Flowable Fills Developed With High Volumes of Fly Ash

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ABSTRACT

Flowable fill, also known as Controlled Low Strength Material (CLSM), is used in place of ordinary geotechnical fill in construction applications. Fly ash playDue to the addition of air quality controls on coal-fired power plants, fly ash characteristics have an increasing amount of free carbon, ammonia, and/or lime residue. This results in more fly ash being disposed in landfills than being beneficially used.

This paper presents the results of a laboratory study that has as objectives 1) to produce excavatable flowable fill with maximum ash incorporation (i.e., maximum amount of variable quality fly ash, minimum amount of Portland cement, and no sand) and 2) to determine the effect of different types of fly ash on the engineering properties of the flowable fills. The fly ashes evaluated for this project differ based on carbon, ammonia, and lime content. The flowable fill mixes were tested for plastic state characteristics, unconfined compressive strength, and confined compressive strength in triaxial compression. Overall, the results indicate that high volumes of coal ash can be successfully used in flowable fill applications.

1.0 Introduction

Industrial manufacturing is a complex set of processes, which directly or indirectly utilize material resources to create final products. Utilities burning coal to produce electricity and refining crude oil to make gasoline, heating oil, and plastics are examples of industrial processes. Waste materials are produced during the manufacturing process (such as fly ash from coal) or as post consumer wastes. The majority of waste material in the United States is currently landfilled. Landfills are designed to minimize contamination of the environment resulting from the permanent storage of waste material.

Permanent storage of waste material in a landfill is a highly inefficient strategy for final material management. As schematically diagramed in Figure 1.1, if industrial-related processes are seen as an ecosystem, the most efficient ecosystem is one that minimizes both the input of limited resources and the output of waste materials. This is achieved by optimizing the interaction of various components within a process; i.e., the raw material, manufacturing, consumer use, and waste management.

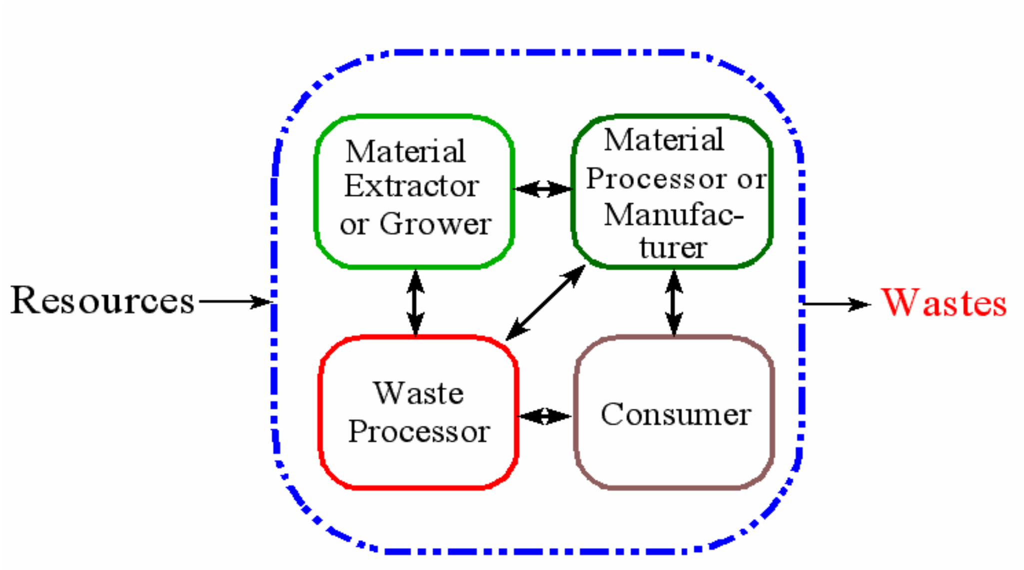

Figure 1.1 Industrial System (after Graedel etal [17])

For example, if waste production can be reduced via recycling and reuse of manufacturing by-products and post-consumer products, the ecosystem will become significantly more efficient and sustainable as less raw resources are required and fewer wastes are produced. Waste recycling and reuse are key components of a long-term efficient industrial system since wastes are minimized, their reuse is maximized, and natural resources are conserved for future generations.

