INNOVATIONS
IN CONTROLLED LOW-STRENGTH MATERIAL (Flowable Fill)

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TECHNICAL EDITORS:

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Innovations in Controlled Low-Strength Material (Flowable Fill)

Jenny L. Hitch, Amster K. Howard, and Warren P. Baas, editors

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Foreword

The Symposium on Innovations in Controlled Low-Strength Material (Flowable Fill) was held in Denver, Colorado on 19 June 2002. ASTM International Committee D18.15 served as sponsor. Symposium chairmen and co-editors of this publication were Jenny Hitch, ISG Resources, Inc., Las Vegas, NV; Amster Howard, Lakewood, CO; Warren Bass, Ohio Ready Mixed Concrete Assoc., Columbus, OH.

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Overview

This book represents the work of several authors at the *Symposium on Innovations in Controlled Low-Strength Material* (Flowable Fill), June 19, 2003, Denver, Colorado. This is the second symposium in the series concerning CLSM. The first symposium on The Design and Application of Controlled Low-Strength Materials (Flowable Fill) was presented June 19–20, 1997 in St. Louis, Missouri (STP 1331).

The use of Controlled Low-Strength Material (CLSM), or flowable fill as it is commonly known, has increased dramatically over the past two decades. It is continuing to gain acceptance in the construction industry despite the rather new technology and limited number of test methods available. Innovations in the field of CLSM continue to push the technology and create higher quality products. The purpose of this symposium was to continue to increase awareness of CLSM by presenting new design procedures, current research, unique project applications, and innovative installation techniques. The information presented is intended to help ASTM Subcommittee D18.15 assess the need for new or improved standards to add to the current five standards concerning CLSM under their jurisdiction.

CLSM is also known as flowable fill, flow fill, controlled density fill, soil-cement slurry, and K-crate™, among others. It is a mixture of cementitious material (portland cement or Class C fly ash), fly ash, soil and/or aggregates, water, and possibly chemical admixtures that, as the cementitious material hydrates, forms a soil replacement material. CLSM is used in place of compacted backfill or unsuitable native soil with the most common uses as pipe embedment and backfill. However, some of the many uses of CLSM are illustrated in the papers contained in this publication by Moberly et al, Jones and Giannakou and Crouch et al.

The symposium was divided into three parts to cover pertinent developments in the use of CLSM, as follows:

*Innovative Ingredients
*Engineering Property Analysis
*Pipeline Applications

Innovative Ingredients

The intent of this section was to explore the use of non-traditional ingredients in CLSM and to determine their suitability or limitations. Three papers dealt with the use of non-traditional pozzolans in CLSM mixes:

Tarunjit S. Butalia, et al, discusses the use of two types of flue gas desulfurization (FGD) materials; spray dryer and wet fixated FGD material, in flowable fill as a replacement for conventional fly ash.

Tarun R. Naik, et al, utilized wood fly ash as the major component in CLSM and found that material to be an acceptable replacement for ASTM C618 fly ash.

Richard L. Moberly, Leslie B. Voss and Michael L. Mings described a case study of the stabilization of an abandoned limestone mine that utilized dry scrubber ash as opposed to ASTM C618 fly ash.

One paper dealt with the use of a local fly ash in CLSM mixes.

B.K. Sahu and K. Swarnadhipati utilized fly ash from the Moruple Thermal Power Station in Botswana to study the effect of varying lime and cement contents on the overall suitability of CLSM.

One paper discussed the use of non-traditional aggregates in CLSM mixes:

J. S. Dingrando, T. B. Edil and C.H. Benson studied the effect on unconfined compressive strength and flow of flowable fills prepared with a variety of foundry sands used as a replacement for conventional fine aggregate.

Engineering Property Analysis

Determining the engineering properties for certain applications of CLSM is very important. This section includes papers that utilized existing ASTM test methods as well as explored new methods to measure parameters, such as excavatibility.

Four papers dealt with the engineering properties of CLSM:

L.K. Crouch and V.J. Dotson tested CLSM mixtures to see if they would pass ASTM D6024 in six hours or less, produce little or no bleeding or shrinkage, have a flow greater than 222 mm per ASTM D6103, and have a 24-hour compressive strength greater than 201 kPa as per ASTM D4832.

H. Tripathi, C. E. Pierce, S.L. Gassman and T.W. Brown evaluated several standard and non-standard methods to measure flow consistency and setting time on various field and laboratory mixes.

L.K. Crouch, et al, studied the relationship between compressive strength and long-term excavatibility for twenty-three flowable fill mixtures.

M. Roderick Jones and Aikaterini Giannakou examined the performance of a range of foamed concretes for use as controlled thermal fill (CTF) in trench fills and ground slabs. Performance criteria included compressive strength, capillary sorption, resistance to aggressive chemical environments, resistance to freezing and thawing, thermal conductivity and drying shrinkage.

Pipeline Applications

As previously stated, one of the most common uses for CLSM is pipe backfill. This section is devoted to that topic with two papers that address some of the issues related to pipeline design.

Teruhisa Masada and Shad M. Sargand reported the results of a research project designed to evaluate the feasibility of constructing an economical drainage pipe system using a flexible thermoplastic pipe and flowable fill.

Fred P. Hooper, et al, analyzed the permeability of backfill materials before freezing, during freezing and after thawing in order to determine their suitability as utility line backfill.

The papers contained in this publication highlight the innovations in technology, test methods and material science that have occurred during the evolution of CLSM. The information presented by the authors will be extremely helpful to ASTM Subcommittee D18.15 in their quest to assist the industry by providing up to date and meaningful standards on CLSM.

ASTM Standards on CLSM

The Appendix to this STP contains the current ASTM Standards on CLSM developed by Committee D18 on Soil and Rock, as follows:

D4832 Standard Test Method for preparation and Testing of Controlled Low Strength Material (CLSM) Test Cylinders

D5971 Standard Practice for Sampling Freshly Mixed Controlled Low-Strength Material

D6023 Standard Test Method for Unit Weight, Yield, Cement Content, and Air Content (Gravimetric) of Controlled Low Strength Material (CLSM)

D6024 Standard Test Method for Ball Drop on Controlled Low Strength Material (CLSM) to Determine Suitability for Load Application

D6103 Standard Test Method for Flow Consistency of Controlled Low Strength Material (CLSM)

Acknowledgments

We wish to thank all the authors and reviewers whose hard work made the symposium an interesting and very useful forum for discussing the current use and intriguing innovations of Controlled Low-Strength Material. We would also like to thank the staff at ASTM for their enormous help in organizing this symposium and STP.

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Section I: Innovative Ingredients

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Flowable Fill Using Flue Gas Desulfurization Material

ABSTRACT: Flowable fills are an effective and practical alternative to commonly used compacted earth backfills. Flowable fill is a cementious material, commonly a blend of cement, fly ash, sand, and water, that does not require compaction, may be self-leveling at time of placement, may harden quickly within a few hours, and can be excavated in the future if need be. 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 two types of FGD materials (spray dryer and wet fixated FGD material) in flowable fill as a replacement for conventional fly ash. Several design mixes were considered. The design mixes consisted of varying amounts of FGD material, cement, lime, 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 d of curing. Without any additives, the FGD material was observed to be as good as a regular (normal set) flowable fill in terms of placeability, unconfined compressive strength, and diggability. FGD material flowable fill with additives and admixtures compares favorably with the characteristics of conventional quick set flowable fills.

