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Potential Use of FGD as a Flowable-Fill

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ABSTRACT

Many flue gas desulfurization (FGD) materials have low unit weight and good shear strength characteristics and thus hold promise for flowable fill applications. This paper focuses on the potential of using spray dryer FGD ash in flowable fill as a replacement for conventional fly ash. Several design mixes were considered. The design mixes consisted of varying amounts of FGD, cement, lime, admixture, and water. The mixes were tested in the laboratory for flowability, unit weight, moisture content, unconfined compressive strength, erodibility, set-time, penetration, and long-term strength characteristics. Tests were conducted for up to 90 days of curing. The FGD flowable fill without any additives was observed to be comparable to regular (normal set) flowable fill in terms of placeability, unconfined compressive strength, and diggability. FGD flowable fill with additives and admixtures compared favorably with the characteristics of conventional quick set-flowable fills.

INTRODUCTION

Flowable fill is a cementious material, commonly a blend of cement, fly ash, sand and, water, that is self-leveling at time of placement, does not require compaction, may harden quickly within a few hours and can be readily excavated in the future if need be. Therefore, flowable fills are an effective and practical alternative to commonly used compacted earth backfills. Most flowable fill mixes are designed to have strengths of 150 to 200 psi for ease of excavation at a later time. Flowable fills are also commonly known by several other terms, including Controlled Density Fill (CDF), Controlled Low Strength Material (CLSM), unshrinkable fill, flowable mortar, plastic-soil cement slurry, etc. The performance criteria for flowable fills is outlined in ACI 229R-94.[1]

Fly ash is currently in common use for flowable fills applications.[2-4] Many FGD materials have low unit weight and good shear strength characteristics and hence also hold promise for flowable fill applications. Research conducted at The Ohio State University (OSU)[5] has investigated the potential of using dry and wet FGD materials in flowable fills. This paper presents the results of the laboratory testing program carried out at OSU to evaluate the suitability of using dry FGD in flowable fill applications.

TESTING PROGRAM

The laboratory test program was divided into ASTM standard tests on flowable fill that are presently used to evaluate the mix design and performance of flowable fill mixtures, and some other additional tests that may be applicable to assist in developing design requirements. Table 1 summarizes the test program. The designation "standard test" was applied to ASTM standard procedures for flowable fill including unconfined compressive strength (UCS), flowability, unit weight, ball drop test, and sampling of flowable fill. Among the standard tests, unconfined compressive strength and flowability tests were performed to determine whether FGD could satisfy the basic requirements of flowable fill. Additional tests include penetration, pinhole, and long term strength tests.

Table 1: Laboratory Tests Performed

	ASTM #	Test Method
Standard Tests	ASTM D 4832-95	Preparation and Testing of CLSM Test Cylinders (UCS test)
	ASTM D 6103-97	Flow Consistency of CLSM (flowability test)
	ASTM D 5971-96	Sampling Freshly Mixed CLSM
	ASTM D 6023-96	Unit Weight, Yield, Cement Content and Air Content of CLSM
	ASTM D 6024-96	Ball Drop on CLSM to Determine Suitability for Load Application
Additional Tests	ASTM C 403	Time of Setting of Concrete Mixtures by Penetration Resistance
	ASTM D 4832-95	Preparation and Testing of CLSM Test Cylinders
	ASTM D 4647-93	Identification and Classification of Dispersive Clay Soils by the Pinhole Test

The test conditions that were varied in the experimental program were the number of days the sample was allowed to cure, and initial moisture content. The total period for conducting all of the tests was 90 days.

The dry FGD material used in the laboratory tests was a spray dryer ash that was generated by an industrial boiler. The sorbent used by the spray dryer scrubber was lime. Three types of design mixes were prepared in the laboratory. As shown in Table 2, the mixes were assigned numbers 1 (driest) to 3 (wettest). The mixes were tested at 7, 14 and 28 days of curing. To evaluate the long-term strength, 60 and 90-day tests were performed. To find the initial set time, penetration tests were conducted at varying times between 12 and 144 hours after the mix had been made.