Fly ash is the by-product of burning coal to make electricity. In the year 2000, 57 million metric tons of fly ash were produced in the United States, and only 31.9 percent of that ash was beneficially reused. The remainder was landfilled. The construction industry is the largest single reuse market in the country.[1]

Recently, the Environmental Protection Agency (EPA) agreed to renew the Resource Conservation and Recovery Act (RCRA) hazardous waste exemption for fly ash, but promised to revisit the issue in the future. The most widespread application for fly ash has been and continues to be for cement replacement in ready-mix concrete provided it meets strict quality criteria set by the ASTM C618 “Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete.”[10]

However, coal fired power generation facilities are under increasing regulatory requirements to reduce NOx (nitrogen oxides) emissions. The existing technologies employed to reduce NOx emissions result in increased levels of carbon, ammonia, and other compounds found in fly ash. The ASTM C618 specification limits LOI (loss of free carbon on ignition) to 6 percent, largely because the higher LOI levels often result in discoloration and poor action of chemical additives such as air entrainment agent (AEA) and plasticizers in concrete.

In fact, use of NOx control technologies may result in once marketable fly ash becoming unusable and destined for landfills. The disposal of ammonia-contaminated fly ash may result in a re-evaluation of landfill disposal practices. Ammonia residues found in fly ash exhibit high water solubility and have the potential to contaminate both ground and surface waters.

Local and federal agencies, such as the Massachusetts Highway Department and the Bureau of Reclamation, control major construction projects, and specify the use of fly ash that satisfies the requirements of ASTM C618. However, ASTM C618, "Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete" is referenced by the construction industry in the use of fly ash as a mineral admixture (pozzolan). Fly ash is commonly used to increase the compressive strength and decrease the permeability of normal strength concrete (f'c $\approx$ 3000 psi). Pozzolans such as fly ash, slag, and silica fume are routinely used in concrete as replacement for a maximum of 10 to 20 percent (by weight) of Portland cement.

This paper presents the results of a laboratory study that aimed to 1) produce excavatable flowable fill with maximum ash incorporation, and 2) determine the effect of different types of fly ash on the engineering properties of the flowable fills. The fly ashes evaluated for this project differ based on carbon, ammonia, and lime content. The flowable fill mixes were tested for plastic state characteristics such as flow and pocket penetrometer tests. Cured mixes were tested for unconfined compressive strength and undrained triaxial compression. Based on the demonstrated mechanical properties, the results indicate that high volumes of coal ash can be successfully used in flowable fill applications.

2.0 Literature Review and Background Information

2.1 Fly Ash

Fly ash is the fine portion of the coal combustion by-products (CCB) produced at power generating stations. It is collected from the flue gases by electrostatic precipitators. The ash cools rapidly when it leaves the flame creating a glassy, non-crystalline particle that contains small portions of crystalline material: mullite, quartz, magnetite and hematite. Most particles are spherodial and less than 250 micrometers in diameter. They have high mechanical strength, a melting point above 1000^{o} C, a density range of 0.26-3 g/cm^{3}, a low thermal conductivity and are mostly chemically inert. [1]

Fly ash is classified as either Class F or Class C based on its chemical composition with the source coal determining the chemical composition of the fly ash. Fly ash is a pozzolan, a material that in the presence of lime and water will be cementious.

The most common applications for fly ash utilize the pozzolanic properties of the material. In the year 2000, the majority of the ash recycled in the US was used in the construction industry, which is the single largest reuse market in the country. Flowable fill applications represent the second largest use of fly ash after its use as a mineral admixture in cement/concrete/grout.[1]

Approximately seven percent of the fly ash produced in the year 2000 was used as flowable fill, a material created by mixing water, cement, low carbon fly ash, and aggregate. In its plastic state, flowable fill is extremely fluid, and later hardens from a hydrolysis reaction. Low carbon fly ash is also employed as a substitute for Portland cement in concrete. Fly ash with high concentrations of carbon cannot be used as a cement substitute because it can lead to air entrainment in concrete.

2.2 Flowable Fill

Flowable fill, also known as controlled low-strength material (CLSM) and controlled density fill (CDF), is a mixture of cement, fly ash, sand, and water. Sand is the principle constituent of the mixture, and usually represents 80 to 90 percent of the total volume. Typically, flowable fill is designed as a low strength, flowable material requiring no subsequent vibration or tamping to achieve 100 percent consolidation. Common flowable fill applications are:

Backfill	Structural Fill	Other Uses
• Sewer trenches	• Road base	• Underground storage tanks
• Utility trenches	• Mud jacking	• Slope stabilization
• Building excavations	• Sub-footing	• Soil erosion control
• Bridge abutments	• Floor slab base	• Mud mats
• Conduit trenches	• Pipe-bedding	• Abandoned sewers and mines

There are several provisional and adopted ASTM and ACI standards and specifications for flowable fill covering constituent material, mixing, quality control, and durability issues including ASTM D5791, D6023, D6024, and D6103.[13, 14, 15, 16] The American Concrete Institute (ACI) established Committee 229 "Controlled Low Strength Materials (CLSM)" who in 1994 compiled a report (ACI 229-R94) containing information on applications, material properties, mix proportioning, construction, and quality-control procedures for flowable fill (CLSM).[2, 3, 4] The report further recommends the use of by-products such as fly ash, bottom ash, and spent foundry sand in flowable fill.