KEYWORDS: FGD material, coal combustion products

Introduction

Flowable fill is a cementious material, commonly a blend of cement, fly ash, sand, and water, that does not require compaction, may be self-leveling at time of placement, may harden quickly within a few hours and can be 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 unconfined compressive strengths of 1000 to 1400 kPa (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 are outlined in ACI 229R-94 [1].

Fly ash is currently in common use for flowable fill applications [2–4]. Many flue gas desulfurization (FGD) materials, generated from sulfur dioxide control equipment at coal-fired power plants, 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) has investigated the potential of using dry and wet FGD materials in flowable fills [5]. This

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paper presents the results of a laboratory-testing program carried out at OSU to evaluate the suitability of using spray dryer and wet fixated FGD materials 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 additional tests that may 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, and sampling of flowable fill. Among the standard tests, unconfined compressive strength and flowability tests were performed to determine whether FGD material could satisfy the basic requirements of flowable fill. Additional tests include penetration, pinhole, and long-term strength tests. The pinhole test (ASTM D4647) evaluated the erosion potential of the FGD material.

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
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 Pinhole Test

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

Two types of FGD materials were studied in this laboratory-testing program. 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. The wet fixated FGD material investigated in this study is a sulfite rich mixture of filter cake, fly ash, and lime. For the fixated FGD material, the fly ash to filter cake ratio was 1.25:1, and the lime content was 6 % (on a dry weight basis).

Five types of design mixes, three using spray dryer and two using fixated FGD materials, were prepared in the laboratory. As shown in Table 2, the mixes were assigned numbers 1 (driest) through 5 (wettest). The mixes were tested at 7, 14, and 28 d of curing. To evaluate the long-term strength, 60 and 90 d tests were performed. To find the initial set time, penetration tests were conducted at varying times between 12 and 144 h after the mix had been made.

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) Water content vs. Flowability, and f) FGD material flowable fill vs. Conventional flowable fill with respect to mix constituent, placeability, early penetration resistance, strength, and diggability.

TABLE 2—*Sample mix proportioning.*

Type of FGD Material	Mix #	Water Added (%)**	Cement Added (%)**	Lime Added (%)**	Dry Unit Weight (kN/m^3)
Spray Dryer	1	65.0			8.95
	2	72.5			8.48
	3	77.0			8.95
Fixated*	4	82.5	6 %		8.33
	5	84.0		6 %	8.48

*Fly ash to filter cake ratio is 1.25:1, with a lime content of 5 %.
**Percentage based on dry weight of FGD material.

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. For a given type of FGD material (spray dryer or fixated), the results show that water content, as represented by flow immediately after mixing, affects the measured strength at all curing times. The addition of lime and cement to the fixated FGD material mixes (Mix 4 and 5) clearly influenced the long-term strength of these materials. The results of the pinhole tests at 7 d of curing are presented in Table 4. The test results show that all the FGD material flowable fill mixes can be considered non-erodable. The results of the penetration resistance tests are presented in Table 5. The spray dryer mixes show gradual increase up to 1400 kPa of penetration resistance throughout the testing period. The fixated FGD material mixes reached 2800 kPa after 48 h.

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 for flowable fill mix increased, flowability increased for each FGD material investigated. However, as the flowability increased, the unconfined compressive strength decreased. At 14 d curing time, the strength showed about 150–300 % increase, compared with the strength at 7 d. For 28 d strength, the spray dryer FGD material mixes showed about 120 % increase compared to 14 d strength. The fixated FGD material mixes showed a much higher strength gain, about 300–700 % increase at 28 d compared to 14 d strength. After 28 d, all the mixes showed continuous increase in strength. The mixes showed 90 d strength of 125–500 % increase compared with the 28 d strength, with higher strength increase gains occurring for the fixated FGD material mixes.

TABLE 3—*Flowability and strength tests.*

Type of FGD Material	Mix #	W_c (%)	Flow (mm)	Unconfined Compressive Strength (kPa)				
				7 d	14 d	28 d	60 d	90 d
Spray Dryer	1	65.0	150	69	186	241	262	352
	2	72.5	200	55	172	186	214	234
	3	77.0	330	34	103	124	165	186
Fixated	4	82.5	150	103	262	1041	1689	2523
	5	84.0	180	NT	62	379	1227	2261

NT: Not tested because sample could not be removed from mold due to insufficient strength.

TABLE 4—*Pinhole erodibility tests.*

Type of FGD Material	Mix #	Hole Diameter (mm)		Flow Rate (mL/s)	
		Initial	After 60 min	Initial	After 60 min
Spray Dryer	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
Fixated	4	1.0	1.0	1.00	1.02
	5	1.0	1.0	1.00	1.02

TABLE 5—*Penetration resistance test results.*

Type of FGD Material	Mix #	Penetration Resistance (kPa)						
		12 (h)	16 (h)	20 (h)	24 (h)	48 (h)	96 (h)	144 (h)
Spray Dryer	1	372	503	627	689	965	1170	1310
	2	310	475	558	620	924	1090	1185
	3	NT	NT	NT	345	620	827	1015
Fixated	4	689	965	1205	1380	2345	3960	4435
	5	593	710	951	1105	2100	2980	3570

NT: Not Tested

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. For each of the FGD materials investigated in this study, the flowability increased with increasing water content (Table 3). Plots of flowability vs. strength (Figs. 1 and 2) show a decrease in strength with increasing flowability. The compressive strength decreases with increasing water content (Figs. 3 and 4).

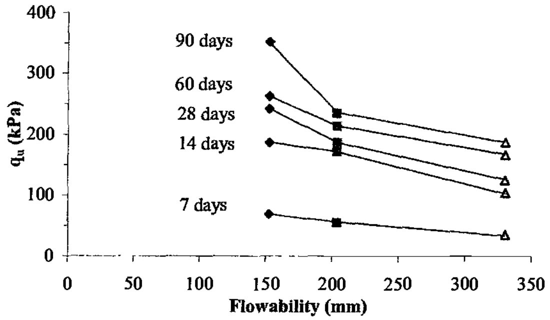

FIG. 1—*Unconfined compressive strength vs. flowability for spray dryer FGD material mixes.*

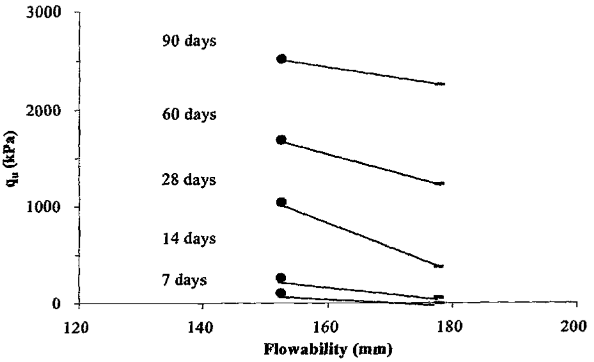

FIG. 2—*Unconfined compressive strength vs. flowability for stabilized FGD material mixes.*

