condition (e.g., new pizza box corrugate and new C-flute corrugate) had Marsh funnel viscosities that were consistent across a majority of corrugate contents. This indicated that the corrugate type did not have a significant impact on the Marsh Funnel viscosity, for the tested variables. The results for mixtures prepared using corrugate in the new condition are presented in Figure 4.1 and those prepared using corrugate in the used condition are presented in Figure 4.2.

Figure 4.1 Marsh Funnel Viscosities for New Condition

Figure 4.2 Marsh Funnel Viscosities for Used Condition

Effect of Use Condition

While similar Marsh Funnel Viscosities were observed for slurries prepared with C-flute and pizza box corrugate for the same use condition, the observed Marsh funnel viscosities for different use conditions is considerably different. The C-flute corrugate subjected to the simulated use cycle shows a marked increase in Marsh funnel viscosities compared with the new material (Figure 4.3).

Figure 4.3 Marsh Funnel Viscosity for C-flute

The increase in viscosity due to wear was not observed for the pizza box corrugate. The pizza box corrugate exhibited no significant difference in viscosity between the new and used condition (Figure 4.4).

Figure 4.4 Marsh Funnel Viscosity for Pizza Box

The difference in the response of the C-flute compared to the pizza box corrugate to changes in use condition is likely due to the difference in the degree of wear experienced in a use cycle. The pizza boxes experienced only light wear, from transit and disposal. The simulated use cycle exposed the C-flute to more severe conditions. Because of this discrepancy in use intensity, the used and new pizza boxes are likely to be in closer wear condition than the new and used C-flute boxes.

Effect of Pulping Time

Several mixtures were prepared using both C-flute and pizza box corrugate to examine the effects of extended pulping periods on the properties of the slurry. These mixes were subjected to 3 minutes of extended pulping in the blender prior to testing. The C-flute corrugate was unaffected by extended mixing time, while the pizza box corrugate exhibited a considerable decrease in viscosity (Figure 4.5 and Figure 4.6).

Figure 4.5 Marsh Funnel Viscosities for Extended Pulping Time for C-Flute Corrugate

Figure 4.6 Marsh Funnel Viscosities for Extended Pulping Time for Pizza Box

The difference in behavior between mixtures prepared with the extended mixing time and those prepared using the standard mixing time was again attributed to the difference in use intensity. Because of the relatively low intensity of use, the used pizza box was much closer to the new condition than the used C-flute. Because the simulated use cycle subjected the C-flute to more intense use, the boxes were likely to have experienced some degradation. Due to the lighter use, the used pizza boxes likely experienced greater additional degradation from extended pulping than the used C-flute corrugate, which had already experienced significant degradation during use.

Effect of High Corrugate Content

Some tests were conducted at high corrugate contents, with more than 50% of the bentonite being replaced (i.e., 2.5% to 4% corrugate content in a 5.5% bentonite baseline mixture). These mixtures were significantly more viscous than mixes prepared at lower corrugate content. These mixes were either unable to pass through the opening in the Marsh funnel due to plugging, or required a much greater time to pass. This behavior was attributed to the presence of an interlocking matrix of fibers. Grab samples were taken from selected slurry mixtures for visual examination. An increase in fiber interlocking and clumping was observed as the corrugate content increased. Photographs of selected mixtures are presented in

Figure 4.7 Consistency of Slurry Samples from Various Mixtures

Engineering Acceptability

A slurry mixture was deemed to have acceptable Marsh funnel viscosity if the value was less than 50 seconds, the value that was determined for the 5.5% baseline bentonite-water slurry mixture. The application of these criteria to the Marsh funnel

viscosity data is presented graphically in Figure 4.8. The shaded zone indicates unacceptable mixtures.

Figure 4.8 Marsh Funnel Viscosity with Acceptance Criteria

Mixtures prepared with both pizza box corrugate and C-flute corrugate in any use condition produced acceptable marsh funnel viscosities at bentonite replacement ratios up to 18%, (i.e., 1% corrugate content for a 5.5% bentonite baseline). In addition, mixtures prepared with C-flute corrugate or pizza boxes in the new condition were acceptable to 27% bentonite replacement ratio, at 1.5% corrugate content.

4.1.2 Slurry Density

The density of the bentonite slurries generally decreased with increasing corrugate content. The lower densities resulted from the lower specific gravity of corrugated paperboard compared to that of bentonite. This trend is illustrated in Figure 4.9. No individual corrugate related factor (i.e., corrugate type or use condition) was determined to have a significant effect on the general trend observed. A minimum density of 1010 kg/m³ was used for this investigation. This minimum density was observed to be a lower limit for the density of bentonite slurries containing corrugate and Aquagel bentonite.

Figure 4.9 Density of Slurry as a Function of Corrugate Content with Acceptance Criteria

Engineering Acceptability

To maintain trench stability slurry must have sufficient density to resist the hydrostatic pressure associated with pore fluids in the soil (i.e., groundwater table). In addition, if a low permeability barrier is to be produced, the slurry density must be greater than that of water such that the slurry remains in the trench and is not displaced by groundwater. Slurries with densities less than that of water would allow groundwater to displace the slurry from the trench. An acceptable lower limit of 1010 kg/m^3 was chosen based on recommendations by the USEPA (1984). The test program demonstrated that all mixtures prepared were within the acceptable limits (Figure 4.9).

4.1.3 Filtrate Loss

Filtrate loss is a measure of the fluid lost to the soil strata during filter cake formation. As filtrate loss increases, additional drilling fluid needs to be added to compensate for this fluid loss. A general trend of increasing filtrate loss with increasing corrugate content was observed in the test program. This trend was consistent between use conditions as well as between corrugate types.

The increase in filtrate loss may have occurred due to a decrease in the clogging of the filter when bentonite was replaced with corrugate. The corrugate may permit greater flow to the filter paper compared to the bentonite fraction. In addition, preferred flow paths may form through the filter cake, along interconnected regions of corrugate fibers.

Engineering Acceptability

An upper limit of 30 mL of filtrate loss was established based on the study reported by Rad et al. (1995). This upper bound limits the amount of additional slurry

required to account for fluid lost to the formation in which the trench is constructed. The control of fluid loss is required to ensure that a project remains economically feasible. As presented in Figure 4.10, mixes within acceptable ranges (unshaded area) for filtrate loss were prepared at up to 2% corrugate content in a 5.5% bentonite baseline mixture (replacement of 36% of bentonite) for all mixtures and up to 2.5% corrugate content in a 5.5% bentonite baseline mixture (replacement of 45% of bentonite) for used pizza box.

Figure 4.10 Filtrate Loss as a Function of Corrugate Content with Acceptance Criteria

4.1.4 Filter Cake Permeability

The results of the filter cake permeability testing are shown in Figure 4.11. The permeability of the bentonite-corrugate mixtures did not vary significantly at low bentonite replacements. From 0 to 1.5% corrugate content the trend was nearly a

horizontal line, whereas an increase in permeability occurred at corrugate contents greater than 1.5% and a sharp increase occurred at corrugate contents greater than 2%. The presence of this trend indicated that there is a critical bentonite content required to maintain permeability lower than 2×10^{-8} cm/s. The increase in filter cake permeability at corrugate contents higher than 1.5% can be attributed to formation of preferential flow paths through the filter cake. As corrugate comprised more of the mixture volume, the likelihood of developing a continuous path of adjacent corrugate fiber through the filter cake increases.

Figure 4.11 Filter Cake Permeability as a Function of Corrugate Content

Engineering Applicability

No permeability acceptance criterion has been selected for this test program. It is more important to note the trend of a significant increase in permeability at higher

bentonite replacements. The permeability requirements vary on a site by site basis and are determined by the local geologic conditions, the wall configuration, and the specific application. Additionally, most slurry wall systems involve backfilling the trench and displacing the bentonite slurry. This leaves only the filter cake on the walls. The resulting permeability is a function of both the filter cake permeability and the backfill permeability.

4.1.5 Economic Considerations

The cost for a unit volume of slurry was determined for each mixture based on the yielded volumes. The cost of the bentonite was assumed to be \$284 per 1000 kg (Preferred Water Pump and Equipment 2011) and \$200 per 1000 kg for the corrugate (Apodaca 2011). Due to a decrease in mixture density as the result of corrugate addition the yielded volume for mixtures containing corrugate increased. The unit cost decreased with increasing corrugate content, due to an increase in yielded volume. The unit cost of mixtures normalized by the unit cost of the baseline mixtures is presented in Figure 4.12 Normalized Cost of Slurry Mixtures for Slurry Trench Applications, all mixtures containing corrugate had a decreased unit cost compared to baseline mixtures. Acceptable mixtures were prepared with up to an approximate 10% cost reduction for new C-Flute and pizza box corrugate, and up to an approximate 7% cost reduction for used C-flute and pizza box corrugate.

Figure 4.12 Normalized Cost of Slurry Mixtures for Slurry Trench Applications

4.2 Drilling Fluid for Directional Drilling Applications

Bentonite slurry mixtures were prepared using Boregel bentonite, at total solids contents ranging from 4.25% to 4.9%. These solids contents were chosen by incrementally increasing bentonite content of baseline mixtures to obtain Marsh funnel viscosities suitable for directional drilling through different native soil deposits. Used C-flute corrugate was used to replace up to 71% of the bentonite. Marsh funnel viscosity, density, filtrate loss, and permeability were determined for each mixture. The results are summarized in Table 4.3.