The wide spread use of non-standard fly ash in flowable fill would provide an economical and environmentally responsible mechanism for the disposal of a significant portion of the millions of tons of fly ash produced in this nation's power generating facilities.

There is little existing literature on the production or testing of flowable fill consisting of solely fly ash, cement and water. Testing procedures used for this testing program incorporated modified versions of methods outlined in either American Society for Testing and Materials (ASTM) or American Concrete Institute (ACI) publications.

Potential mix designs for the program were chosen based on maximum ash incorporation and strength tests performed at 24 hours and 28 days. The mix designs presented in the Table 2.1 were the only reviewed mix designs that did not contain aggregate, thus satisfying the project objective of maximum fly ash incorporation.

Table 2.1 Reviewed Mix Designs of “Sandless” Flowable Fills

Source	Michigan DOT	Flowable Fly Ash Slurry		
	Mix 1	Mix S-2	Mix S-3	Mix S-4
Cement (T/m^3)	0.059	0.058	0.094	0.085
Fly Ash (T/m^3)	1.19	0.81	0.75	0.69
Coarse Aggregate (T/m^3)	0	0	0	0
Fine Aggregate (T/m^3)	0	0	0	0
Water Content (T/m^3)	0.39	0.63	0.37	0.68
Compressive Strength At 56 Days (kPa)	-	276	517	482
Source: (5)				

2.3 Regulatory Aspects of Recyclable Material Reuse

2.3.1 Mechanical Requirements

Massachusetts flowable fill specifications are found in *Subsection M4.08.0 Controlled Density Fill (CDF)* of the MASS Highway Supplemental Specification to the 1988 Standard Specifications for Highways and Bridges.[18] The statute identifies two main categories of flowable fill (CDF), excavatable and non-excavatable, and it subdivides the main categories by flowability. The Mass Highway categories of CDF’s are:

- Type1, Very Flowable (Non Excavatable)
- Type 1E, Very Flowable (Excavatable)
- Type 2, Flowable (Non Excavatable)
- Type 2E, Flowable (Excavatable)

Type 1 and 2 are intended for permanent installations, such as structural fill under a building. Type 1E is intended for temporary use for applications where distance of installation and hard-to-reach areas are of concern. Type 2E is also intended for temporary use, but where size and distance of the installation do not require the flowable characteristics of a Type 1E mix. The four types of flowable fill described above must meet the requirements listed in Table 2.2.

Table 2.2 Mass Highway Strength and Slump Requirements

Controlled Density Fill	Type 1 & 2	Type 1E & 2E
Compressive Strength @ 28 Days	30-150 psi (210-1030 kPa)	30-80 psi* (210-550 kPa)
Compressive Strength @ 90 Days	200 psi Maximum (1380 kPa Max.)	100 psi Maximum* (700 kPa Max.)
Slump	10-12 inches (25-30 cm)	10-12 inches (25-30 cm)
** May be changed by Design Engineer to fit particular job requirements.*		

The 25-30 cm slump requirement required by Mass Highway results in the desired flowable material, but the upper limit is unrealistic in that 30 cm is also the height of the slump cone and a measured slump of 30 cm would mean that the flowable fill had no appreciable height. In lieu of the slump test, flow may be measured using a 7.6 x 15.2 cm cylinder in accordance with the ASTM D6103 method. The diameter of the resulting "pancake" must be between 22.9 and 35.6 cm. The 22.9 to 35.6 cm range is excessive for many flowable fill applications. Flowable fill that has measured flow of 20.3±2.5 cm possesses the necessary fluidity to be successfully used in many flowable fill applications.

3.0 Research Objectives and Materials

3.1 Objectives and Goals

The objectives of the study were to 1) produce excavatable flowable fill with maximum ash incorporation, and 2) determine the effect of different types of fly ash on the engineering properties of the flowable fills. Traditionally, Portland cement, fly ash, sand, and water are the four principle materials used to make flowable fill. However, the mixes used in this study contained only cement, fly ash, and water in order to maximize the amount of fly ash utilized in the mixes. In addition, a number of non-standard fly ashes were used to create the flowable fills in this study including ashes with free carbon in excess of the ASTM C618 limit, high ammonia sulfate contents, and slow-hydrating lime.