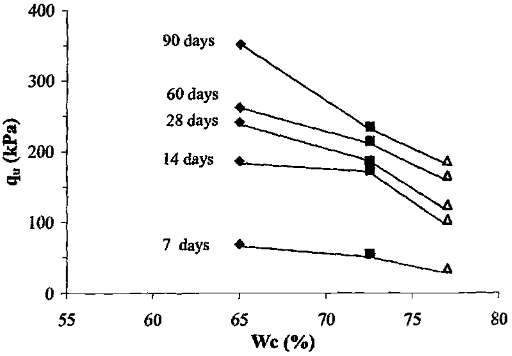

FIG. 3—*Unconfined compressive strength vs. water content for spray dryer FGD material mixes.*

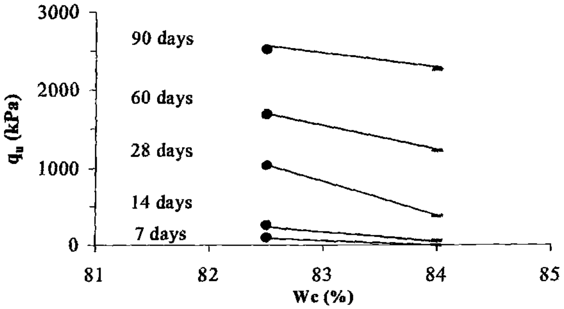

FIG. 4—*Unconfined compressive strength vs. water content for stabilized FGD material mixes.*

The penetration resistance (i.e., curing time relationships) are shown in Figs. 5 and 6. The 24 h penetration resistance values for spray dryer FGD material mixes were all less than 700 kPa, and even after 144 h (6 d), penetration resistance values were less than 1400 kPa. The spray dryer mixes exhibited slow development of penetration resistance, requiring approximately two to three weeks to reach 2800 kPa. Normal flowable fill has a similar characteristic of slow gain of penetration resistance [6]. The fixated FGD material mixes with cement or lime as additives reached 2800 kPa at 48 h. Mix 4 (with cement as additive) reached initial set faster and exhibited penetration resistance that was 110–135 % higher at each recorded time than the values measured for Mix 5 (with lime as additive). However, the fixated FGD material mixes did not reach 2800 kPa in less than 24 h as recommended by Federal Highway Administration and others [2,4,6].

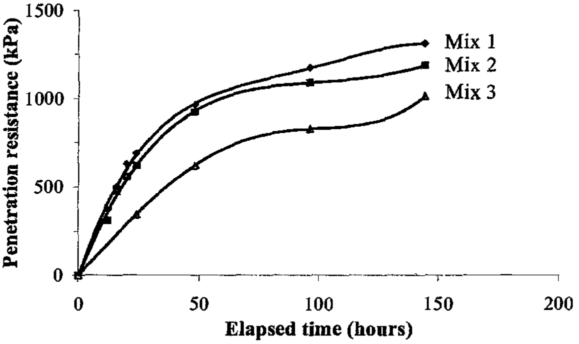

FIG. 5—*Time vs. penetration resistance for spray dryer FGD material mixes.*

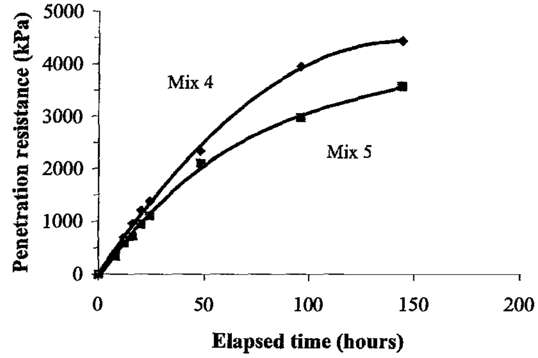

FIG. 6—*Time vs. penetration resistance for stabilized FGD material mixes.*

The penetration resistance characteristics of FGD material flowable fill show that it should be suitable for replacing conventional flowable fill. However, FGD material flowable fill may need to be modified when field applications need the flowable fill to set within 24 h. Modifications of the design mixes to improve short-term penetration resistance were carried out. The modified mixes designated M-1 through M-7 are shown in Table 6. To reduce set time, cementitious material and admixtures were added.

TABLE 6—*Modified mixes for improved penetration resistance.*

Type of FGD Material	Mix #	Water Added (%)**	Cement Added (%)**	Lime Added (%)**	Admixture Added (%)**	Flow (mm)
Spray Dryer	M-1	60				200
	M-2	56	6			180
	M-3	56		6		180
	M-4	45			1.3	330
	M-5	36	10		5.9	300
Fixated*	M-6	30	10			250
	M-7	30	10		5.9	300

*Fly ash to filter cake ratio is 1.25:1, with a lime content of 5 %.
**Percentage based on dry weight of FGD material.

For the spray dryer FGD material mixes, which had no additional materials in the original mixes, five test mixes were chosen. Mix M-1, which was the control mix, consisted of spray dryer ash at 60 % water content giving a 200 mm flow. M-2 mix was made by reducing the amount of water and adding 6 % Type I cement. In Mix M-3, lime was substituted for the cement. Mix M-4 was the same as Mix M-1 but with an admixture (1.3 % of POZZUTEC) added. Mix M-5 was similar to Mix M-2 with additional cement increasing the total added Type I cement to 10 % and 5.9 % admixture (i.e., 5.9 % of the dry weight of cement) included. For the fixated FGD material, an additional 4 % cement was added to Mix M-6 to bring the total cement content to 10 %. Mix M-7 is Mix M-6 with 5.9 % of the admixture added to it. The amount of admixture for Mix M-5 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 material 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 spray dryer mix with 10 % cement and the admixture (M-5) showed 2800 kPa penetration resistance at 24 hs 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 d of curing to reach 2800 kPa. The control (M-1) as well the mixes with 6 % added lime (M-3) and only admixture (M-4) did not reach 2800 kPa after 6 d of cure. The modified mixes for fixated FGD materials (M-6 and M-7) reached 2800 kPa at less than 48 h.

Penetration resistances vs. time relationships for the modified mixes are shown in Figs. 7 and 8. 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 2800 kPa in one day. Although the modified mixes for penetration tests did not set within three to four h after placing, it is obvious from Figs. 7 and 8 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 Figs. 7 and 8, cement seems to be more effective than lime in speeding up the set time. The fixated FGD material mixes with added cement always showed more than 100 % higher penetration resistance. The spray dryer FGD material mixes with added cement showed as much as 200 % higher penetration resistance.

TABLE 7—*Penetration resistance for modified mixes.*

Type of FGD Material	Mix #	Penetration Resistance (kPa)								
		4 h	8 h	12 h	16 h	20 h	24 h	48 h	96 h	144 h
Spray Dryer	M-1	NT	276	414	552	689	827	1105	1240	1450
	M-2	414	621	827	965	1105	1450	3105	5860	8275
	M-3	NT	NT	335	414	483	552	965	1380	1930
	M-4	NT	NT	NT	NT	NT	276	483	827	1105
	M-5	655	1170	1655	2070	2415	2760	5515	7585	8965
Fixated	M-6	483	896	1310	1655	1930	2070	3380	4205	5445
	M-7	689	1170	1585	2000	2205	2415	3790	4825	5860

NT: Not Tested.