Table 4.3 Summary of Test Results for Drilling Fluids for Directional Drilling

	% Bentonite	% Corrugate	Marsh Funnel Viscosity (s)	Density (g/cm ³)	Filtrate Loss (mL)	Filter Cake Permeability (cm/s)	Filter Cake Thickness (cm)
4.25% Solids Baseline	4.25	0	41	1.02	13.6	8.8x10 ⁻⁰⁹	0.15
	3.75	0.5	38	1.01	13.8	9.7 x10 ⁻⁰⁹	0.19
	3.25	1	37	1.01	17	1.5 x10 ⁻⁰⁸	0.21
	2.75	1.5	38	0.98	18.4	9.0 x10 ⁻⁰⁹	0.24
	2.25	2	43	0.97	24.4	1.5 x10 ⁻⁰⁸	0.43
	1.75	2.5	62	0.96	30	9.3 x10 ⁻⁰⁸	0.67
	1.25	3	N/A	0.97	29	6.6 x10 ⁻⁰⁹	0.16
4.4% Solids Baseline	4.4	0	50	1.02	11.9	1.0 x10 ⁻⁰⁸	0.15
	3.9	0.5	41	1.01	14.5	1.0 x10 ⁻⁰⁸	0.17
	3.4	1	39	1.00	15.1	7.8 x10 ⁻⁰⁹	0.24
	2.9	1.5	41	1.00	17.5	1.3 x10 ⁻⁰⁸	0.26
	2.4	2	43	0.98	22.6	3.3 x10 ⁻⁰⁸	0.33
	1.9	2.5	59	0.98	24.2	2.4 x10 ⁻⁰⁸	0.39
	1.4	3	N/A	0.96	29	3.6 x10 ⁻⁰⁸	0.25
4.6% Solids Baseline	4.6	0	62	1.03	12.6	1.7 x10 ⁻⁰⁸	0.19
	4.1	0.5	45	1.02	15	1.4 x10 ⁻⁰⁸	0.23
	3.6	1	44	1.01	16.8	2.6 x10 ⁻⁰⁸	0.27
	3.1	1.5	41	1.00	20.5	1.8 x10 ⁻⁰⁸	0.43
	2.6	2	N/A	0.99	19.6	1.4 x10 ⁻⁰⁸	0.16
4.8% Solids Baseline	4.8	0	68	1.03	11.8	1.8 x10 ⁻⁰⁸	0.26
	4.3	0.5	43	1.01	14.6	1.1 x10 ⁻⁰⁸	0.16
	3.8	1	43	1.01	14.3	1.4 x10 ⁻⁰⁸	0.22
	3.3	1.5	44	1.00	17.6	3.3 x10 ⁻⁰⁸	0.41
	2.8	2	56	0.99	17.6	1.6 x10 ⁻⁰⁸	0.20
	2.3	2.5	N/A	0.98	19.9	1.4 x10 ⁻⁰⁸	0.15
4.9% Solids Baseline	4.9	0	79	1.03	13.2	1.1 x10 ⁻⁰⁸	0.21
	4.4	0.5	43	1.01	15.2	1.5 x10 ⁻⁰⁸	0.20
	3.9	1	44	1.01	15.8	6.5 x10 ⁻⁰⁹	0.25
	3.4	1.5	47	1.00	17.1	9.6 x10 ⁻⁰⁹	0.35
	2.9	2	57	1.00	14.5	1.1 x10 ⁻⁰⁸	0.37
	2.4	2.5	73	0.99	19	2.8 x10 ⁻⁰⁸	0.62
	1.9	3	N/A	0.99	20.4	6.7 x10 ⁻⁰⁹	0.17

4.2.1 Marsh Funnel Viscosity

The results of Marsh funnel viscosity testing for drilling fluids for directional drilling are presented in Figure 4.13 and Figure 4.14 as a function of corrugate and bentonite content, respectively. The viscosity of the drilling fluid mixtures initially decreased with increasing corrugate content, followed by an increase in viscosity at corrugate contents higher than 1%. This trend was attributed to a disruption in the viscosity building mechanism of the polymer-modified bentonite. The corrugate fibers may have prevented interaction of polymer chains. At higher replacements, the corrugate fibers themselves may have dispersed in the slurry due to the decrease in bentonite content, these fibers may have then flocculated and bridged in the funnel orifice creating a higher retention time in the Marsh funnel.

Figure 4.13 Marsh Funnel Viscosity as a Function of Corrugate Content for Directional Drilling Applications

Mixtures with a range of corrugate contents (0.5 to 1.5%) yielded Marsh funnel viscosities of approximately 40 seconds. This may indicate a lower limit to the viscosity that can be obtained with this particular bentonite in slurries containing corrugate.

An increase in Marsh funnel viscosity was observed for both low and high bentonite contents. Data points near the low range of bentonite content (and therefore higher corrugate content) showed higher viscosities due to an interlocking fibrous network of corrugate fibers, whereas the mixtures at the high range of bentonite content (above 4.4%) contained only bentonite and exhibited higher viscosities due to increased bentonite content alone.

Figure 4.14 Variation of Marsh Funnel Viscosity as a Function Bentonite Content for Directional Drilling Applications (triangles denote baseline mixtures)

If the plots of Marsh funnel viscosity versus bentonite content are normalized based on the bentonite fraction of the solids (mass of bentonite divided by total solids

mass), a clear trend of decreasing Marsh funnel viscosity with increasing normalized bentonite content is observed (Figure 4.15). As an increasing fraction of bentonite was replaced by corrugate the viscosity increased. The large spread of data at a bentonite to total solids ratio of 1 represents the data from all baseline mixtures. A Marsh Funnel viscosity of approximately 40 seconds was obtained for normalized bentonite contents ranging between approximately 0.65 and 0.9. This range corresponded to the grouping of data around 40 seconds as seen in Figure 4.13 and 4.15. In addition, the range of data was larger at lower normalized bentonite contents, indicating that as corrugate content increased the mixture variability also increased.

Figure 4.15 Marsh Funnel Viscosity as a Function of Normalized Bentonite Content for Directional Drilling Applications

The total solids content was determined to be a poor indicator of funnel viscosity, as presented in Figure 4.16. A slight trend of increasing viscosity at higher solids content

was observed. However, the large range of viscosities obtained at a given solids content renders solids content unsuitable for use as a predictor of Marsh Funnel viscosity due to the significant difference in engineering performance between bentonite and corrugated board.

Figure 4.16 Variation in Marsh Funnel Viscosity as a Function of Total Solids Content for Directional Drilling Applications

The Marsh funnel viscosity was dependent on both bentonite content and corrugate content. A three dimensional plot of Marsh funnel viscosity with respect to bentonite content and corrugate content is presented in Figure 4.17. The plot shows a trend represented by a “half saddle” shape with curves emanating off a central spine.

Figure 4.17 Three Dimensional Plot of Marsh Funnel Viscosity with Respect to Bentonite Content and Corrugate Content

The results of the tests on various total solids contents are presented in Figure 4.18. Each of these series presented in of mixtured Figure 4.18 individually exhibited a

similar trend to that presented for all data points. By viewing each series individually, it was noted that the pure bentonite-water slurry mixtures often had higher viscosities than those containing corrugate. Figure 4.18c does not exhibit this trend. The variation in the trend is explained by this mixture series reaching failure due to clogging of the Marsh Funnel at higher bentonite replacements.

Figure 4.18 Marsh Funnel Viscosity as a Function of Bentonite Fraction of Total Solids for Various Total Solids Contents for Directional Drilling Applications

4.2.2 Density

The density of the bentonite slurry mixtures decreased as corrugate content increased. The densities ranged from 0.960 g/cm³ at 3% corrugate to 1.030 g/cm³ at 0% corrugate. The results from the mud balance tests for density are presented in Figure 4.19 and 4.20 as a function of corrugate content and bentonite content, respectively.

The density was affected by the addition of corrugate to the mixture. However a fairly large corrugate content was needed to affect a modest decrease in density. For the series of mixtures associated with each baseline bentonite content, the maximum decrease in density was between 3.4% and 5.9%. The spread of data was higher at corrugate contents greater than or equal to 1.5%. This was attributed to regions of segregation of bentonite and corrugate present in the mixtures.

Figure 4.19 Drilling Fluid Density as a Function of Corrugate Content for Directional Drilling Applications

Figure 4.20 Drilling Fluid Density as a Function of Bentonite Content for Directional Drilling Applications

4.2.3 Filtrate Loss

The results from filtrate loss tests on the drilling fluid mixtures are presented with respect to bentonite content and corrugate content (Figures 4.21 and 4.22). There was a decrease in filtrate loss with increasing bentonite content, and an increase in filtrate loss with increased corrugate content. In addition, the variability in the filtrate loss increases with increasing corrugate content. The total solids content of the mixture did not correlate well with the filtrate loss. The absence of a correlation to total solids content was explained by the total solids being a combination of both the corrugate and the bentonite. The individual trends for increasing bentonite solids and increasing corrugate solids were reversed from one another.

Filtrate loss as a function of time was examined for selected mixtures (Figure 4.23). The filtrate loss demonstrated a faster rate of increase initially, with a tapering as time progressed.

Figure 4.23 Filtrate Loss as a Function of Time for Directional Drilling Applications

The normalized filtrate loss (Figure 4.24), defined as the filtrate loss for a mixture divided by the filtrate loss of the control mixture, was nearly constant for all time steps. The data points at one minute are a notable exception, demonstrating a lower normalized filtrate loss than at other time steps for the same mixtures. This can be attributed to the data point at 1 minute being measured before the full formation of the filter cake. As corrugate content increased the factor by which the normalized filtrate loss is scaled increased.

Figure 4.24 Normalized Filtrate Loss as a Function of Time for Directional Drilling Applications

4.2.4 Filter Cake Permeability

The permeability of the filter cake for the slurry mixtures tested for directional drilling applications ranged from 6.50×10^{-9} cm/s to 3.60×10^{-8} cm/s. No trend was observed for the permeability of these mixtures as a function of corrugate content, bentonite content, or total solids content. Nearly all of the values fall within one order of magnitude of each other (Figure 4.25).