The following criteria were adopted for the engineering characteristics of the flowable fill:

1. Minimum segregation and bleeding (ASTM C243)[9] during placement and hardening. Bleeding was measured by observing the amount of water accumulated on the top of the flowable fill samples placed in a small plastic buckets after 24 hours. The buckets were covered with saran wrap to prevent evaporation. Since fly ash and cement particles are equivalent size, segregation was not an issue.
2. A minimum spread (flow) of 20.3 cm inches for ease of placement and flow. Flow was measured using a 7.6 x 15.2 cm cylinder in accordance with the ASTM D6103.
3. A minimum 28-day unconfined compressive strength of 193 kPa. Compressive strength was measured by testing 7.6 x 15.2 cm cylindrical specimens cured for 28 days. The 192 kPa limit, as prescribed in the Massachusetts Building Code (780 CMR 1804), is an allowable bearing pressure for loose sand.

Additionally, quantifying the early age compressive strength and bearing capacity of the flowable fill were also a goal of the study. As a comparison to the 28-day strength, unconfined compression tests were performed for 1, 7, and 56-day ages as well. In an attempt to measure the effect of confinement on strength, confined compression tests, similar to unconsolidated-undrained triaxial compression tests for soil, were performed on specimens with an age of one day.

3.2 Materials

3.2.1 Various Fly Ashes

The fly ashes used for this study were:

- Processed fly ash (PA [ASTM Class F]) that contains less than 2% carbon (by weight).
- "Raw" coal ash also called "Feed" ash (FA) that contains more than 6% carbon.
- Residue fly ash (RA) is a by-product ash from a beneficiation (carbon separation) process used to make processed ash. Residue ash contains up to 30% carbon.
- Ammoniated fly ash (AA) is an ash that contains ammonia sulfate (100-500 ppm) because of the urea injection process used to reduce emissions of nitrogen oxides at the plant.
- CFB fly ash - a lime-containing ash from a circulating fluidized bed process.

These ashes were provided by a US electric utility which uses bituminous coal to power a number of its powerplants. The actual amount of carbon (LOI) in the fly ashes is listed in Table 3.1 below.

Table 3.1 Fly Ash Carbon Content

Type of Fly Ash	LOI (%)
Processed Ash	1.59
Feed Ash	13.58
Residue Ash	18.37
Ammoniate Ash	30.25
CFB Ash	17.26

The cement used in the study was Type I Portland cement (ASTM C150)[8]. Tap water was used for all mixes (ASTM C94)[7].

4.0 Experimental Methods and Results

The flowable fills produced during the study was mixed using a mixing paddle attached to a drill. There was an attempt to use a 0.084 cubic meter, portable concrete mixer to make the first batch of flowable fill. However, this mixing method did not result in a homogenous mixture, and significantly more water was needed to achieve the desired flow of 20.3±2.5 cm. The final product also had excessive bleeding. It is hypothesized that use of the concrete mixer failed because of a lack of shearing agitation.

At the completion of mixing, test specimens were cured on level surfaces in a high humidity (relative humidity > 85%) moist room. Specimens remained in their molds until they were tested.

4.1 Mix Proportions and Properties

Table 4.1 lists the mix proportions and the calculated water to cementitious material (cement + fly ash) ratio for the various flowable fill mixes. The use of "bags" to designate the mixes is derived from the common terminology of the cement content of a specific concrete (e.g., 60 kg of cement in 1 m^3 of concrete).