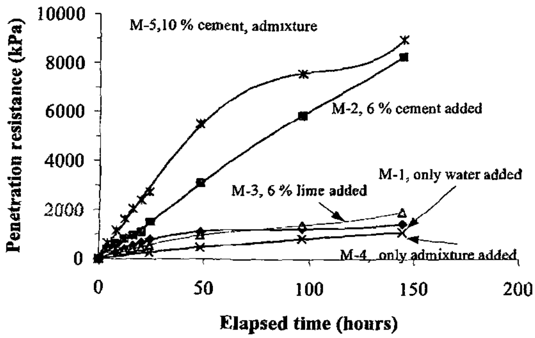

FIG. 7—*Penetration resistance vs. time for modified spray dryer FGD material mixes.*

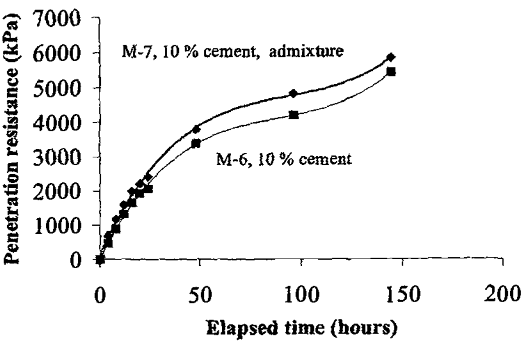

FIG. 8—*Penetration resistance vs. time for modified stabilized FGD material mixes.*

Discussion

The recommended value for 28 d strength of flowable fill ranges from 170–410 kPa (25–60 psi) [6]. The minimum specified strength is intended to provide sufficient support for construction and vehicular loads, whereas the maximum specified strength ensures that the material will be diggable. A flowable fill with an unconfined compressive strength of 410 kPa 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 material 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. Spray dryer mixes 1 and 2 satisfied the 28 d strength recommendation. Mixes 1 and 2 can be used for any kind of normal-set flowable fill applications. Fixated FGD material Mix 5 gained significant strength during curing. For areas where diggability is required, Mix 5 may not be preferred since it developed strength of more than 2100 kPa at 90 d. Spray Dryer Mix 3 strength was less than 170 kPa at 28 d.

Although 330 mm of flowability provides good workability and placeability, a high moisture content in the spray dryer mix without any additive resulted in insufficient strength development. Fixated FGD material Mix 4 gained too much strength in the first 28 d of curing. This situation can be controlled at the plant by reducing the amount of cement to less than 6 % as long as the set-time criterion is satisfied. In addition, limiting the amount of cementitious materials in Mix 4, entrained air can be used to keep the compressive strength low.

A flowability range of 180–250 mm would provide enough strength and good flowability for various fill applications. The minimum flowability value of 180 mm 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 one 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 material mixes. The mixes were modified in order to reduce the time required to reach a resistance of 2800 kPa at 24 h or less. At penetration resistance values of 2800 kPa, 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 material, 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 material 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 material flowable fill mixes 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 material treated at the plant to enable early set could be used.

A comparison of the characteristics of FGD material 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 material, or fine aggregate sand. In terms of placeability, unconfined compressive strength, and diggability, FGD material flowable fill can be considered as good as regular flowable fill (normal set). To be considered as a practical quick-set flowable fill, FGD material flowable fill needs additional cement and admixture. If the mixes are designed properly to satisfy a specific application, there is a good possibility that FGD material flowable fill can act like quick-set flowable fill.

TABLE 8—*Comparison of FGD material and quick-set flowable fills.*

Properties	FGD Material Flowable Fill	Quick-set Flowable Fill [6]
Mix	FGD material + Cement*/Lime*+water + Admixture**	Cement+sand+ Water+Admixture
Placeability	Excellent	Excellent
Early Penetration Resistance	2800 kPa obtained in 1~2 d	2800 kPa obtained in 1/3–6 h
Diggability	Diggable at UCS of up to 1000–2100 kPa	Easily diggable at UCS of up to 410 kPa
Corrosivity	Needs to be studied if necessary	Provides a non-corrosive environment
Resilient Modulus	Needs to be studied	170 MPa @24 h

*, ** Optional.

Conclusions

A laboratory test program was conducted to study the suitability of spray dryer and fixated FGD materials as flowable fill. FGD material 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 material flowable fill. Flowability, strength development, time of set, and erosion resistance were studied.

The unconfined compressive strength test results showed that FGD material 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. For the fixated FGD material mixes, the admixture reduced the initial set time by about 5 to 6 h. For the spray dryer FGD material, a 4 % 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 material flowable fill is resistant to erosion and flood damage. Test results on the five candidate mixes and seven modified mixes for penetration resistance showed that FGD material 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 d 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 reactions and mechanisms 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, swell potential, and corrosivity characteristics also need to be studied. FGD materials change with various conditions such as FGD system, sorbent type, chemical constituents of material, and temperature. Ash variability could change initial set time, ultimate strength, water content, corrosivity, durability, and workability. Hence, it is important to check FGD material quality before field mixing to ensure total quality of construction.

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Beneficial Reuse of Foundry Sands in Controlled Low Strength Material

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ABSTRACT: A study was conducted to determine how the unconfined compressive strength and flow of flowable fills prepared with foundry sand depends on the bentonite content of the sand. The study showed that there are several advantages of using foundry sands with bentonite content > 6 % as the fine aggregate in flowable fill. These advantages include: (i) lower long-term strength gain (making the design of excavatable mixtures simpler and less risky), (ii) less flow loss, (iii) fewer components and fewer interactions between components that are difficult to characterize, and (iv) a larger fraction of inexpensive foundry sand being used in the mixture. The unconfined compressive strength (UCS) of flowable fills prepared with foundry sands is sensitive to the water-cement ratio (W/C), at least when the W/C spans a broad range (4–11). Mixtures with W/C < 6.5 generally will have excessive UCS, whereas a suitable UCS is generally associated with W/C > 6.5. Bentonite content does not affect the UCS systematically, but it does have an indirect effect in that foundry sands with more bentonite require more water to flow, which affects strength. The amount of water required to achieve adequate flow primarily is a function of the bentonite content of the foundry sand. In general, as the bentonite content of the foundry sand increases, the water content of the mixture should increase correspondingly. The amount of fly ash has only a modest effect on the amount of water required. The most important factor affecting flow loss is the presence of cementitious fly ash in the mixture. Flow loss can be reduced appreciably by using a foundry sand with at least 6 % bentonite so that fly ash fines need not be added to the mixture.

KEYWORDS: flowable fill, foundry sand, bentonite, fly ash, cement, flow, compressive strength

Introduction

Increasing landfill disposal costs have led the US foundry industry to find ways to reuse excess foundry sand, a byproduct of the casting process [1, 4]. Controlled low strength material (CLSM), or flowable fill, is an application where foundry sand has been found to be an effective replacement for conventional fine aggregate [1, 4, 10]. Flowable fill is a slurry typically composed of sand, cement, fly ash, and water that is mixed, delivered, and placed much like ready-mix concrete. However, unlike concrete, flowable fill has soil-like properties after it cures, including lower strength, which permits future excavation if necessary. Common applications of flowable fill include backfill for trenches and bridge abutments and filling of underground voids (tanks, pipelines, solution cavities, etc.).

Three key characteristics of flowable fill are strength, flow, and setting time. The fill must be strong enough to support loads but not so strong to preclude future excavation. The unconfined compressive strength (UCS) is often required to be at least 0.3 MPa, whereas the maximum strength is often limited to 1.0–1.4 MPa to permit future removal using conventional excavators [3]. The flow must be high enough so that the fill is self-leveling, yet not so high that excessive bleeding (release of excess water) or aggregate segregation occurs. Generally the flow is targeted to be approximately 230 mm, as defined by ASTM Standard Test Method for Flow

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Consistency of Controlled Low Strength Material (CLSM) (D 6103). For example, the Wisconsin Department of Transportation (WisDOT) requires a minimum flow of 225 mm. The fill also must harden in a reasonable amount of time, but it must set slow enough so that the fill flows when delivered to the project site. These characteristics are achieved by varying the relative proportions of the sand, cement, fly ash, and water.