Table 2: Sample Mix Proportioning

Mix #	Mix W_c (%)	Dry Unit Wt.(pcf)
1	65.0	57
2	72.5	54
3	77.0	57

The testing program was designed to be able to make the following comparisons – a) Mix proportioning vs. Unconfined compressive strength, b) Strength gain vs. Curing time, c) Water content vs. Unconfined compressive strength, d) Mix proportion vs. Erodability, e) FGD process vs. Initial set time, f) Water content vs. Flowability, g) FGD flowable fill vs. Conventional flowable fill with respect to mix constituent, placeability, early penetration resistance, strength, and diggability.

RESULTS

A summary of the strength and flow tests is presented in Table 3. The strength of each mix is shown as a function of time. The results show that water content, as represented by flow immediately after mixing, affects the measured strength at all curing times. The results of the pinhole tests at 7 days of curing are presented in Table 4. The test results show that all the FGD mixes can be considered non-erodable. The results of the penetration tests are presented in Table 5. The spray dryer mixes show gradual increase up to 200 psi of penetration resistance throughout the testing period.

Table 3: Flowability and Strength Tests

Mix #	W_c (%)		Flow (inches)	Unconfined Compressive Strength (psi)				
	Initial	Mix		7 (days)	14 (days)	28 (days)	60 (days)	90 (days)
1	20	65.0	6	10	27	35	38	51
2	20	72.5	8	8	25	27	31	34
3	20	77.0	13	5	15	18	24	27

Table 4: Pinhole Erodibility Tests

Sample Number	Hole Diameter (mm)		Flow Rate (ml/sec)	
	Initial	After 60 min.	Initial	After 60 min.
1	1.0	1.0	1.00	1.02
2	1.0	1.0	1.00	1.02
3	1.0	1.0	1.00	1.03

Table 5: Penetration Test Results

Mix #	Penetration Resistance (psi)						
	12 (hrs)	16 (hrs)	20 (hrs)	24 (hrs)	48 (hrs)	96 (hrs)	144 (hrs)
1	54	73	91	100	140	170	190
2	45	69	81	90	134	158	172
3	NT	NT	NT	50	90	120	147

NT: Not Tested

The relationship between unconfined compressive strength and the curing time can be observed from Table 3. Measured strength increased with curing time for all samples. As the amount of water in a flowable fill mix increased, flowability increased. However, as the flowability increased, the unconfined compressive strength decreased. At 14 days curing time, the strength showed about 250-300 % increase compared with the strength at 7 days. For 28 day strength, the mixes showed about 120 % increase compared to 14 day strength. After 28 days, all the mixes showed continuous increase in strength. The mixes showed 90-day strength of 125-150 % increase compared with the 28-day strength.

The flow behavior is a very important property, and therefore it is essential to understand how different components of the flowable fill affect this behavior. The amount of water in the mix is mainly responsible for flow. Flowability increases with increasing water content (Table 3). A plot of flowability vs. strength (Figure 1) shows a decrease in strength with increasing flowability. The compressive strength decreases with increasing water content (Figure 2).