Table 4.1 Mix Proportions for All Flowable Fills

	0.5 Bags	1.0 Bag	1.5 Bags	2.0 Bags	2.5 Bags
Processed Fly Ash (PA)					
Cement (T/m^3)	-	-	0.08	0.11	0.14
Fly Ash (T/m^3)	-	-	1.16	1.14	1.12
Water (T/m^3)	-	-	0.44	0.45	0.44
Flow (cm)	-	-	13.5	19.6	19.8
Water/(Cem.+PA)	-	-	0.35	0.36	0.35
Feed Fly Ash (FA)					
Cement (T/m^3)	-	-	0.08	0.11	0.14
Fly Ash (T/m^3)	-	-	1.16	1.15	1.12
Water (T/m^3)	-	-	0.65	0.61	0.61
Flow (cm)	-	-	22.2	20.6	19.7
Water/(Cem.+FA)	-	-	0.52	0.49	0.48
Residue Fly Ash (RA)					
Cement (T/m^3)	-	-	0.08	0.11	0.14
Fly Ash (T/m^3)	-	-	1.16	1.15	1.12
Water (T/m^3)	-	-	0.74	0.74	0.74
Flow (cm)	-	-	22.2	22.2	23.1
Water/(Cem.+RA)	-	-	0.60	0.58	0.58
Ammoniated Fly Ash (AA)					
Cement (T/m^3)	-	-	0.08	0.11	0.14
Fly Ash (T/m^3)	-	-	1.16	1.15	1.12
Water (T/m^3)	-	-	0.87	0.83	0.99
Flow (cm)	-	-	19.3	20.1	20.3
Water/(Cem.+AA)	-	-	0.70	0.66	0.78
CFB Fly Ash (CFB)					
Cement (T/m^3)	0.03	0.06	0.08	0.11	0.14
Fly Ash (T/m^3)	1.22	1.19	1.16	1.15	1.12
Water (T/m^3)	0.70	0.72	0.75	0.77	0.69
Flow (cm)	18.8	19.7	20.6	19.7	19.7
Water/(Cem.+CFB)	0.56	0.58	0.60	0.61	0.55

The mixes made with ammoniated fly ash required the largest amount of water compared to all of the other flowable fill mixes.

Table 4.2 presents plastic and hardened state properties of the mixes. The effect of higher carbon content is evident in the unit weights and specific gravities of the flowable fill mixes. Depending on the carbon content, the average unit weights of flowable fills decreased by 8% to 15% as compared with the average unit weight of the flowable fill made with the processed fly ash. This decrease in unit weight is because of the higher carbon content in the fly ashes that in general is much lighter in weight as compared with other constituents of fly ash.

The extensive bleeding that occurred with the ammoniated fly ash mixes is attributed to large amounts of water needed to achieve a flow of 20.3$\pm$2.5 cm. In

Table 4.2 Fresh and Hardened State Properties of Flowable Fills

Processed Fly Ash (PA)					
	0.5 Bags	1.0 Bag	1.5 Bags	2.0 Bags	2.5 Bags
Specific Gravity	-	-	1.69	1.70	1.71
Unit Weight (kN/m^3)	-	-	16.69	17.01	17.01
Bleeding (in, After 24 Hrs.)	-	-	None	None	None
Feed Fly Ash (FA)					
Specific Gravity	-	-	1.55	1.59	1.58
Unit Weight (kN/m^3)	-	-	15.42	15.73	15.58
Bleeding (in. After 24 Hrs.)	-	-	0.05	None	None
Residue Fly Ash (RA)					
Specific Gravity	-	-	1.50	1.53	1.53
Unit Weight (kN/m^3)	-	-	14.78	15.10	15.10
Bleeding (in. After 24 Hrs.)	-	-	0.2	0.1	0.1
Ammoniated Fly Ash (AA)					
Specific Gravity	-	-	1.43	1.42	1.12
Unit Weight (kN/m^3)	-	-	14.14	14.14	14.14
Bleeding (in. After 24 Hrs.)	-	-	0.5	0.5	0.5
CFB Fly Ash (CFB)					
Specific Gravity	1.57	1.57	1.55	1.55	1.57
Unit Weight (kN/m^3)	15.42	15.58	15.42	15.42	15.58
Bleeding (in. After 24 Hrs.)	-	-	-	-	-

addition to the excessive bleeding, AA mixes posed an additional problem in that once water was added, ammonia gas is released creating a very evident and unpleasant odor. Even though no solution to the ammonia release problem was found, ammoniated fly ash was used to make a flowable fill mix, because it contained the largest amount of free carbon (LOI = 30.25%) of all the non-standard fly ashes.

4.2 Testing

After measuring each mix for plastic state characteristics, such as specific gravity and flow, cured specimens from each mix were tested for;

- Unconfined compressive strength at the ages of 1, 7, 28, and 56 days[11]
- Confined compression tests (CC) at confining pressures of 0, 34.5, and 68.9 kPa were performed on specimens from 1.5 Bag mixes of processed (PA), feed (FA), residue (RA), and circulated fluidized bed (CFB) ash after curing for 24 hours.[12]

5.0 Test Procedures, Results and Discussion

5.1 Unconfined Compressive Strength Test

Table 5.1 shows the results of unconfined compression tests on the various mixes. Results reported are an average of three cylinders tested at each age [unless noted by an * (asterisk) indicating only two tests were successfully performed]. The table also includes the following information: unit weight, specific gravity, and water-to-cementitious materials ratio.