Foundry sand is used in flowable fill in place of natural fine aggregate because foundry sand consists primarily (> 80 %) of fine uniform silica sand (often called "base sand"). Foundry sand also contains a binding agent, water, and organic additives (usually organic material). There are two general types of foundry sands: green sands and chemically bonded sands. Green sands use clay (typically 3–16 % sodium bentonite) as the binding agent, whereas chemically bonded sands use a polymeric resin. Organic additives are used to improve the surface finish of castings and usually comprise less than 8 % of foundry sand by mass. The most common is "sea coal" (powdered coal), although cellulose, cereals, and petroleum distillates are also used [1, 4]. Although each of these components can affect the properties of foundry sands, bentonite content is by far the most influential property affecting the engineering properties relevant to civil engineering applications [2, 6].

Because the composition of foundry sand varies temporally and between sources, flowable fills using foundry sand are generally designed on a case-by-case basis. This process can be simplified by understanding how the properties of foundry sand control the behavior of flowable fills. The objective of this study was to determine how the bentonite content of foundry sand affects the UCS and flow of flowable fill. Tests to evaluate setting time and environmental degradation were also performed but are not included in this paper due to length limitations [5].

Previous Studies on Flowable Fill Containing Foundry Sand

Bhat and Lovell studied the characteristics of flowable fill containing foundry sand and Class F fly ash [4]. Mixtures were prepared with Class F fly ash and either foundry sand, a base sand, or a river sand meeting requirements for use in concrete (ASTM Standard Specification for Concrete Aggregates (C 33)). Three foundry sands and two Class F fly ashes were used. A unique relationship (called a flow curve) was found between the ratio $M_F/(M_F+M_S)$, where M_F is the mass of fly ash and M_S is the mass of sand and the water-solids ratio for a given type of sand and fly ash. The source of fly ash did not affect the amount of water required to reach the target flow significantly, but the type of sand was important. Mixtures prepared with foundry sands required much more water than the river sand or base silica sand. Also, mixtures prepared with two of the foundry sands had adequate flow characteristics without the addition of fly ash. Unconfined compressive strength (UCS) of the mixtures was measured at curing times between 3 and 90 d. The UCS increased by 15–25 %, on average, between 28 and 90 d, but factors contributing to greater strength gain were not identified. The UCS at 28 d showed a correlation to the water-cement ratio (W/C) similar to that for concrete.

Naik and Singh [10] evaluated the effect of replacing various percentages of fly ash with foundry sand in excavatable flowable fill, which they defined as having a 28 d UCS < 0.69 MPa. Mixtures were prepared with three sands (a concrete sand, a base silica sand, and a steel foundry sand) and two Class F fly ashes. Reference mixtures without sand but only fly ash were compared with mixes containing four different levels of fly ash replacement with sand (30, 50, 70, and 85 % by mass). They found that the UCS typically increased with increasing sand replacement, at least to a point beyond which additional sand replacement caused the UCS to decrease. They also found that the volume of bleed water depends on the source of the fly ash, and it increases with increasing sand content for mixtures with the same flow. For all mixtures, shrinkage cracking was non-existent, and settlement ceased within 3 d of curing. Settlements less than 3 mm required a flow less than 280 mm.

Materials

Foundry Sands

Sixteen foundry sands were used in this study. Index properties of the sands are summarized in Table 1. All of the sands were used for flow testing. Four of the green sands and the chemically bonded sand were used to study how foundry sand affects the UCS. Particle size distribution curves for these five foundry sands are shown in Fig. 1. The sands used for the evaluation of UCS were selected so that they had a broad range of bentonite contents (0–13 %).

Reference Sand

A uniform silica base sand ($C_u = 1.4$, $C_c = 1.1$, $D_{50} = 0.2$ mm) was used as the reference sand. The particle size distribution curve for the reference base sand is shown in Fig. 1.

Fly Ash

An "off-specification" fly ash acquired from an electric-power generating station in Wisconsin was used as a source of fines. Off-specification implies that the fly ash that does not meet the criteria required to classify as C or F according to ASTM Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete (C 618). Properties of the ash are summarized in Table 2.

TABLE 1—*Index properties of foundry sands and reference sands used in study.*

Sand	Binder Type	Fines (%)	Clay (%)	Liquid Limit	Plasticity Index	USCS Class	AASHTO Class	Specific Gravity
1	Clay	10.7	6.7	NP	NP	SP-SM	A-3(0)	2.62
2	Clay	12.7	7.7	21	3	SM	A-2-4(0)	2.54
3	Chemical	4.3	2.9	NP	NP	SP	A-3(0)	2.64
4	Clay	14.3	9.2	18	1	SM	A-2-4(0)	2.53
5	Clay	11.3	7.7	20	2	SW-SM	A-2-4(0)	2.52
6	Clay	2.7	0.8	NP	NP	SP	A-3(0)	2.64
7	Clay	12.1	8.8	27	8	SC	A-2-4(0)	2.56
8	Clay	13.2	9.3	23	4	SC-SM	A-2-4(0)	2.63
9	Clay	12.4	8.0	23	5	SC-SM	A-2-4(0)	2.54
10	Clay	10.2	5.2	20	3	SP-SM	A-2-4(0)	2.61
11	Clay	16.4	9.8	23	6	SC-SM	A-2-4(0)	2.58
12	Clay	13.2	10.0	21	3	SM	A-2-4(0)	2.54
13	Clay	10.0	3.5	NP	NP	SP-SM	A-3(0)	2.73
14	Clay	14.9	-	29	7	SM-SC	A-2-4(0)	...
15	Clay	16.0	13.2	27	7	SM-SC	A-2-4(0)	2.51
16	Chemical	0.2	...	NP	NP	SP	A-3(0)	...
Base	...	...	0.0	NP	NP	SP	A-3 (0)	2.66

Note: NP = non-plastic; clay defined as particles finer than 2 μm.

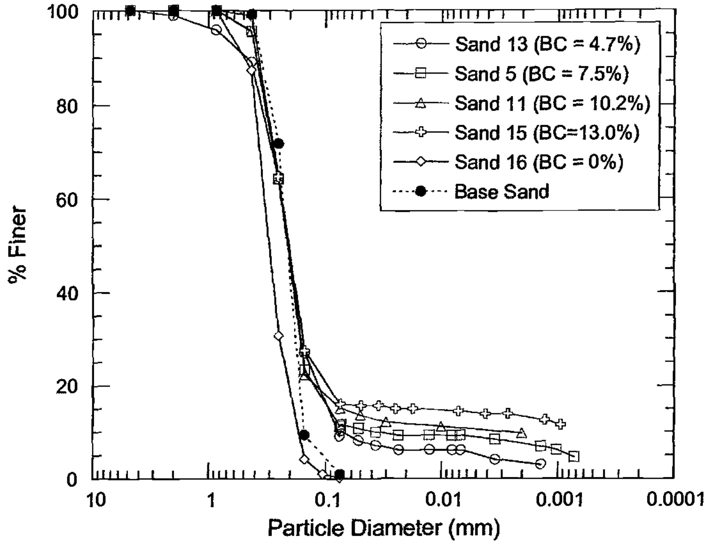

FIG. 1—*Particle size distribution curves for foundry sands and reference sands.*

TABLE 2—*Properties of fly ash.*

Property	Units	Average	Range
Gravimetric water content	%	1.75	0.5–3.0
Loss on ignition	%	16.4	15.8–16.9
Pozzolanic index @ 7 d	%	87.4	84.8–90.0
Pozzolanic index @ 28 d	%	69.2	67.2–71.1
Water requirement	%	117.8	115.7–119.8
P_{325} (< 45 μm)	%	68.7	67.7–69.7
P_{200}	%	72.3	71.8–72.8
Specific gravity	...	2.53	2.53

Cement

Type I Portland cement from a single bag was used as a binder for all mixes. No properties of the cement were determined.