Figure 4.25 Filter Cake Permeability as a function of Bentonite Content for Directional Drilling Applications

4.2.5 Economic Considerations

The cost for a unit volume of drilling fluid was determined for each mixture based on the yielded volumes. The cost of the bentonite was assumed to be \$537 per 1000 kg (Preferred Water Pump and Equipment 2011) and \$200 per 1000 kg for the corrugate (Apodaca 2011). Due to a decrease in mixture density as the result of corrugate addition, the yielded volume for mixtures containing corrugate increased. The unit cost decreased with increasing corrugate content due to an increase in yielded volume. The unit cost of mixtures normalized by the unit cost of the baseline mixtures is presented in Figure 4.26. All mixtures containing corrugate had a decreased unit cost compared to baseline mixtures. Acceptable mixtures were prepared in the test program with up to a 41% cost reduction.

Figure 4.26 Normalized Unit Cost of Mixtures for Directional Drilling Applications

4.2.6 Engineering Acceptability

For directional drilling applications, the fluid flow characteristics (e.g., circulation rate and uphole velocity) and the drilling fluid properties (e.g., viscosity and density) are equally important in determining the effectiveness as a drilling fluid. Due to the temporary nature of the boreholes used for directional drilling the filtrate loss and permeability are not considered critical parameters in regards to the engineering acceptability. The governing engineering properties for directional drilling are dependent on the inclination of the borehole. For boreholes that are shallower than 45 degrees from vertical, turbulent flow is desired, whereas for boreholes angled steeper than 45 degrees from vertical laminar flow is desired. The engineering acceptability of the prepared

mixtures is separated into cases as a function of required flow conditions (turbulent or laminar flow).

For cases where turbulent flow is preferred, a relatively low kinematic viscosity is desired. Kinematic viscosity is decreased by increasing the fluid density or by decreasing the dynamic viscosity. Due to the small variation in the density (a maximum decrease of 5.9% occurred for corrugate replacement of approximately 60% of the bentonite), the governing property is the dynamic viscosity. Therefore, the Marsh funnel viscosity is used as an indicator of the performance of mixtures for turbulent flow conditions.

As corrugate content increased, the Marsh funnel viscosity of the drilling fluids decreased to a point and then increased as presented in Figure 4.27. The criterion for acceptability was a viscosity decrease compared to baseline conditions, the acceptable mixtures with associated normalized unit costs are presented in Table 4.4 .

Figure 4.27 Marsh Funnel Viscosity as a Function of Corrugate Content for Directional Drilling Applications

Table 4.4 Acceptable Mixtures Based on Turbulent Flow Criteria

Baseline Series	Bentonite Content (%)	Corrugate Content (%)	Normalized Unit Cost (%)
4.25% Total Solids	3.75	0.5	92
	3.25	1	84
	2.75	1.5	74
4.40% Total Solids	3.9	0.5	92
	3.4	1	84
	2.9	1.5	77
	2.4	2	68
4.60% Total Solids	4.1	0.5	92
	3.6	1	85
	3.1	1.5	77
4.80% Total Solids	4.3	0.5	92
	3.8	1	85
	3.3	1.5	78
	2.8	2	71
4.90% Total Solids	4.4	0.5	92
	3.9	1	85
	3.4	1.5	79
	2.9	2	72
	2.4	2.5	65

For borehole orientations steeper than 45 degrees from horizontal the evaluation criteria are similar to the criteria for vertical borings. These mixtures did not meet some of the FHWA recommended properties for drilling fluid (density and filtrate loss) used in vertical drilling.

The engineering acceptability of mixtures not meeting the FHWA recommendation for density was established assuming that a weighting additive for drilling fluids, such as barite, can be used to increase the density of the mixtures to acceptable limits. Filtrate loss limits are a function of economic considerations more than

engineering considerations and as such failures of mixtures due to filtrate loss have not been considered for establishing engineering acceptability.

The Marsh funnel viscosity of the mixtures decreased at low corrugate contents, however at higher corrugate contents the Marsh funnel viscosity increased, to a point of exceeding the baseline value for some mixtures. These changes in viscosity influence the soil formation types in which a mixture can be used. The Marsh funnel viscosities and corresponding suitable formation types are presented in Table 4.5.

In order for slurry mixtures to be economically feasible, a reduction in the use of bentonite compared to the baseline mixture is required for use in a given soil formation type. The acceptable mixtures for use in various soil formation types and the normalized unit cost for acceptable mixtures are summarized in Table 4.6. Mixtures with acceptable engineering properties were prepared with up to 41% reduction in unit cost.

Table 4.5 Summary of Marsh Funnel Viscosities and Corresponding Suitable Formation Types

	% Bentonite	% Corrugate	Marsh Funnel (s)	Suitable Soil Formation
4.25% Solids Baseline	4.25	0	41	Fine Sand
	3.75	0.5	38	Fine Sand
	3.25	1	37	Fine Sand
	2.75	1.5	38	Fine Sand
	2.25	2	43	Fine Sand
	1.75	2.5	62	Coarse Sand
	1.25	3	N/A	Not Suitable
4.4% Solids Baseline	4.4	0	50	Medium Sand
	3.9	0.5	41	Fine Sand
	3.4	1	39	Fine Sand
	2.9	1.5	41	Fine Sand
	2.4	2	43	Fine Sand
	1.9	2.5	59	Coarse Sand
	1.4	3	N/A	Not Suitable
4.6% Solids Baseline	4.6	0	62	Coarse Sand
	4.1	0.5	45	Fine Sand
	3.6	1	44	Fine Sand
	3.1	1.5	41	Fine Sand
	2.6	2	N/A	Not Suitable
4.8% Solids Baseline	4.8	0	68	Gravel
	4.3	0.5	43	Fine Sand
	3.8	1	43	Fine Sand
	3.3	1.5	44	Fine Sand
	2.8	2	56	Coarse Sand
	2.3	2.5	N/A	Not Suitable
4.9% Solids Baseline	4.9	0	79	Coarse Gravel
	4.4	0.5	43	Fine Sand
	3.9	1	44	Fine Sand
	3.4	1.5	47	Medium Sand
	2.9	2	57	Coarse Sand
	2.4	2.5	73	Gravel
	1.9	3	N/A	Not Suitable

Table 4.6 Summary of Acceptable Mixtures for Laminar Flow Criteria

Soil Formation (Associated Bentonite Baseline)	Bentonite Content (%)	Corrugate Content (%)	Normalized Unit Cost (%)
Fine Sand (4.25% Bentonite Baseline)	3.75	0.5	92
	3.25	1	84
	2.75	1.5	74
	2.25	2	67
	3.9	0.5	92
	3.4	1	84
	2.9	1.5	77
	2.4	2	68
	4.1	0.5	92
	3.6	1	85
	3.1	1.5	77
	3.8	1	85
	3.3	1.5	78
	2.8	2.1	71
Medium Sand (4.4 % Bentonite Baseline)	3.4	1.5	78
Coarse Sand (4.6 % Bentonite Baseline)	2.9	2	72
	2.8	2	65
	1.75	2.5	59
Gravel (4.8 % Bentonite Baseline)	2.4	2.5	65
Coarse Gravel (4.9 % Bentonite Baseline)	No Acceptable Mixtures		N/A

Bentonite slurry mixtures containing corrugate can be used for directional drilling in cases where laminar flow is required in all formations except coarse gravel. The highest number of acceptable mixtures was determined for use in fine sand. This is due to the sharp decrease in Marsh funnel viscosity at low corrugate contents. For a baseline mixture appropriate for drilling in coarse gravel, the viscosity readily decreases to a level acceptable for use in fine sand at 0.5 and 1.0% corrugate content replacement.

4.3 Vertical Drilling Applications

Bentonite slurry mixtures were prepared with Quikgel bentonite at a range of total solids contents from 2.6 % to 3.4%. These solids contents were established by incrementally increasing bentonite content of baseline mixtures to obtain various Marsh funnel viscosities suitable for vertical borings in different native soil types. Used C-flute corrugate was used to replace up to 77% of the bentonite. Marsh funnel viscosity, density, filtrate loss, and permeability were determined for each mixture. The results are summarized in Table 4.7.