Table 5.1 Results of Unconfined Compression Tests on Flowable Fill Mixes

MIX DESIGNATION (Ash Carbon Content)	Unit Weight (kN/m^3)	Specific Gravity	Curing Time (Days)	Compressive Strength (kPa)	
				Average	Standard Deviation
PA 1.5 Bag (1.59%) *w/c* = 5.3	16.67	1.69	1	329.3	20.7
			7	892.9	45.5
			28	835.8*	-
PA 2.0 Bag (1.59%) *w/c* = 4.0	16.67	1.70	1	549.1	64.1
			6	1349.8	46.2
			28	1608.1	621.5
PA 2.5 Bag (1.59%) *w/c* = 5.2	16.94	1.71	1	786.8	2.1
			6	1539.9	479.5
			28	2249.6	75.8
FA 1.5 Bag (13.58%) *w/c* = 7.9	15.30	1.55	1	165.4	15.8
			7	459.6	13.1
			28	661.4	135.0
			56	717.2	14.5
FA 2.0 Bag (13.58%) *w/c* = 5.42	15.85	1.59	1	259.1	54.4
			7	799.9	64.1
			28	1430.4	118.5
			56	1887.2	218.4
FA 2.5 Bag (13.58%) *w/c* = 4.3	15.57	1.58	1	341.7	37.9
			7	1067.3	87.5
			28	1776.9	107.5
			56	2177.2	179.8
RA 1.5 Bag (18.37%) *w/c* = 8.93	14.75	1.50	1	135.0	0.7
			6	311.4	11.0
			28	509.9	61.3
			56	729.0	16.5
RA 2.0 Bag (18.37%) *w/c* = 6.5	15.03	1.53	1	157.8	55.1
			7	392.7	71.7
			28	710.4	92.3
			56	778.6	86.1
RA 2.5 Bag (18.37%) *w/c* = 5.2	15.03	1.53	1	170.9	3.4
			7	518.1	50.3
			28	1106.5	17.2
			56	1407.6	88.9

Table 5.1 (cont.) Results of Unconfined Compression Tests on Flowable Fill Mixes

MIX DESIGNATION (Ash Carbon Content)	Unit Weight (kN/m^3)	Specific Gravity	Curing Time (Days)	Compressive Strength (kPa)	
				Average	Standard Deviation
AA 1.5 Bag (30.25%) *w/c* = 10.4	14.14	1.43	1	108.9	21.4
			7	246.7	40.0
			28	384.5	82.7
			56	516.8	51.7
AA 2.0 Bag (30.25%) *w/c* = 7.4	14.14	1.42	1	120.6	9.6
			7	316.3	48.9
			28	373.4	33.1
			56	610.5	138.5
AA 2.5 Bag (30.25%) *w/c* = 6.9	14.14	1.42	1	93.7	10.3
			7	309.4	32.4
			28	432.7	3.4
			56	693.8	103.4
CFB 0.0 Bag (17.26%) *w/c* = N/A	15.10	1.52	1 / 7	-	-
			28	-	-
			56	149.5	42.0
CFB 0.5 Bag (17.26%) *w/c* = 23.5	15.42	1.57	1	35.1	-
			7	267.3	31.0
			28	859.9	35.8
			56	988.0	247.4
CFB 1.0 Bag (17.26%) *w/c* = 12.2	15.58	1.57	1	53.1	6.9
			7	241.8	104.0
			28	1117.6	407.2
			56	1411.8	135.0
CFB 1.5 Bag (17.26%) *w/c* = 9.0	15.42	1.55	1	84.1	13.1
			7	251.5	69.6
			28	1475.8	44.1
			56	1722.5	216.3
CFB 2.0 Bag (17.26%) *w/c* = 6.8	15.42	1.55	1	130.2	29.6
			7	381.7	123.3
			28	1271.2	138.5
			56	2124.9	110.2
CFB 2.5 Bag (17.26%) *w/c* = 4.8	15.58	1.57	1	175.0	15.8
			7	804.8	46.2
			28	3228.0	68.9
			56	4030.7	32.4

These results demonstrate the following trends:

(1) increasing the amount of portland cement in a flowable fill mix results in an increase in compressive strength regardless of the type of fly ash used in the mix,

(2) as the carbon content of a fly ash increases, more water was necessary to achieve the same level of fluidity in a flowable fill mix, and the increase in water resulted in lower strengths,

(3) flowable fill made with CFB fly ash had the highest compressive strength regardless of the amount of cement used,

(4) the lime found in CFB fly ash does not affect the early strength (1-day) of a flowable fill, but will increase the strength of the flowable fill as it ages,

(5) almost all mixes achieve compressive strengths of 689 kPa at 28 days, indicating they would be classified as non-excavatable (exceptions are the 1.5 bag mix for RA and all AA mixes).