Methods

Unconfined Compressive Strength

Mixtures for UCS testing were prepared by hand due to the small volumes that were needed. The mixture was placed into a cylindrical polypropylene mold (diameter = 76 mm, length = 152 mm) using a scoop. No effort was used to densify the mixture. The surface was struck off with a straight edge, and then the specimen was placed in a 100 % relative humidity room for curing.

Unconfined compressive strength was tested at various curing times following the method described in ASTM Standard Test Method for Preparation and Testing of Controlled Low Strength Material (CLSM) Test Cylinders (D 4832). The cylinders were capped with sulfur mortar in accordance with ASTM Standard Practice for Capping Cylindrical Concrete Specimens (C 617) to provide flat and parallel surfaces for compression testing. The rate of loading was chosen such that failure would occur in not less than 2 min. The rate ranged between 0.75 and 1.5 mm/min, but it was constant during a given test. The peak load, displacement rate, time to failure, and failure mode (as defined in ASTM Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens (C 39) were recorded for each test.

Flow

The flow of all mixtures was determined according to ASTM D 6103, herein referred to as a flow test. Mixtures for flow tests were prepared in 20-L buckets. Flow curves were created by preparing a mixture without fly ash having a flow of 230 mm ± 5 mm. Fly ash was then added to the mixture, followed by water to reach the target flow. This process was repeated until a flow curve was established.

This procedure assumes that temporal changes of the mixture do not occur during the flow test. A flow curve with 8–10 points usually required 70–90 min to complete. Flow loss tests showed that the flow could decrease significantly over a period of this duration. Therefore, the amount of water needed to reach the target flow during the later stages of a flow curve test was probably greater than otherwise would be required for a fresh mixture.

Segregation was a key issue when preparing mixtures for the flow tests. Two ways of identifying segregation were used when a mixture was placed into the pouring cylinder: (i) immediate bleeding of free water and (ii) variations in flow between the material in the upper and lower parts of the cylinder (i.e., the lower material did not flow, and the upper material was very thin). When segregation was problematic, fly ash was added to the mixture in small increments until segregation was eliminated.

Flow Loss

Flow tests were conducted periodically for 90 min to evaluate the flow loss. Prior to each test, the material was thoroughly re-mixed for 1 min. A similar procedure was used by Meyer and Perenchio [9] to examine concrete slump loss. At 90 min, additional mixing water, known as "retempering water," was added until the flow was increased back to the initial target value.

The rate of flow loss was evaluated for mixtures containing no fly ash and those containing a high proportion of fly ash ($M_F/(M_F+M_S) = 20$ %). Mixtures were prepared following the same procedures used for the flow curve tests. All mixtures were prepared in 10 min to reduce the effects of mixing time.

Results of Compressive Strength Tests

Water/Cement Ratio and Cement Content

UCS tests were conducted according to ASTM D 4832 on 26 mixtures after 7 d and 28 d of curing. Properties of each mixture are given in Table 3. Twenty-three of these mixtures were prepared with foundry sands. Mixtures 9, 10, and 24 were prepared with base sand. The water-cement (W/C) ratios ranged from approximately 4 to 11, but most were greater than 6 with the intent of achieving a 28 d UCS between 0.3 and 1.0 MPa.

TABLE 3—*Mixtures used in compressive strength testing program.*

Mix-ture	Sand Type	Binder	Sand (kg/m^3)	Fly Ash (kg/m^3)	Water (kg/m^3)	Cement (kg/m^3)	W/C	BC of Sand (%)	UCS_7 (MPa)	UCS_{28} (MPa)
1	Foundry	Clay	1141	143	474	54	8.7	7.5 %	1.16	1.44
2	Foundry	Clay	1165	146	453	85	5.3	7.5 %	1.63	1.99
3	Foundry	Clay	1256	0	485	54	9.0	7.5 %	0.26	0.38
4	Foundry	Clay	1225	0	486	88	5.5	7.5 %	...	0.85
5	Foundry	Clay	1243	164	463	53	8.8	4.7 %	1.28	1.50
6	Foundry	Clay	1247	145	458	89	5.2	4.7 %	1.71	1.98
7	Foundry	Clay	1259	0	497	48	10.3	10.2 %	0.26	0.38
8	Foundry	Clay	1360	0	457	52	8.8	10.2 %	0.39	0.65
9	Base	None	1131	323	433	42	10.2	0.0 %	0.31	0.59
10	Base	None	1102	322	438	66	6.6	0.0 %	0.36	0.63
11	Foundry	Clay	962	314	488	47	10.5	10.2 %	0.08	0.11
12	Foundry	Clay	934	324	487	73	6.7	10.2 %	1.20	1.24
13	Foundry	Clay	1056	304	479	45	10.7	4.7 %	0.20	0.31
14	Foundry	Clay	1025	296	486	70	7.0	4.7 %	0.22	0.37
15	Foundry	Clay	1149	0	526	50	10.5	13.0 %	0.37	0.64
16	Foundry	Clay	1140	0	521	80	6.5	13.0 %	0.39	0.95
17	Foundry	Clay	914	228	529	53	9.9	13.0 %	0.62	0.70
18	Foundry	Clay	893	223	529	84	6.3	13.0 %	2.11	2.55
19	Foundry	Clay	849	212	531	148	3.6	13.0 %	3.46	4.84
20	Foundry	Chemical	1008	438	435	40	11.0	0.0 %	0.63	0.79
21	Foundry	Chemical	994	432	436	62	7.0	0.0 %	0.90	1.13
22	Foundry	Chemical	955	415	443	108	4.1	0.0 %	1.09	1.53
23	Foundry	Clay	1353	0	444	62	7.2	7.5 %	0.39	0.68
24	Base	None	816	449	500	48	10.5	0 %	0.50	1.23
25	Foundry	Clay	1208	0	503	50	10.0	13.0 %	0.36	0.67
26	Foundry	Clay	1018	255	510	53	9.7	4.7 %	...	0.31

Notes: BC = bentonite content determined by methylene blue analysis (ASTM Standard Test Method for Methylene Blue Index of Clay (C 837), UCS_7 = average UCS at 7 d, UCS_{28} = average UCS at 28 d).