Table 4.7 Summary of Test Results for Vertical Drilling

	% Bentonite	% Corrugate	Marsh Funnel Viscosity (s)	Density (g/cm ³)	Filtrate Loss (mL)	Filter Cake Permeability (cm/s)	Filter Cake Thickness (cm)
2.6% Solids Baseline	2.6	0.0	41	1.01	23	8.8 x10 ⁻⁰⁹	0.07
	2.1	0.5	36	1.00	28	2.4 x10 ⁻⁰⁸	0.15
	1.6	1.0	33	0.96	35	4.0 x10 ⁻⁰⁸	0.21
	1.1	1.5	32	0.99	58	7.3 x10 ⁻⁰⁸	0.20
	0.6	2.0	N/A	0.95	54	6.3 x10 ⁻⁰⁹	0.03
3.0 % Solids Baseline	3.0	0.0	47	1.01	19	1.8 x10 ⁻⁰⁸	0.10
	2.5	0.5	40	1.00	25	2.5 x10 ⁻⁰⁸	0.10
	2.0	1.0	40	0.97	27	5.1 x10 ⁻⁰⁸	0.14
	1.5	1.5	35	0.98	36	5.6 x10 ⁻⁰⁸	0.14
	1.0	2.0	N/A	0.96	44	2.2 x10 ⁻⁰⁸	0.04
3.2% Solids Baseline	3.2	0.0	57	1.01	22	2.9 x10 ⁻⁰⁸	0.11
	2.7	0.5	42	1.01	19	4.1 x10 ⁻⁰⁸	0.13
	2.2	1.0	41	0.99	29	6.8 x10 ⁻⁰⁸	0.20
	1.7	1.5	42	0.97	36	6.5 x10 ⁻⁰⁸	0.21
3.3% Solids Baseline	3.3	0.0	66	1.02	22	3.4 x10 ⁻⁰⁸	0.11
	2.8	0.5	50	1.01	25	4.7 x10 ⁻⁰⁸	0.13
	2.3	1.0	41	0.98	29	6.6 x10 ⁻⁰⁸	0.18
	1.8	1.5	38	0.94	38	8.9 x10 ⁻⁰⁸	0.20
	1.3	2.0	41	0.95	58	2.1 x10 ⁻⁰⁷	0.36
	0.8	2.5	N/A	0.94	250	N/A	N/A
3.4% Solids Baseline	3.4	0.0	83	1.02	19	1.2 x10 ⁻⁰⁸	0.20
	2.9	0.5	55	1.00	19	5.1 x10 ⁻⁰⁸	0.39
	2.4	1.0	44	0.97	26	8.5 x10 ⁻⁰⁸	0.44
	1.9	1.5	41	0.97	197	N/A	N/A
	1.4	2.0	39	0.95	237	N/A	N/A

4.3.1 Marsh Funnel Viscosity

The results of Marsh funnel viscosity testing for drilling fluids for vertical drilling are presented in Figure 4.28 and 4.29 as a function of corrugate content and bentonite content, respectively. Marsh funnel viscosity decreased with increasing corrugate content. This decrease in Marsh funnel viscosity was attributed to a disruption in the viscosity-

building mechanism of the polymer modified bentonite. A similar decrease in viscosity was observed in the directional drilling test program. However, the increase in viscosity at higher corrugate contents observed for directional drilling applications was not observed for vertical boring applications. This increase was attributed to the lower total solids content of the vertical drilling fluid mixtures. For the same corrugate content, the bentonite content was lower, which allowed more interaction (i.e., entanglement) of the corrugate fibers in the mixtures prepared for the vertical drilling test program than the mixtures prepared for the horizontal drilling test program.

Figure 4.28 Marsh Funnel Viscosity as a Function of Corrugate Content for Vertical Drilling Applications

Figure 4.30 Marsh Funnel Viscosity as a Function of Total Solids Content for Vertical Drilling Applications

The Marsh funnel viscosity is a function of both the corrugate content and the bentonite content. Figure 4.31 presents a three dimensional plot of the Marsh funnel viscosity. The data displays a “quarter saddle” trend, with curves emanating from a central.

Figure 4.31 Three Dimensional Plot of Marsh Funnel Viscosity with Respect to Corrugate Content and Bentonite Content

Marsh funnel viscosity results for individual series of mixtures associated with a given baseline solids content are presented in Figure 4.32. Each of these series individually exhibited a similar trend to that presented for all data points. However, the pure bentonite-water slurry mixtures generally resulted in higher viscosities than those containing corrugate. The data varies considerably in Figure 4.32c and Figure 4.32d; this variability was attributed to the clumps present in the mixtures.

Figure 4.32 Marsh Funnel Viscosity as a Function of Corrugate Content for Individual Baseline Series Separated by Total solids % for Vertical Drilling Applications

4.3.2 Density

The density of the bentonite slurry mixtures decreased with increasing corrugate content. The densities ranged from 0.935 g/cm³ at 2.5% corrugate content to 1.015 g/cm³ at 0% corrugate content. The results from the mud balance test for density are presented in Figure 4.33 and Figure 4.34 as a function of corrugate content and bentonite content, respectively. For each of the series of mixtures associated with a given bentonite content, the maximum decrease in density is between 4.0% and 7.9%.

Figure 4.33 Drilling Fluid Density as a Function of Corrugate Content for Vertical Drilling Applications

Figure 4.34 Drilling Fluid Density as a Function of Bentonite Content for Vertical Drilling Applications

4.3.3 Filtrate Loss

The results from filtration tests on the slurry mixtures are presented with as a function of bentonite content and corrugate content (Figure 4.35 and Figure 4.36). Filtrate loss decreased with increasing bentonite content and filtrate loss increased with increasing corrugate content. In addition, as corrugate content increased the variability in the filtrate loss increased. This trend is similar to that observed for the Boregel bentonite used in directional drilling. The increased filtrate loss and increased variability at higher corrugate contents was attributed to preferential flow paths for the water through the corrugate fibers. The variability of the filtrate loss at high corrugate contents was attributed to random formation of these preferential flow paths in the filter cake due to segregated regions of bentonite and corrugate fibers.

Figure 4.35 Filtrate Loss as a Function of Bentonite Content for Vertical Drilling Applications

Figure 4.36 Filtrate Loss as a Function of Corrugate Content for Vertical Drilling Applications

Filtrate loss as a function of time was examined for selected mixtures (Figure 4.37). The filtrate loss increased rapidly and the rate decreased over time.

Figure 4.37 Filtrate Loss of Mixtures as a Function of Time for Vertical Drilling Applications

For each time step the normalized filtrate loss (filtrate loss divided by filtrate loss of the bentonite only baseline mixture), was relatively consistent (Figure 4.38). Normalized filtrate loss increased as corrugate content increased due to increased permeability of corrugate fibers compared to bentonite. The decrease in normalized filtrate loss at 5 and 7.5 minutes for 2% corrugate did not follow the trend of increased normalized filtrate loss observed for 1% corrugate as well as that observed for directional drilling applications, Therefore these data points are considered as outliers.

Figure 4.38 Normalized Filtrate Loss as a Function of Time for Vertical Drilling Applications

4.3.4 Filter Cake Permeability

The results of permeability testing for vertical drilling applications are presented in Figure 4.39. The permeability generally increased as corrugate content increased. At higher corrugate contents (2% corrugate), several points show very low permeability. These values for permeability are believed to be artificially low, due to difficulty in obtaining an accurate filter cake measurement caused by poor cohesion of the filter cake resulting in damage.

Figure 4.39 Filter Cake Permeability as a Function of Corrugate Content for Vertical Drilling Applications

The permeabilities obtained were generally within a single order of magnitude across the range of solids contents. The permeability increased as corrugate content increased. The mixtures at 2% corrugate content exhibited a higher degree of variability in permeability. Two mixtures at higher corrugate contents exhibited lower permeability and are notable exceptions to the general trend.

4.3.5 Filter Cake Thickness

The thickness of the filter cake needs to be minimized for use in drilled shaft applications to ensure that the filter cake does not attach itself to the reinforcing cage after placement of the concrete (FHWA 2010). For water wells the thickness of filter cake is not of great concern. The filter cake thickness is plotted as a function of the corrugate content of the slurry mixtures in Figure 4.40.

Figure 4.40 Filter Cake Thickness as a Function of Corrugate Content for Vertical Drilling Applications

An overall trend of increasing filter cake thickness with increasing corrugate content was observed for all baseline series of mixtures. In addition, as solids content increased, the filter cake thickness tended to increase. The one exception is the 2.6% solids series, which started at the lowest thickness yet eventually had high filter cake thickness than all mixtures except for the highest solids content mixtures.

When the filter cake permeability was normalized by the filter cake thickness (k_c/t_c), as presented in Figure 4.41, a uniformly increasing trend was observed, this was attributed to high permeability filter cakes typically having a greater thickness due to the presences of low specific gravity corrugate fibers.

Figure 4.41 Normalized Filter Cake Permeability as a Function of Corrugate Content for Vertical Drilling Applications

4.3.6 Economic Considerations

The cost for a unit volume of drilling fluid was determined for each mixture based on the yielded volumes. The cost of the bentonite was assumed to be \$328 per tonne (Preferred Water Pump and Equipment 2011) and \$200 per tonne for the corrugate (Apodaca 2011). The unit cost decreased with increasing corrugate content, due to an increase in yielded volume. The unit cost of mixtures normalized by the cost of the baseline mixtures is presented in Figure 4.42. Acceptable mixtures were prepared with up to a 29% cost reduction.

Figure 4.42 Normalized Unit Cost as a Function of Corrugate Content for Vertical Drilling Applications

4.3.7 Engineering Acceptability

Mixtures were prepared to achieve target Marsh funnel viscosities based on the recommendations of Driscoll (1986). These mixtures did not meet some of the FHWA recommended properties for drilling fluid (i.e., density between 1.03 and 1.06 g/cm³ and filtrate loss under 10 mL) used in vertical drilling however, other criteria such as filter cake thickness were met for a majority of the mixtures.

The engineering acceptability of these mixtures assumes that a weighting additive for drilling fluids, such as barite, could be used to increase the density of the mixtures to acceptable limits. Filtrate loss limits are a function of economic considerations more than engineering considerations and as such failures of mixtures due to filtrate loss have not been considered for establishing engineering acceptability.

Most mixtures produced a filter cake that was under the limit of 0.32 cm filter cake thickness, suggested by the FHWA (FHWA 2010). Within each baseline series associated with a given total solids content, the filter cake thickness increased as the corrugate content increased. The filter cake thickness reached the failure criteria (0.32 cm) in only the 3.3% and 3.4% solids baseline mixture series. For the 3.3% solids baseline, a corrugate content of up to 1.5% could be used, whereas for the 3.4% baseline, the filter cake thickness threshold was below the lowest tested value and therefore none of the prepared mixtures were deemed acceptable.