5.2 Confined Compression Test (CC-Test)

Many flowable fill applications, such as the subbase layer for pavements, require that the material have adequate early age strength so as to minimize the down time needed for the flowable fill to gain sufficient strength before construction activities can resume. Thus, a secondary goal of the project was to achieve 1-day strengths of at least 192 kPa (to support low-pressure-tired vehicles). However, unconfined compressive strengths on 1.5 bag mixes show that the measured 1-day strengths rarely exceeded this objective; except for processed ash mixes.

To provide a more realistic measurement of flowable fill compressive strength, confined compression (CC) tests were performed. Providing confinement (σ_3) to the flowable fill more closely models actual field conditions of flowable fill and increases the ultimate compressive strength (defined as the deviator stress at failure, σ_{df}) of the material.

Confined compression tests were performed with confining pressures of 0, 34.5, and 68.9 kPa on 5.1 x 10.2 cm cylindrical specimens cast from 1.5 bag mixes made with processed (PA), feed (FA), residue (RA), and CFB fly ash. The samples were cured for 24 hours before testing. Three samples were tested at each confining pressure, and the tests with σ_3 = 0 kPa (i.e., a UC-test) were executed with and without a thin walled latex membrane surrounding the specimens. Specimens made from the 1.5 bag ammoniated ash mix were found to be too unstable during de-molding to be tested. The testing procedure followed closely that outlined in ASTM Standard D2850 for unconsolidated-undrained testing of soils. Cell pressures (σ_3) were kept constant during the tests. A seating pressure of 13.8 kPa was applied to all specimens except the second set of CFB fly ash specimens (seated with 3.45 kPa), which were tested for 7-day confined strengths (mix is designated CFB 1.5 Bag-7). Specimens were loaded at a constant rate of strain of one percent per minute. Test durations were approximately ten minutes. Test results are summarized in Table 5.3. The angles of friction and the predicted strengths presented in Table 5.2 were calculated using modified Mohr-Coulomb failure envelopes such as that shown in Figure 5.1 for the residue ash test results.

The results of the CC-tests show that with minimal confinement (σ_3 = 34.5 kPa) the 1.5 bag mix design results in the measurement of 24 hour compressive strengths greater than 192 kPa for the PA, FA, and RA mixes. The exception to this finding was the CFB mix tested after curing for 24 hours. This mix had the same w/c ratio as the RA mix, yet the test results show that the measured strengths (σ_3 = 34.5 kPa) were less than half of the RA strengths. This may indicate that the lime (CaO) in this CFB fly ash may actually retard the early strength gain of the flowable fill. However, with time, the strength of CFB-based flowable fill increased significantly, as demonstrated by the 7 day CC-test results.

6.0 Conclusions

Based on the results of this study, the following conclusions can be drawn.

1. Non-standard fly ash (high carbon, ammoniated, and CFB) can be used in high volumes (up to 11.6 kN per cubic meter) to produce flowable fill with engineering properties similar to other currently available flowable fills.
2. The flowable fill made with fly ash and cement had engineering characteristics similar to the engineering properties of flowable fills that contain sand and reported in the literature.
3. Regardless of the type of ash, a minimum of 2.2 kN/m^3 (1.5 bags) of Portland cement content is needed to make a flowable fill with a minimum unconfined compressive strength of 192 kPa. This strength is equivalent to the design strength of a layer of structural fill for normal building foundations (Massachusetts Building Code 780 CMR 1804.0).[18]
4. Increase in the amount of Portland cement in the flowable fill mixes significantly increased the compressive strength both at early (1 day) and later (56 days) ages.
5. As the carbon content of fly ash increased, more water was necessary to achieve the same level of fluidity as low carbon fly ash. The lower strength observed in the high carbon and ammoniated ash was primarily due to higher water requirement to maintain a flow of 20.3$\pm$2.5 cm.
6. The flowable fill made with the CFB fly ash and no cement gained some strength after 28 days of curing. This indicates the self-cementing properties of this particular fly ash similar to some Type C fly ash.
7. The flowable fill made with CFB fly ash had the highest compressive strength regardless of the amount of cement used. The strength increased significantly after the first week. This is another of its self-cementing and pozzolanic capability.
8. A high amount of ammonia was released during making flowable fill with the ammoniated fly ash. No ammonia release was detected once the samples were cast. This may be a hurdle in the use of ammoniated fly ash in flowable fill, unless some measures are taken to vent the ammonia released during the mixing and exposure of the work crew is minimized.
9. The unit weights of flowable fills made in this study were less than 16.9 kN/m^3. This is about 25% lighter than flowable fills made with sand. Depending on the application, this may be an advantageous to other types of fill used.