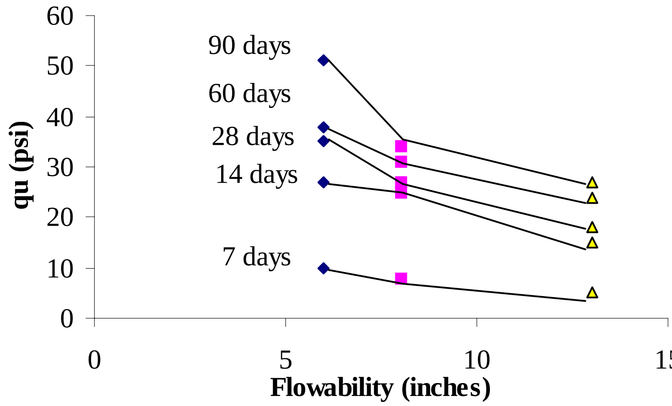

Figure 1: Unconfined Compressive Strength vs. Flowability

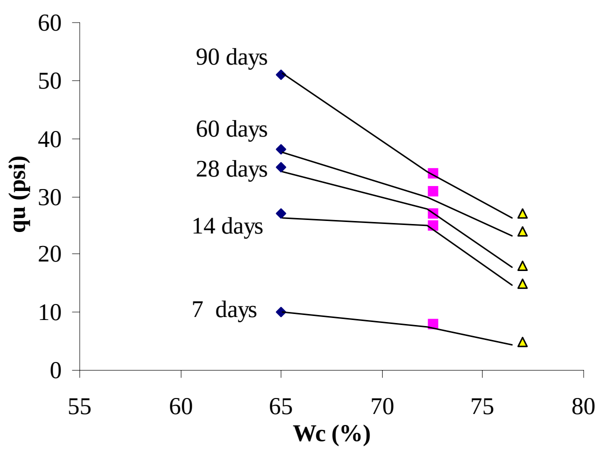

Figure 2: Unconfined Compressive Strength vs. Water Content

The penetration resistance – curing time relationship is shown in Figure 3. The 24 hour penetration resistance values were all less than 100 psi and even after 144 hours (6 days) resistance values were less than 200 psi. The mixes exhibited slow development of penetration resistance requiring approximately two to three weeks to reach 400 psi. Normal flowable fill[6] has a similar characteristic of slow gain of penetration resistance.

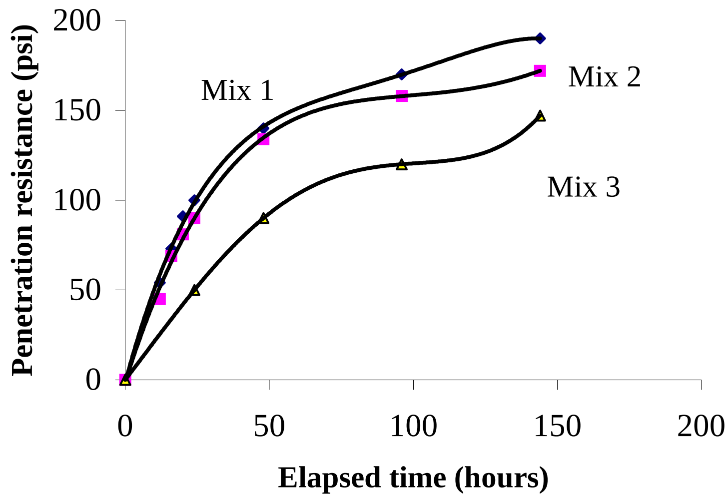

Figure 3: Time vs. Penetration Resistance

The penetration resistance characteristics of FGD flowable fill show that it should be suitable for replacing conventional flowable fill. However, FGD flowable fill may need to be modified when field applications need the flowable fill to set within 24 hours. Modifications of the design mixes to improve short term penetration resistance were carried out. The modified mixes designated M-1 through M-5 are shown in Table 6. To reduce the set time, cementitious material and acceleration admixtures were added. M-1, which was the control mix, consisted of spray dryer ash at 60 % water content giving an 8-inch flow. M-2 mix was made by reducing the amount of water and adding 6 % cement. In M-3, lime was substituted for the cement. M-4 was M-1 with an admixture (1.3% of POZZUTEC) added. M-5 was similar to M-2 with additional cement increasing the total added cement to 10 % and 5.9 % admixture included. The amount of admixture for M-5 (5.9% of the dry weight of cement) was the maximum dosage for concrete application according to the admixture manufacturer's guide. In this test, the dosage rate was calculated using the dry weight of FGD instead of cement. In mix M-4, a lower dosage recommended for reducing concrete set time was tried.

The penetration test results for the modified mixes are shown in Table 7. The mix with 10 % cement and the admixture (M-5) showed 400 psi penetration resistance at 24 hours and a continuous steep increase in resistance after that time. The mix with 6 % added cement (M-2) showed resistance increase with time as well but required 2 days of curing to reach 400 psi. The control (M-1) as well the mixes with 6 % added lime (M-3), and only admixture (M-4) did not reach 400 psi after 6 days of cure.

Penetration resistance vs. time relationship for the modified mixes is shown in Figure 4. Depending on the mix proportions, each mix showed various hardening curves. Mixes with increased cement and admixture added showed noticeable increases in early penetration resistance. Only the M-5 mix (with both cement and accelerating admixture) reached 400 psi in one day. Although the modified mixes for penetration tests did not set within three to four hours after placing, it is obvious from Figure 4 that increased cement content and the addition of the admixture reduce initial set time. Comparison between M-5, and M-2 shows that 4 % increased cement and added admixture reduced the set time by more than one day. As can be seen in Figure 4, cement seems to be more effective than lime in speeding up the set time. The FGD mixes with added cement always showed as much as 200% higher penetration resistance.