Mixtures were prepared to achieve target Marsh funnel viscosities appropriate for various formation types. A general decrease in viscosity was observed as corrugate content increased. This decrease in viscosity changed the appropriate soil formation compared to baseline mixtures not containing corrugate. Table 4.8 provides a summary of the Marsh funnel viscosities and the corresponding appropriate soil formation types for each mixture.

Marsh funnel viscosity decreased significantly with increasing corrugate content. At 1.0% corrugate content, the Marsh funnel viscosity decreased to or below a level only suitable for drilling in fine sands. The mixtures containing corrugate were not well suited for drilling in coarse sand or gravel.

Table 4.8 Marsh Funnel Viscosity and Corresponding Appropriate Soil Formation for Vertical Boring Applications

	% Bentonite	% Corrugate	Marsh Funnel Viscosity (seconds)	Suitable Soil Formation
2.6 % Solids Baseline	2.6	0.0	41	Fine Sand
	2.1	0.5	36	Fine Sand
	1.6	1.0	33	Fine Sand
	1.1	1.5	32	Fine Sand
	0.6	2.0	N/A	No Suitable Formation
3.0 % Solids Baseline	3.0	0.0	47	Medium Sand
	2.5	0.5	40	Fine Sand
	2.0	1.0	40	Fine Sand
	1.5	1.5	35	Fine Sand
	1.0	2.0	N/A	No Suitable Formation
3.2 % Solids Baseline	3.2	0.0	57	Coarse Sand
	2.7	0.5	42	Fine Sand
	2.2	1.0	41	Fine Sand
	1.7	1.5	42	Fine Sand
3.3 % Solids Baseline	3.3	0.0	66	Gravel
	2.8	0.5	50	Medium Sand
	2.3	1.0	41	Fine Sand
	1.8	1.5	38	Fine Sand
	1.3	2.0	41	Fine Sand
	0.8	2.5	N/A	No Suitable Formation
3.4 % Solids Baseline	3.4	0.0	83	Coarse Gravel
	2.9	0.5	55	Medium Sand
	2.4	1.0	44	Fine Sand
	1.9	1.5	41	Fine Sand
	1.4	2.0	39	Fine Sand

An additional consideration for the acceptability of these mixtures is the reduction in bentonite usage. For a mixture to be considered economically feasible, the mixture must reduce the total quantity of bentonite used. Applying these criteria to the data and taking into account both filter cake thickness and Marsh funnel viscosity, a summary of the acceptable mixtures for construction of CIDH piles by the soil formation type and

associated normalized unit cost is presented in Table 4.9 Acceptable Mixtures for Construction of CIDH Piles in Various Soil Formations mixtures with acceptable properties were obtained for CIDH pile applications with up to 24% cost reduction. A similar analysis was conducted for vertical water well construction, without using filter cake thickness as a criterion. The results of this analysis are provided in Table 4.10. Mixtures were obtained for water well applications with up to 29% cost reduction.

Table 4.9 Acceptable Mixtures for Construction of CIDH Piles in Various Soil Formations

Soil Formation (Associated Bentonite Baseline)	Bentonite Content (%)	Corrugate Content (%)	Normalized Unit Cost (%)
Fine Sand (2.6% Bentonite Baseline)	2.1	0.5	92
	2.5	0.5	93
	2.0	1.0	84
	1.5	1.5	78
	2.2	1.0	86
	1.7	1.5	78
	2.3	1.0	85
	1.8	1.5	93
Medium Sand (3.0 % Bentonite Baseline)	2.80	0.50	76
Coarse Sand (3.2 % Bentonite Baseline)	No Acceptable Mixtures		N/A
Gravel (3.3 % Bentonite Baseline)	No Acceptable Mixtures		N/A
Coarse Gravel (3.4 % Bentonite Baseline)	No Acceptable Mixtures		N/A

Table 4.10 Acceptable Mixtures for Construction of Vertical Borings in Various Soil Formations

Soil Formation (Associated Bentonite Baseline)	Bentonite Content (%)	Corrugate Content (%)	Normalized Unit Cost (%)
Fine Sand (2.6% Bentonite Baseline)	2.1	0.5	92
	2.5	0.5	93
	2.0	1.0	84
	1.5	1.5	78
	2.2	1.0	86
	1.7	1.5	78
	2.3	1.0	85
	1.8	1.5	93
	1.3	2.0	71
	2.4	1.0	85
Medium Sand (3.0 % Bentonite Baseline)	2.8	0.5	76
	2.9	0.50	93
Coarse Sand (3.2 % Bentonite Baseline)	No Acceptable Mixtures		N/A
Gravel (3.3 % Bentonite Baseline)	No Acceptable Mixtures		N/A
Coarse Gravel (3.4 % Bentonite Baseline)	No Acceptable Mixtures		N/A

4.4 CLSM Results

CLSM mixtures were prepared with a range of replacements of fine aggregate with used C-flute corrugate, and a range of cement to cementitious materials ratios. A total of 21 mixtures were prepared for the test program. Each mixture was tested for flow consistency, unit weight, air content, and compressive strength. The results are summarized in Table 4.11, and are discussed in greater depth individually in the following sections. Table 3.7 Summary of CLSM Mixtures Prepared presents the as-prepared mixture proportions for each batch.

Table 4.11 Summary of CLSM Test Results

Mix Designation	Batch Size	Compressive Strength		Unit Weight		Air Content %
		psi	MPa	pcf	kg/m ³	
0C-100	Small Scale	560	3.9	128.4	2057	2.7
0.25C-100	Small Scale	355	2.4	124.1	1988	5.6
0.5C-100	Small Scale	175	1.2	116.2	1862	6.0
1.0C-100	Small Scale	96	0.7	108.3	1735	8.0
2.0C-100	Small Scale	37	0.3	102.8	1647	7.0
4.0C-100	Small Scale	13	0.1	88.0	1410	6.0
6.0C-100	Small Scale	6.0	0.0	81.1	1300	5.0
0.0C-65	Small Scale	162	1.1	128.2	2053	1.3
0.25C-65	Small Scale	153	1.1	106.2	1702	5.6
0.5C-65	Small Scale	103	0.7	116.2	1861	3.4
1.0C-65	Small Scale	50	0.3	111.0	1779	6.0
2.0C-65	Small Scale	26	0.2	101.0	1618	7.0
4.0C-65	Small Scale	7.0	0.0	97.6	1564	7.0
6.0C-65	Small Scale	4.0	0.0	91.6	1468	8.5
0C-29	Full Scale	106	0.7	122.6	1964	0.7
0.25C-29	Small Scale	56	0.4	124.9	2001	5.0
0.5C-29	Small Scale	45	0.3	120.3	1928	4.3
1.0C-29	Small Scale	25	0.2	111.6	1788	4.3
2.0C-29	Full Scale	23	0.2	96.7	1549	9.4
4.0C-29	Full Scale	11	0.1	81.2	1301	21.0

6.0C-29	Full Scale	N/A	N/A	89.7	1437	5.0
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4.4.1 Flow Consistency

Flow consistency testing was used to maintain comparability between batches. Water was added to the CLSM mixtures until good flowability, defined as greater than 200 mm (8 in.) (ACI 2011) was obtained or until bleeding became excessive. The amount of additional water required to achieve good flowability was indicative of the water demand of the mixture. Mixtures with excessive bleeding were unacceptable for the testing program. Figure 4.43 shows the water cement ratio for which either the acceptance or rejection criteria was obtained for each mixture.

Figure 4.43 Water Requirement of Mixes as a Function of Corrugate Content

The water to cement ratio required to obtain either the acceptance or rejection criteria is shown to increase with increasing corrugate content. The corrugate absorbed

significant quantities of water during the pulping and mixing phases of the batching process leading to the increase in water demand. A portion of this water became free water as the corrugate fibers compressed and released water to the mixture during mixing and placement. This water was present as increased water for hydration and also as bleed water.

4.4.2 Unit Weight

The unit weight of each mixture was determined. The yield, or actual produced volume, and as prepared mixture proportions were calculated based on the measured unit weights. The unit weight of each batch as a function of corrugate content is presented in Figure 4.44.

Figure 4.44 Unit Weight of CLSM Mixtures

A general trend of decreasing unit weight with an increase in corrugate content was observed. The decrease in unit weight was attributed primarily to the increased water content of mixtures containing corrugate. In addition, the lower specific gravity of corrugate compared to fine aggregate and increased air content of the CLSM mixture contributed to the decreased unit weight. The combination of increased water content and increased air content correlated well with the decrease in density. The relationship between the volume of voids (i.e., volume of water plus volume of air) and unit weight is presented in Figure 4.45.

Figure 4.45 Unit Weight of CLSM Mixtures as a Function of Volume of Voids

This decrease in unit weight corresponded to an increase in the yield of the CLSM batch. The normalized yield of CLSM mixtures, the quotient of the yielded volume of the

mixture and the yielded volume of the associated baseline mixture, as corrugate content increases is presented in Figure 4.46.

Figure 4.46 Yielded Volume of CLSM Mixtures Normalized by Baseline Volume

4.4.3 Air Content

The air content measured for each CLSM batch as a function of corrugate content is presented in Figure 4.47. Air content generally increased with increasing corrugate content; however, the trend was not well defined. This may have been due to the compressibility of the corrugate inducing some variability. In addition; the air content of mixtures that exhibited excessive bleeding may not have been accurately determined.

Figure 4.47 Air Content of CLSM Mixtures

The air content for the mixture 4.0C-29 was measured to be 21%. This value does not seem to reflect an accurate measure of the air content of the mixture, and as such was considered an anomaly and disregarded.

4.4.4 Strength

The strength of CLSM mixtures is the most commonly specified engineering property. The specification of a given mixture is often solely determined by the compressive strength. The compressive strength of all mixtures was determined at 28 days and the strength development over time was examined for selected mixtures. The relationship between strength and corrugate content is presented in Figure 4.48.