The 28 d UCS is shown vs. W/C in Fig. 2, along with data from Bhat and Lovell [4] and Naik and Singh [10]. The relationship between UCS and W/C suggested by Bhat and Lovell is also shown in Fig. 2, along with bounds corresponding to 0.3 and 1.0 MPa. A large drop in UCS occurs as the W/C increases from 4 to around 6.5. For W/C > 6.5, the UCS appears largely insensitive to W/C and typically falls within 0.3 and 1.0 MPa. This insensitivity may be due to insufficient cement being present to form a continuous cement matrix. Incomplete hydration is an unlikely cause because there is abundant water to hydrate the cement when the W/C is high.

Cement content (mass of cement per total volume) is another way to examine the effect of cement on compressive strength. A graph of compressive strength versus cement content for all mixtures (Fig. 3) shows a general trend of increasing strength with increasing cement content. However, no general inferences can be made regarding the cement content required to meet the target range of UCS for all mixtures.

The effect of bentonite content of the foundry sand and fly ash content on UCS is shown in Fig. 4 for mixtures with W/C > 6.5. A systematic trend does not exist between UCS and bentonite content (Fig. 4*a*) or UCS and fly ash content (Fig. 4*b*), suggesting that neither has a controlling influence on the UCS of flowable fills prepared with foundry sand.

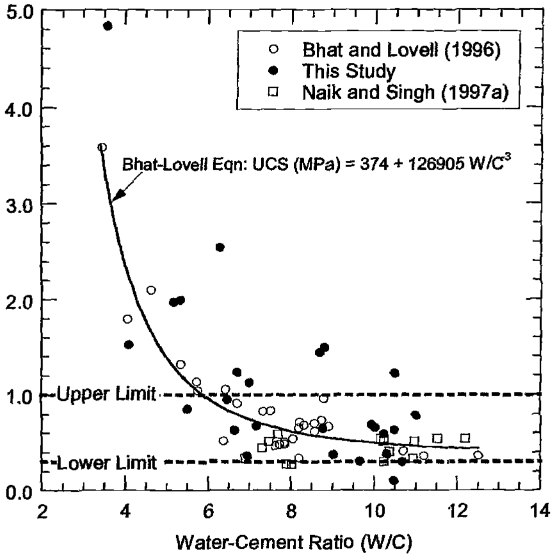

FIG. 2—*Effect of W/C on 28 d UCS of flowable fill.*

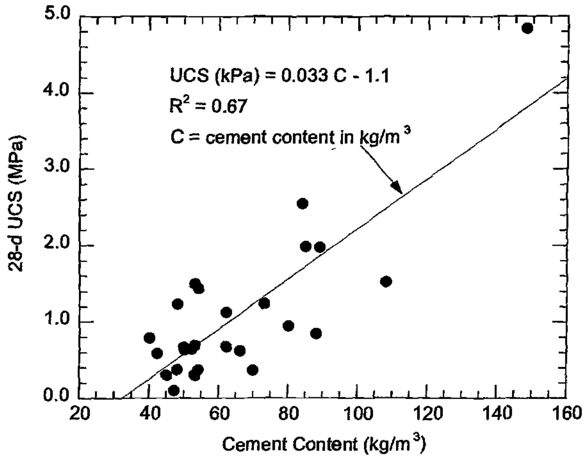

FIG. 3—*Effect of cement content on 28 d UCS for all W/C ratios.*

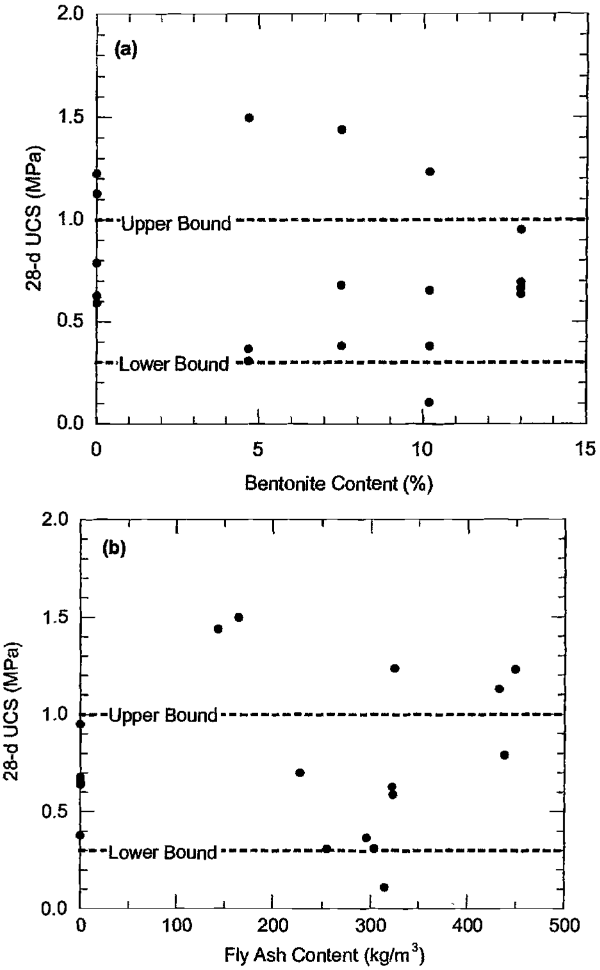

FIG. 4—*Effect of bentonite content (*a*) and fly ash content (*b*) on 28 d UCS of mixtures with W/C > 6.5.*

Long-Term Strength Gain

Mixtures 23–26 were chosen to evaluate changes in UCS over a longer time period (up to 155 d). Mixtures 23, 25, and 26 were prepared with foundry sand, whereas Mixture 24 was prepared with base sand. Mixtures 24 and 26 were prepared with fly ash, whereas Mixtures 23 and 25 contained no fly ash. All four mixtures were designed with the intention of producing a 28 d UCS < 1.0 MPa (i.e., excavatable fill).

UCS as a function of time is shown in Fig. 5. The most significant strength gain occurred between 0 and 28 d for all mixtures, as expected. The three mixtures containing foundry sand (Mixtures 23, 25, and 26) continued to gain strength after 28 d, but at a slow rate compared to Mixture 24, which contained base sand and a large amount of fly ash (fly ash content = 449 kg/m^3). Also, the two mixtures containing fly ash (Mixtures 24 and 26) exhibited greater strength gain between 90 and 120 d than the two mixtures without fly ash (Mixtures 23 and 25), although all mixtures containing foundry sand showed only small increases in strength beyond 28 d. The additional strength gain obtained with fly ash may be due to pozzolanic reactions occurring in the fly ash, or a synergistic effect between the fly ash and Portland cement. The moderating effect that foundry sand has on strength gain may be due to the bentonite interfering in the cement reactions, perhaps as a result of calcium-for-sodium exchange on the bentonite surface.

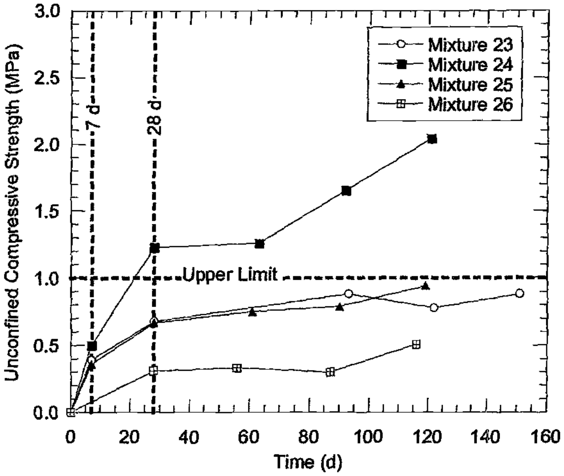

FIG. 5—*Effect of curing time on UCS of Mixtures 23–26.*

An analysis was also conducted to determine if the 28 d UCS (UCS$_{28}$) could be determined from the 7 d UCS (UCS$_7$). Least-squares regression on the data in Table 3 showed that this relationship can be described by:

$$UCS_{28} = 1.3\, UCS_7 \quad (1)$$

which has $R^2 = 0.96$. An identical equation was obtained when the data set was limited to W/C > 6.5. Equation 1 indicates that, on average, a 30 % gain in UCS occurs between 7 and 28 d of curing.