Table 6: Modified Mixes for Improved Penetration Resistance

Mix #	Water added (%)	Cement added (%)	Lime added (%)	Admixture added (%)	Flow (inch)
M-1	60				8
M-2	56	6			7
M-3	56		6		7
M-4	45			1.3	13
M-5	36	10		5.9	12

Note: Percentage based on dry weight of FGD

Table 7: Penetration Resistance for Modified Mixes

Mix #	Penetration Resistance (psi)								
	4 (hrs)	8 (hrs)	12 (hrs)	16 (hrs)	20 (hrs)	24 (hrs)	48 (hrs)	96 (hrs)	144 (hrs)
M-1	NT	40	60	80	100	120	160	180	210
M- 2	60	90	120	140	160	210	450	850	1200
M- 3	NT	NT	50	60	70	80	140	200	280
M- 4	NT	NT	NT	NT	NT	40	70	120	160
M- 5	95	170	240	300	350	400	800	1100	1300

NT: Not Tested

DISCUSSION

The recommended value for 28 day strength of flowable fill ranges from 25 psi to 60 psi.[6] The minimum specified strength is intended to provide sufficient support for construction and vehicular loads, whereas the maximum specified strength assures that the material will be diggable. A flowable fill with an unconfined compressive strength of 60 psi has at least two to three times the bearing capacity of a well compacted earthen backfill.[2] The test data show that the strength of the FGD flowable fill increases with curing time. As the amount of water in the flowable fill increased, flowability also increased. However, as the flowability increased, the unconfined compressive strength decreased. Mixes 1 and 2 satisfied the 28-day strength recommendation. Mixes 1 and 2 can be used for any kind of flowable fill applications. Mix 3 strength was less than 25 psi at 28 days. Although 13 inches of flowability provides good workability and placeability, a high moisture content in the spray dryer mix without any additive resulted in insufficient strength development.

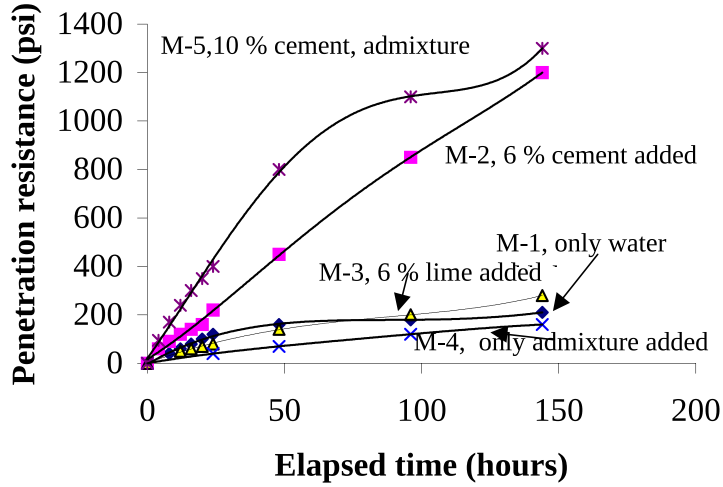

Figure 4: Penetration Resistance vs. Time for Modified Mixes

A flowability range of seven to eight inches would provide enough strength and good flowability for various fill applications. The minimum flowability value of seven inches is the recommended value for ensuring sufficient placeability. The upper value is important in the mixes without additives to achieve at least the minimum strength criterion. Cement, lime or suitable chemical admixture could be added to gain a higher strength if necessary. In such cases, the amount of cementitious material should be determined by long term strength tests to ensure later diggability.