Table 6.1 Summary of CC-Test Results

MIX DESIGNATION (Ash Carbon Content)	Applied Cell Pressure, σ_3 (kPa)	Maximum Deviator Stress $\sigma_{df} = \sigma_1 - \sigma_3$ (kPa)	
		Average	Standard Deviation
PA 1.5 Bag-2 (1.59%)	0 (NM)	307.8	31.6
w/c = 5.3	0	389.4	18.7
ϕ= 45.8°	34.5	553.7	84.4
c = 76.8 (kPa)	68.9	710.7	16.3
FA 1.5 Bag (13.58%)	0 (NM)	135.9	9.0
w/c = 7.9	0	177.4	22.3
ϕ = 33.8°	34.5	271.1	39.2
c = 46.9 (kPa)	68.9	336.0	29.0
RA 1.5 Bag (18.37%)	0 (NM)	117.4	9.4
w/c = 9.0	0	127.1	5.9
ϕ = 35.3°	34.5	211.2	27.4
c = 31.7 (kPa)	68.9	311.3	11.2
CFB 1.5 Bag (17.26%)	0 (NM)	43.3	7.0
w/c = 9.0	0	64.8	3.3
ϕ = 14.8°	34.5	81.2	4.5
c = 23.9 (kPa)	68.9	104.2	19.4
CFB 1.5 Bag-7 (17.26%)	-	-	-
w/c = 9.0	0	465.4	-
ϕ = 32.1°	34.5	553.9	22.5
c = 117.8 (kPa)	68.9	513.1	97.8

(NM) indicates that no membrane was used for the test.

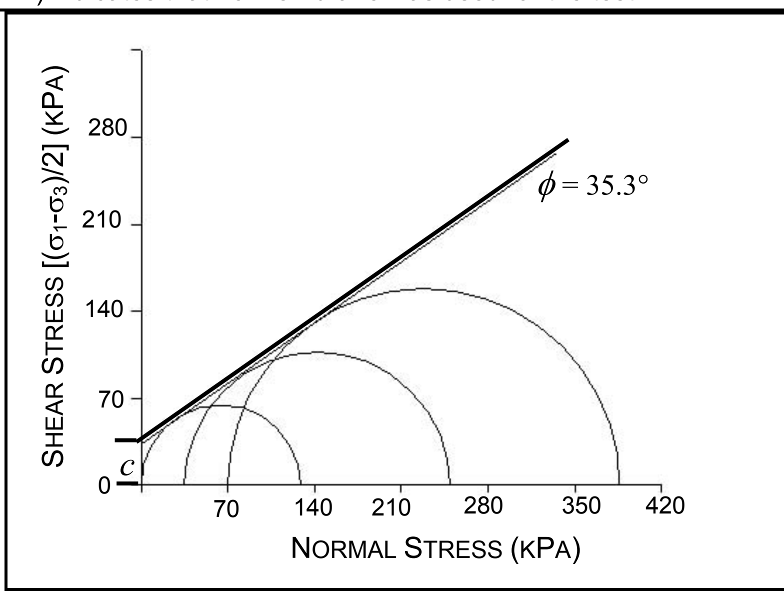

Figure 6.1 Modified Mohr-Coulomb Failure Envelope

7.0 Recommendations

As this study was limited to finding a mix of flowable fill that could incorporate maximum amount of non-standard fly ash and yet satisfy the strength concerns, we recommend performing the following study to gain a better understanding on its long-term durability and potential applications in the field.

1. We recommend conducting a study that simulates the placement of flowable fill under water, which may occur for some applications. This study can include testing the water for potential leachates as well as testing the hardened flowable fill for water intrusion and the impact that this type of placing may have on the compressive strengths of flowable fill.
2. It is necessary to investigate the long-term durability of this flowable fill particularly when it is placed at low or freezing temperature.
3. Some efforts are necessary to convince the regulatory agencies on the suitability of this material as fill for construction application and even filling mines or abandoned quarries. We recommend investigating the requirements and compiling the necessary technical documentations for such an undertaking.

8.0 Acknowledgements

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