Figure 4.48 Compressive Strength of CLSM Mixtures as a Function of Corrugate Content

Compressive strength first decreased significantly as corrugate content increased, and then began to level off (Figure 4.48). The compressive strength normalized by the baseline values as a function of corrugate content is presented in Figure 4.49. Normalizing compressive strength provides a means to assess the strength decrease caused by increased corrugate content for various cement to cementitious materials ratios while eliminating the difference in strength caused by using different cement to cementitious materials ratios. The decrease in normalized compressive strength presented in Figure 4.50 is well correlated to an increase in water to cementitious materials ratio.

Figure 4.49 Normalized Compressive Strength of CLSM Mixtures as a Function of Corrugate Content

Figure 4.50 Normalized Compressive Strength as a Function of Water to Cement Ratio

Specimens of select CLSM mixtures were prepared to determine the strength development over time. These mixtures had cement to cementitious materials ratio of 0.29 and corrugate contents of 0, 2, 4, and 6%. The strength development of these mixtures is presented in Figure 4.51 and Figure 4.52. The samples prepared with 6% corrugate did not gain sufficient strength to be demolded and tested.

The strength development from 14 to 28 days for each nominal corrugate substitution rate is presented in Figure 4.51. The strength development normalized by the 28 day compressive strength of each mixture is presented in Figure 4.52. The rate of compressive strength development was generally consistent across all mixtures. These results indicated that the addition of corrugate did not significantly alter the strength development rate but did affect the overall maximum strength.

Figure 4.51 Compressive Strength Development of CLSM Mixtures

Figure 4.52 Compressive Strength Development of CLSM Mixtures Normalized by 28-Day Compressive Strength

4.4.5 Economic Considerations

The acceptability of a CLSM mixture is typically based on the required compressive strength. However, a mixture also must be economical to be adopted by the construction industry. The cost per cubic meter of each CLSM batch was computed based on material prices supplied by Idiart (2011) and Apodaca (2011). The unit material prices used for this economic analysis are provided in Table 4.12.

Table 4.12 Material Costs Used for Economic Analysis

Materials	\$/ tonne
Cement	99.18
Fly Ash	82.65
Sand	22.04
Corrugate	200
Water	0.79

Table 4.13 provides a summary of the cost of each CLSM mixture. The absolute unit cost for these mixtures generally decreased as the corrugate content increased (Figure 4.53). The decreased cost can be attributed to the increase in volume of the mixtures due to corrugate addition.

Table 4.13 Estimated Cost of CLSM Mixtures

Mix Designation	Unit Cost		Compressive Strength (MPa)
	\$/m ³	\$/ yd ³	
0C-100	55	42	3.9
0.25C-100	56	43	2.4
0.5C-100	48	37	1.2
1.0C-100	43	33	0.7
2.0C-100	39	30	0.3
4.0C-100	32	24	0.1
6.0C-100	24	18	0.0
0.0C-65	54	41	1.1
0.25C-65	47	36	1.1
0.5C-65	50	38	0.7
1.0C-65	48	37	0.3
2.0C-65	37	28	0.2
4.0C-65	32	25	0.0
6.0C-65	27	21	0.0
0C-29	50	39	0.7
0.25C-29	56	43	0.4
0.5C-29	53	40	0.3
1.0C-29	46	35	0.2
2.0C-29	43	33	0.2
4.0C-29	37	28	0.1
6.0C-29	43	33	N/A

Figure 4.53 Cost of CLSM as a Function of Corrugate Content

Mixtures were compared on an equivalent strength basis to determine economically viable mix designs. Compressive strength of CLSM mixtures as a function of unit cost is presented in Figure 4.54. This chart can be used to select mixture ratios and evaluate whether an economic gain can be realized by selecting a mixture design with corrugate, and if so, determine an appropriate replacement level.

Figure 4.54 Compressive Strength of CLSM Mixtures as a Function of Cost with Acceptance Criteria

CLSM mixtures with compressive strengths less than 0.34 MPa are not acceptable, and are therefore excluded from the set of viable mixtures. Mixtures to the right of the vertical lines in Figure 4.54 are omitted from the set of viable mixes because an equivalent or greater strength can be achieved without using corrugate for a lower unit cost for these mixtures. Unacceptable mixtures fall within the shaded region of figure 4.54. A summary of viable mixtures and the associated cost savings is provided in Table 4.14. The baseline used for comparison varies based on the compressive strength of the mixtures. CLSM mixtures containing corrugate produced compressive strengths in the appropriate range at a cost savings of between 4 and 14% compared to baseline mixtures without corrugate.

Table 4.14 Summary of Viable CLSM Mixtures and Associated Cost Savings

Mixture Designation	Compressive Strength (MPa)	Cost (\$/m ³)	Baseline Compressive Strength (MPa)	Baseline Cost (\$/m ³)	Savings (\$/m3)	Savings (%)
0.25C-65	1.05	47	1.12	54	7	13%
0.5C-100	1.21	48	1.12	54	6	11%
1.0C-65	0.34	48	0.73	50	2	4%
1.0C-100	0.66	43	0.73	50	7	14%

Chapter 5: Engineering Significance

This chapter summarizes the engineering significance of the experimental test program. The topics covered include general trends and comparison between applications, economics, and sustainability.

The incorporation of corrugate had a significant impact on engineering properties of bentonite slurry and drilling fluid mixtures. In general, density decreased, filtrate loss increased, and permeability increased with increasing corrugate content. The relationship between Marsh funnel viscosity and corrugate content was different for each bentonite type. Generalized trends of Marsh funnel viscosity with increasing corrugate content for each bentonite content are presented in Figure 4.55.

Figure 4.51a represents the trends observed in the slurry wall construction test program using Aquagel bentonite. Marsh funnel viscosity displayed a continual increase with increasing content until failure is reached. This trend is different from that observed for both Boregel and Quikgel bentonites used for directional and vertical drilling, respectively (Figure 4.55a and 4.55b). For both bentonites used in drilling fluids a decrease in Marsh funnel viscosity was observed, which was attributed to the disruption of the viscosity-building mechanism of the polymer modified bentonite. This decrease is not observed for slurry wall applications because Aquagel is not a polymer modified bentonite.

For directional drilling applications, the Marsh funnel viscosity increased as corrugate content increased, often meeting or exceeding the baseline Marsh funnel viscosity at higher corrugate contents. This is attributed to the formation of a fibrous network of interlocking corrugate fibers. For vertical drilling applications, the Marsh

funnel viscosity did not increase at higher corrugate contents. The difference in behavior between drilling fluid applications is attributed to the variation in total solids content. For vertical drilling, lower total solids content is used; therefore the corrugate represents a larger portion of the solids. Failure of the Marsh funnel viscosity test occurs due to an interlocking fibrous network and clogging of the funnel orifice before an increase in viscosity is obtained.

Figure 4.55 Generalized Trends of Marsh Funnel Viscosity for Different Application Types

The use of corrugate in each application provided some economic benefit from a materials standpoint. The cost of mixtures containing corrugate was reduced for every mixture in bentonite based slurry and drilling fluid applications compared to baseline values, making every mixture with acceptable engineering properties economical. For CLSM, selected mixtures provided the requisite strength at an economical cost. However,

for mixtures to be truly economically feasible, the cost of integration into existing construction practices must be analyzed. This utilization of corrugate requires the use of specialized equipment to pulp and store corrugate pulp. The storage of corrugate pulp represents an additional issue, as corrugate tends to decompose over time if left in a moist environment. One solution is to use portable pulping and mixing equipment at the jobsite, allowing freshly pulped corrugate to be prepared and used as needed. It is likely that these added capital costs would only be feasible on large projects, where the large volume of material would outweigh potentially increased capital equipment costs.

The use of corrugate to replace raw, quarried materials provides an environmental benefit. Each kilogram of corrugate used in these applications would conserve a kilogram of bentonite or fine aggregate from being used, allowing the same quantity of raw material to complete more projects. If adopted on a wide scale the quarrying of these raw materials could be reduced, providing a subsequent reduction in emissions due to quarrying activities. The environmental impact of construction projects is becoming increasingly important. The use of corrugate to reduce raw material usage is a sustainable practice that would divert materials from MSW landfills, reduce raw material consumption, and potentially decrease quarrying activities.

Finally, some degradation of corrugate was observed in mixtures allowed to age. This degradation was not studied in depth and is noted as an observation that will impact potential implementation of these uses for corrugate. Due to the degradation, the use of corrugate may not be suited for long term applications. However, for short term applications such as for temporary support of slurry walls and boreholes during construction the corrugate will not be in use for long enough to significantly degrade.

Further investigation of the influence of corrugate degradation on engineering properties of mixtures is warranted.

Chapter 6: Conclusions

This chapter presents conclusions based on the results of the experimental test programs for bentonite for slurry wall, drilling fluids for vertical and directional drilling applications, and controlled low strength materials.

Based on the results of the experimental test program for slurry wall applications the following conclusions were drawn:

1. Marsh funnel viscosity increased as corrugate content increased. Viscosity increased from a baseline value of 41 seconds to between 55 and 60 seconds at a 36 % replacement of bentonite with corrugate (2% corrugate content mixture for a 5.5% total solids baseline). This was attributed to the formation of an interlocking fibrous network.
2. Corrugate type had little effect on the Marsh funnel viscosity.
3. Use condition effected C-flute corrugate more than pizza box corrugate, due to variations in usage intensity between corrugate types.
4. Extended pulping had a greater effect on pizza box corrugate than C-flute corrugate, due to variations in usage intensity between corrugate types.