The short term strength gain (up to about a day) is an important characteristic in order to support foot traffic and allow further loading. Generally, the flowable fill is considered to have hardened if it can be walked upon. The hardening characteristics were evaluated in the laboratory by measuring penetration resistance using a mortar penetrometer. The penetration resistance test results showed slow increase for the FGD mixes. The mixes were modified in order to reduce the time required to reach a resistance of 400 psi at 24 hours or less. At penetration resistance values of 400 psi, the flowable fill appeared to be hard and stable and capable of supporting a person's weight. It is obvious that the major factors affecting the early strength gain are the admixture and cement content in the mix. The environment conducive to cement hydration, the nature of FGD, and the drainage condition around the flowable fill, flowability, ambient temperature, humidity, and the depth of fill may be considered as other factors affecting initial set time. The higher amount of admixture and cement content causes the flowable fill to harden faster. Using fine aggregate or filler material to increase flowability instead of adding water could be a technique to make the mix more flowable without losing strength and retarding set time. Regulated set cement could be used in FGD flowable fill, because it can give shorter set time. However, before using that cement, some laboratory examination should be conducted such as penetration resistance and strength development tests. As discussed in the test results, the original FGD flowable fill showed low penetration resistance compared to quick set flowable fill. However, by modifying the original mixes with more cementitious material and proper admixtures, early hardening time can be reduced to one day. If field applications need a quick set flowable fill, FGD treated at the plant to enable early set, could be used.

A comparison of the characteristics of FGD flowable fill and a quick-set flowable fill[6] are shown in Table 8. The major difference between the two flowable fills is the inclusion of FGD or fine aggregate, sand. In terms of placeability, unconfined compressive strength, and diggability, FGD flowable fill can be considered as good as regular flowable fill (normal set). To be considered as a practical quick-set flowable fill, FGD flowable fill needs additional cement and admixture. If the mixes are properly designed to satisfy a specific application, there is a good possibility that FGD flowable fill can act like quick-set flowable fill.

Table 8: Comparison of FGD and Quick-Set Flowable Fills

	FGD Flowable Fill	**Quick-set Flowable Fill[6]**
Mix	FGD+Cement*/Lime*+water + Admixture**	Cement+sand+ Water+Admixture
Placeability	Excellent	Excellent
Early Penetration Resistance	400 psi obtained in 1~2days	400 psi obtained in 1/3~6hrs
Diggability	Diggable at UCS of up to 150~300 psi	Easily diggable at UCS of up to 60 psi
Corrosivity	Needs to be studied if necessary	Provides a non-corrosive environment
Resilient Modulus	Needs to be studied	25,000psi @24hrs

*, ** Optional

CONCLUSIONS

A laboratory test program was conducted to study the suitability of spray dryer FGD material as flowable fill. FGD flowable fill can be an economic alternative to conventional compacted fills and conventional flowable fills. The test program was designed to evaluate the important properties needed to characterize the FGD flowable fill. Flowability, strength development, time of set, and erosion resistance were studied.

The unconfined compressive strength test results showed that FGD flowable fill gains sufficient strength for various flowable fill applications. The strength mainly depends on cement and water content. The higher the cement content the higher the strength. As the water content increased, the strength decreased. Penetration resistance tests were conducted to compare the hardening behavior of different mixes. Although, the original mixes exhibited the slow strength development characteristics of regular flowable fill, a comparison between the mixes modified by adding accelerators and/or additional cement and the original mixes indicated that the major factors affecting penetration resistance are the cement and admixture content. A four percent increase in cement and added admixture reduced the set time by more than one day. The time to set could also be shortened by using high early set cement or high early strength cement. Pinhole test results indicate that FGD flowable fill is resistant to erosion and flood damage. Test results on the three candidate mixes and five modified mixes for penetration resistance showed that FGD flowable fill gains good strength to replace conventional compacted fill and has good placeability that originates from self leveling characteristic of flowable fill. Also, set-time could be reduced by appropriate mix proportioning when quick-set application is needed. It is recommended that mixes be designed to satisfy a set time requirement and then modified without compromising diggability limit.

Since flowable fill will typically continue to gain strength beyond the conventional 28 day testing period, it is suggested, especially for high cementitious content flowable fill, that long term strength tests be conducted to estimate the potential for later excavation. Furthermore, chemical reaction and mechanism that accelerate initial set-time need to be studied. It is important to keep the strength low enough to be diggable when necessary, but it is also necessary to make the mix set fast and gain proper strength. Long term strength tests for more than one year are needed and full scale field tests would be valuable. Resilient modulus, stress-strain behavior, freeze-thaw, and corrosivity characteristics also need to be studied. FGD materials change with various conditions such as FGD system, sorbent type, chemical constituents of material, temperature. Ash variability could change initial set time, ultimate strength, water content, corrosivity, durability, and workability. Hence, it is important to check ash quality before field mixing to ensure total quality of construction.

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