5. Density of mixtures decreased from 1.03 g/cm³ to a minimum of 1.01 g/cm³ as corrugate content increased. This decrease was attributed to the lower specific gravity of the corrugate compared to the bentonite.
6. Filtrate loss increased as a corrugate content increased. Filtrate loss increased from a baseline value of 16 mL to between 33 and 40 mL. This increase was attributed to higher permeability of corrugate fibers compared to bentonite and formation of preferential flow paths through filter cake.
7. Permeability of filter cake increased as corrugate content increased; this increase was more pronounced beyond a 36% replacement of bentonite with corrugate. The permeabilities of mixtures containing corrugate were within the same order of magnitude to the baseline mixture.
8. Acceptable mixtures were prepared for new C-flute and pizza box corrugate at up to 27% replacement of bentonite with corrugate (1.5% corrugate out of 5.5% total solids). For used C-flute and pizza box corrugate, acceptable mixtures were prepared at up to 18% replacement of bentonite with corrugate (1% corrugate out of 5.5% total solids).
9. Acceptable Mixtures were prepared at a cost reduction of up to 10% for both pizza box and C-flute corrugate in new condition and up to 7% in the used condition.

Based on the results of the experimental test program for directional drilling applications the following conclusions were drawn:

1. Marsh funnel viscosity initially decreased with addition of corrugate due to disruption of the viscosity building mechanism of the bentonite. As the corrugate content increased, the Marsh funnel viscosity increased due to formation of an interlocking fibrous network.
2. Marsh funnel viscosities in the range of 40-50 s were obtained for a broad range of bentonite to total solids ratios. These viscosities were obtained for mixtures with approximately 10 to 35% bentonite replacement.
3. Density decreased as corrugate content increased. A maximum density reduction of between 3.4 to 5.9% was observed due to lower specific gravity of the corrugate compared to bentonite.
4. For some mixtures at higher corrugate contents, the resulting densities were below 1.0 g/cm³. For these mixtures a weighting agent would be appropriate to counteract the decrease in density.
5. Filtrate loss increased as corrugate content increased. The filtrate loss increased at levels between 41 and 144% compared to the baseline mixtures. This increase

was attributed to higher permeability of corrugate fibers compared to bentonite and formation of preferred flow paths through filter cake.

6. Normalized filtrate loss increased by a uniform factor for a given corrugate content with time.
7. Permeabilities of filter cake containing corrugate generally increased compared to baseline mixtures but were on the same order of magnitude to that of baseline mixtures. For all mixtures permeability was less than 1.0×10^{-7} .
8. Acceptable mixtures were prepared for drilling in all target soil types, except coarse gravel. For vertically aligned borings (where laminar flow is desirable), up to 59% of bentonite was replaced with corrugate (2.5% corrugate out of 4.25% total solids). For horizontally aligned borings and borings in the transition region (where turbulent flow is favored), up to 51% of bentonite was replaced with corrugate (2.5% corrugate out of 4.9% total solids).
9. Acceptable Mixtures were prepared at a cost reduction of up to 35% for borings with primarily horizontal orientations and up to 41% for boreings with primarily vertical orientations.

Based on the results of the experimental test program for vertical boring applications the following conclusions were made:

1. Marsh funnel viscosity decreased as corrugate content increased due to disruption of the viscosity-building mechanism of the bentonite by the corrugate fibers.
2. Density decreased as corrugate content increased. A maximum density reduction of between 5.0 and 7.9% was observed from baseline densities due to the lower specific gravity of corrugate compared to bentonite.
3. For some mixtures the density decreased to below 1.0 g/cm³. For these mixtures a weighting agent is needed to counteract the decrease in density.
4. Filtrate loss increased as corrugate content increased. The filtrate loss increased by between 63 and 163%. This increase was attributed to increased permeability of corrugate fibers compared to bentonite and formation of preferential flow paths through filter cake.
5. Permeability generally increased as corrugate content increased. However, the permeabilities of filter cake containing corrugate were on the same order of magnitude to that of the baseline mixtures. For all mixtures permeability was less than 1.0×10^{-7} .
6. Acceptable mixtures were prepared for drilling in fine and medium grained sands. For drilling fluids associated with CIDH pile construction, up to 50% of bentonite was replaced with corrugate (1.5% corrugate out of 3% total solids). For drilling

fluids associated with water well construction, up to 61% of bentonite was replaced with corrugate (2.0% corrugate out of 3.3% total solids).

7. Acceptable Mixtures were prepared at a cost reduction of up to 24% for CIDH piles and up to 29% for other vertical borings.

Based on the results of the experimental test program for CLSM the following conclusions were drawn:

1. Water demand of mixtures containing pulped corrugate increased as corrugate concrete increased. The required water to cementitious materials ratio increased between 80 and 648% compared to the baseline due to the high absorption of the corrugate fibers.
2. Unit weight of mixtures containing corrugate decreased as corrugate content increased. The unit weight decreased between 29 and 37% at the highest examined corrugate content compared to the baseline mixtures. This decrease in unit weight was due to entrapment of air and the lower specific gravity of corrugate compared to the fine aggregate.
3. An increase in volume of between 40 and 60% was observed compared to baseline mixtures. Which was attributed to bulking and air entrapment of the mixtures containing corrugate.

4. Compressive strength decreased as corrugate content increased however, mixtures were prepared that obtained adequate compressive strength. Significant strength reductions (up to 99%) were observed at high corrugate contents. This strength decrease was attributed primarily to the increase in water to cementitious materials ratio.
5. The normalized rate of strength development was similar for different corrugate contents, indicating that corrugate content affected the compressive strength of the mixture but the rate of strength development was not significantly affected.
6. A design chart was developed for establishing mixture proportions of CLSM that incorporate corrugate.
7. The unit cost of mixtures containing corrugate decreased as corrugate content increased. This decrease in cost was due to increased yield of the mixtures. Acceptable mixtures were prepared with cost savings up to 14% compared to the baseline mixtures.
8. Mixtures were prepared that resulted in acceptable compressive strength up to a 1% replacement of fine aggregate with corrugate.

This research has provided a foundation for future research into the use of corrugated paperboard in civil engineering applications. Based on the results of this experimental test program and review of literature, the following recommendations for further research are provided:

1. Analysis of sorption characteristics of corrugated paperboard in bentonite slurry wall applications for contaminant mitigation.
2. Investigation of alternative pulping and dewatering techniques.
3. Exploration of full viscosity profile using a direct indicating viscometer or similar instrument.
4. Bench and field scale testing to evaluate performance, and further investigate issues surrounding incorporation into construction practices.
5. Investigation of long term performance of mixtures containing corrugate.

References

- Abichou, T., Edil, T. B., Benson, C.H., and Bahia, H. (2004). "Beneficial Use of Foundry By-Products in Highway Construction." *GeoTrans 2004: Geotechnical Engineering for Transportation Projects*. Los Angeles, CA., 715-722.
- American Concrete Institute (ACI) (2011). *ACI 229R-99 (Reapproved 2005): Controlled Low-Strength Materials*. Farmington Hills, MI.
- ACI (2011). *ACI 211.1-91 (Reapproved 2009): Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete*. Farmington Hills, MI.
- American Petroleum Institute (API) (2003). "*Recommended Practice Standard Procedure for Field Testing Water-Based Drilling Fluids*." Specification RP13B-1. Washington, D.C.
- Apodaca (2011). Personal Communication. Weyerhaeuser Co. Hueneme Paper Mill Plant, Oxnard, CA, February 1st 2011.
- ASTM International. (2010). "Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens)." *C109/C109M-08*, West Conshohocken, PA.
- ASTM International. (2010). "Standard Test Method for Density of Hydraulic Cement." *C188- 09*, West Conshohocken, PA.
- ASTM International. (2010). "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate." *C128-07a*, West Conshohocken, PA.
- ASTM International. (2010). "Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates." *C136-06*, West Conshohocken, PA.
- ASTM International. (2010). "Standard Specification for Portland Cement." *C150/C150M-09*, West Conshohocken, PA.
- ASTM International. (2010). "Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method." *C231/C231M-10*, West Conshohocken, PA.

- ASTM International. (2010). "Standard Specification for Concrete Aggregates." *C33/C33M-08*, West Conshohocken, PA.
- ASTM International. (2010). "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens." *C39/C39M-09a*, West Conshohocken, PA.
- ASTM International. (2010). "Standard Specification for Blended Hydraulic Cements." *C595/C595M-10*, West Conshohocken, PA.
- ASTM International. (2010). "Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete." *C618-08a*, West Conshohocken, PA.
- ASTM International. (2010). "Standard Test Method for Preparation and Testing of Controlled Low Strength Material (CLSM) Test Cylinders." *D4832-10*, West Conshohocken, PA.
- ASTM International. (2010). "Standard Test Method for Marsh Funnel Viscosity of Clay Construction Slurries." *D6910/D6910M-09*, West Conshohocken, PA.
- ASTM International. (2010). "Standard Test Method for Density of Bentonitic Slurries." *D4380-84(2006)*, West Conshohocken, PA.
- ASTM International. (2010). "Standard Test Method for Flow Consistency of Controlled Low Strength Material (CLSM)." *D6103-04*, West Conshohocken, PA.
- ASTM International. (2010). "Standard Test Method for Density (Unit Weight), Yield, Cement Content, and Air Content (Gravimetric) of Controlled Low-Strength Material (CLSM)." *D6023-07*, West Conshohocken, PA.
- ASTM International. (2010). "Standard Test Method for Swell Index of Clay Mineral Component of Geosynthetic Clay Liners." *D5890-06*, West Conshohocken, PA.
- ASTM International. (2010). "Standard Practice for Performance Testing of Shipping Containers and Systems." *D4169-09*, West Conshohocken, PA.
- Baroid Industrial Drilling Products-Halliburton (2011). *Soda Ash Product Data Sheet*, <www.baroididp.com>(March 7, 2012).

- Baumert, M. E., Allouche, E. N., Moore, I. D. (2005). "Drilling Fluid Considerations in Design of Engineered Horizontal Directional Drilling Installations." *International Journal of Geomechanics*, 5(4),339-349.
- CETCO (2010). <www.cetco.com> (Last Accessed, May 5, 2011).
- Cheung, T., Jansen, D. C., and Hanson, J. L. (2008). "Engineering Controlled Low Strength Materials Using Scrap Tire Rubber." *Geocongress 2008: Characterization, Monitoring, and Modeling of GeoSystems, GSP 179.*, New Orleans, LA., 622-629.
- Cheung, T. (2007). "The Use of Scrap Tire Rubber Buffings in Flowable Fill," *M.S. Thesis*, California Polytechnic State University. San Luis Obsipo,CA.
- Chorom, M., Rengasamy, P., and Murray, R. S. (1994). "Clay Dispersion as Influenced by pH and Net Particle Charge of Sodic Soils." *Australian Journal of Soil Research*, 32(6),1243-1252.
- D'Appolonia, D. J., and Ryan, C. R. (1979). "Soil-Bentonite Slurry Trench Cut-Off Walls." *Geotechnical Technical Conference*. Chicago, IL.
- Deng, A. and Tikalsky, P.J. (2008). "Geotechnical and Leaching Properties of Flowable Fill Incorporating Waste Foundry Sand." *Waste Management*. 28, 2161-2170.
- Dewan, J. T., and Chenevert, M. E. (2001). "A Model for Filtration of Water-base Mud During Drilling: Determination of Mudcake Parameters." *Petrophysics*. 42(3), 237-250.
- Driscoll, F. P. (1986). *Groundwater and Wells*. Johnson Division, St. Paul, MN.
- Evans, J. C. (1994). "Hydraulic Conductivity of Vertical Cutoff Walls." *Hydraulic Conductivity and Waste Contaminant Transport in Soil, ASTM STP 1142*, Daniel, D.E., and Trautwein, J., Eds., American Society for Testing and Materials, Philadelphia, PA.
- Federal Highway Administration (FHWA) (2010). *Drilled Shafts: Construction Procedures and LRFD Design Methods: NHI Course No. 132014, Geotechnical Engineering Circular No. 10.*, National Highway Institute, U.S. Department of Transportation, Washington, D.C.
- FHWA (2011). < <http://www.fhwa.dot.gov/pavement/recycling/fach05.cfm>>, (February 26, 2012).
- Fibre Box Association (1999). *Fibre Box Handbook*. Fibre Box Association, Rolling Meadows, IL.

- Filz, G. M., Boyer, R. D., and Davidson, R. R. (1997). "Bentonite-Water Slurry Rheology and Cutoff Wall Trench Stability." Proc., *In-Situ Remediation of the Geoenvironment*, Geo-Institute and Environmental Engineering Division of ASCE, VA., 139-153.
- Fox, R. W., McDonald, A. T., Pritchard, P. J. (2006). *Introduction to Fluid Mechanics*. 6th Ed., John Wiley and Sons Inc., Hoboken, NJ.
- Geosolutions (2011). <www.geosolutions.com> (June 1, 2011).
- Hewlett, P., Ed. (2004). *Lea's Chemistry of Cement and Concrete*, 4th Ed., Butterworth-Heinemann, Burlington, MA.
- Horizontal Drilling International (1999). *Horizontal Directional Drilling Training Manual*. Houston, TX.
- Idiart, K. (2011). Personal Communication. East Bay Technical Services Manager, Central Concrete. San Jose, CA, January, 2011.
- International Safe Transit Association (ISTA) (2001). "ISTA 2 Series Partial Simulation Performance Test Procedure," <<http://www.ista.org/forms/1Aoverview.pdf>>, (Last Accessed, December 26, 2009.)
- Kaneshiro, J., Navin, S., Wendel, L., and Snowden, H. (2001). "Controlled Low Strength Materials for Pipeline Backfill- Specifications, Case Histories, and Lessons Learned." *Pipelines 2001: Advances in Pipeline Engineering and Construction*., San Diego, CA.
- Kosmatka, S. H., Kerkhoff, B., and Panarese, W.C. (2002). *Design and Control of Concrete Mixtures*, 14th Ed. Portland Cement Association, Chicago, IL.
- Mitchell, J. K., and Soga, K. (2005). *Fundamentals of Soil Behavior*, 3rd Ed., John Wiley and Sons, New Jersey.
- Naganawa, S. Oikawa, A., Masuda, Y. Yonezawa, T., Hoshino, M., and Acuna, P. (2002). "Cuttings Transport in Directional and Horizontal Wells While Aerated Mud Drilling." *IADC/SPE Asia Pacific Drilling Technology Conference*. Jakarta, Indonesia, 73-80.
- Naik, T. R. and Singh, S. S. (1997). "Flowable Slurry Containing Foundry Sands." *Journal of Materials in Civil Engineering*. 9(2),93-102.
- Okrajni, S. S., and Azar, J. J. (1986). "The Effects of Mud Rheology on Annular Hole Cleaning in Directional Wells." *SPE Drilling Engineering*, 1(4), 297-308.

- Opdyke, S. M., and Evans, J. C. (2005). "Slag-Cement-Bentonite Slurry Walls." *Journal of Geotechnical and Geoenvironmental Engineering*. 131(6),673-681.
- Pierce, C. E. and Blackwell, M. C. (2003). "A Lightweight Flowable Fill Using Granulated Rubber Tires." *Journal of Solid Waste Technology and Management*. 29(1), 31-41.
- Pitt, M. J. (2000). "The Marsh Funnel and Drilling Fluid Viscosity: A New Equation for Field Use." *SPE Drilling and Completion*. 15(1), 3-6.
- Preferred Water Pump and Equipment (2011). Personal Communication. Sacramento, CA, May, 2011.
- Rad, N. S., Bachus, R. C., and Jacobsen, B. D. (1995). "Soil-Bentonite Design Mix for Slurry Cutoff Walls used as Containment Barriers." *Dredging, Remediation, and Containment of Contaminated Sediments*, ASTM STP 1293, K.R. Demars, G.N. Richardson, R.N. Young, and R.C.Chaney, Eds., American Society for Testing and Materials, Philadelphia, 239-251
- Riggs, E. H. and Keck, R. H. (1998). "Specifications and Use of Controlled Low-Strength Materials by State Transportation Agencies." *The Design and Application of Controlled Low-Strength Materials (Flowable Fill)*, ASTM STP1331. A.K. Howard and J.L. Hitch, Eds., American Society for Testing and Materials, West Conshohocken, Pa.
- Ryan, C.R. and Day, S.R. (2003). "Soil-Bentonite Slurry Wall Specifications", *Pan American Conference on Soils Mechanics & Geotechnical Engineering*. Cambridge, MA, June 2003.
- Ryan, C.R. (1976). "Slurry Cut-Off Walls Design Parameters and Final Properties and Interim Report", *Technical Course Slurry Wall Construction, Design, Techniques, and Procedures..* Miami, FL, March 1977.
- Shaanxi University (2011). <test3.duoyao.net>, (Last Accessed, June 1, 2011).
- Sharma, H. D, and Lewis, S. P. (1994). *Waste Containment Systems, Waste Stabilization, and Landfills*. John Wiley & Sons, Inc., New York, NY.
- Technical Association of the Pulp and Paper Industry (TAPPI) (2010). "Edgewise Compressive Strength of Corrugated Fiberboard using the Clamp Method (Short Column Test)." *T 839 om-08*. TAPPI, Norcross, GA.
- TAPPI (2010). "Bursting Strength of Corrugated and Solid Fibreboard." *T 810 om-06*. TAPPI, Norcross, GA.

- TAPPI (2010). "Grammage of Paper and Paperboard (Weight Per Unit Area)." *T 410 om-08*. TAPPI, Norcross, GA.
- TAPPI (2010). "Water Absorptiveness of Sized (Non-Bibulous) Paper, Paperboard, and Corrugated Fiberboard (Cobb Test)." *T 441 om-09*. TAPPI, Norcross, GA.
- Tikalsky, P. J., Smith, E., and Regan, R. W. (1998). " Proportioning Spent Casting Sand in Controlled Low Strength Materials." *ACI Materials Journal*. TAPPI, 95(6), 740-746.
- Turkel, S. (2006). "Long-term Compressive Strength and Some Other Properties of Controlled Low Strength Materials Made with Pozzolanic Cement and Class C Fly Ash." *Journal of Hazardous Materials*. B137, 261-266.
- Turkel, S. (2007). "Strength Properties of Fly Ash Based Controlled Low Strength Materials." *Journal of Hazardous Materials*. 147, 1015-1019.
- United States Environmental Protection Agency (USEPA) Office of Solid Waste (2010). *Municipal Solid Waste in the United States: 2009 Facts and Figures*. Washington, D.C.
- USEPA Office of Emergency and Remedial Response (1984). *Slurry Trench Construction for Pollution Migration Control*. Cincinnati, OH.
- Wang, H. -Y. (2009). "A Study of the Engineering Properties of Waste LCD Glass Applied to Controlled Low Strength Materials." *Construction and Building Materials*. 23, 2127-2131.
- Won, J. -P., Lee, Y. -S., Park, C. -G., and Park, H. -G. (2004). "Durability Characteristics of Controlled Low-Strength Materials Containing Recycled Bottom Ash." *Magazine of Concrete Research*. 64(7), 429-436.
- Xanathakos, P. P. (1979). *Slurry Walls*. McGraw-Hill, New York.