Results of Flow Tests

Achieving Flow Requirements

Data from the flow tests were compiled to find the water required to achieve the typical target flow of 230 mm ± 5 mm. The water-solids (W/S) ratio needed to achieve the target flow is shown as a function of bentonite content (BC) in Fig. 6. Trend lines relating W/S to bentonite content are shown for mixtures containing no fly ash (solid lines) and mixtures containing a relatively high percentage of fly ash (dashed lines, 500 g of fly ash for every 2000 g of foundry sand). No data are shown for mixtures without fly ash for bentonite contents < 5 %. Mixtures without fly ash could not be prepared with adequate flow and without segregation for bentonite contents < 5 %. The lack of fines in these mixtures prohibits formation of a cohesive mixture, leading to segregation.

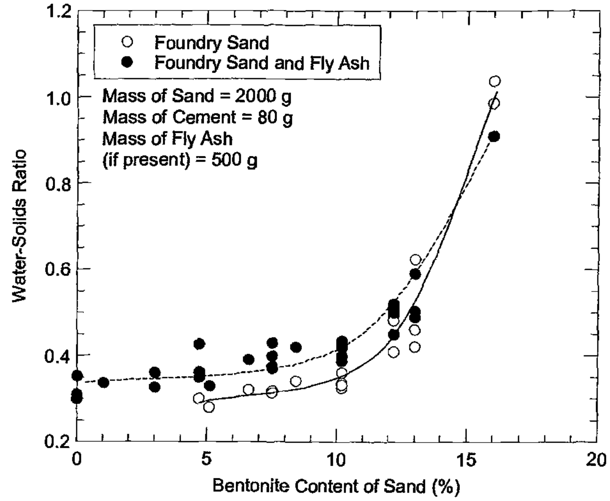

FIG. 6—*Effect of bentonite content on water-solids ratio required to achieve target flow.*

As the bentonite content increases, more water is required to achieve the target flow, regardless of whether fly ash is present in the mixture. There are two reasons for this behavior. First, some of the water is bound to the bentonite particles and thus is not effective in reducing particle contact and lowering the viscosity of the mixture. Flow is impeded by the hydrated bentonite particles, which swell appreciably and become sticky as they hydrate [8]. At a bentonite content of 10–12 %, the impedance to flow caused by the bentonite particles tends to dominate, resulting in much greater water requirements as the bentonite content increases. To confirm that this effect was caused by the bentonite, tests were also conducted with mixtures prepared with base sand, along with different percentages of commercially available powdered bentonite. These tests also showed that the water requirements are closely tied to the bentonite content of the sand [5], and the data exhibited a similar shape as the data in Fig. 6.

Some data in Fig. 6 are from mixtures prepared with a blend of two different foundry sands or a blend of foundry sand and base sand [5]. For these mixtures, a composite bentonite content was calculated based on the total mass of bentonite in the blended sands. The absence of outliers in Fig. 6 suggests that the water requirements for mixtures containing multiple foundry sands can be predicted using the same trend as mixtures with only one type of sand, as long as the composite bentonite content is known.

Effect of Bentonite Content on Fines Required to Prevent Segregation

Flowable fill must contain a sufficient amount of fines so that a paste forms to suspend the heavier particles. Plasticity of the fines is also influential; plastic fines bind with water more readily and are more effective in developing a paste.

The amount of fines required to prevent segregation is shown in Fig. 7 for mixtures prepared with foundry sand and mixtures prepared with base sand and powdered bentonite. Fly ash was used as the source of fines in all mixtures. The mass of fines is normalized by the total mass of solids, except for the cement. Cement fines were not included in the normalization because the cement content of each mixture was identical (80 g), and a portion of the cement dissolves into solution. Thus, the amount of cement fines that remains as particulate matter is difficult to estimate.

The amount of fines required to prevent segregation decreases as the bentonite content increases for both the foundry sand mixtures and the mixtures prepared with base sand and bentonite. The trend is similar for both types of mixtures, indicating that the bentonite is the primary factor affecting segregation. The data in Fig. 7 suggest that additional fines are not needed to prevent segregation, provided that the foundry sand contains at least 6 % bentonite.

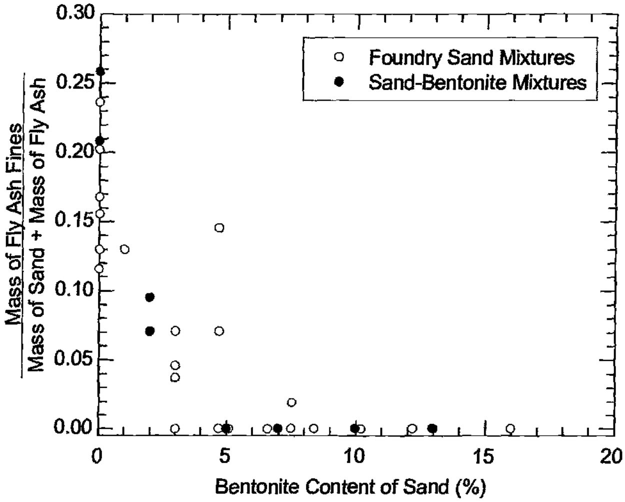

FIG. 7 —*Normalized mass of fines required to prevent segregation as a function of bentonite content.*

Flow Loss

Flow loss refers to the reduction of flow over time. Flow loss is caused by loss of water due to hydration reactions in the cement and/or bentonite and due to formation of cement bonds. Flow loss can be an important consideration in mix proportioning because it decreases as the material is transported from the batching location to the project site. Flowable fill containing Class C fly ash is particularly prone to problems with flow loss, because the ash has a tendency to "flash set" [7].

To separate the contributions of bentonite hydration and cementation to flow loss, the flow of two mixtures was monitored over time. The mixtures were identical, except one contained cement, whereas the other did not. Foundry Sand 15 (10.2 % bentonite) was used in the mixture as the aggregate so that fly ash fines would not be needed to prevent segregation. Two additional tests were conducted on the same mixtures, but fly ash was included as well to ascertain the its effect.

Flow vs. time elapsed is shown in Fig. 8. The cement and cement-free mixtures without fly ash (circles) exhibit the same rate of flow loss until about 60 min. Subsequently, the mixture with cement begins to lose flow more quickly than the cement-free mixture, indicating that cementation effects eventually dominate over bentonite hydration effects. In contrast, the mixtures containing fly ash (squares) drop below the acceptable flow within 10 min, regardless of whether they contain cement. Any late cementation effects in these mixtures are masked by the near absence of flow at later times (i.e., the flow diameter nearly equals the cylinder diameter, 75 mm). Thus, using foundry sands in lieu of natural sand and cementitious fly ash can result in longer times with acceptable flow (but possibly longer set times as well).

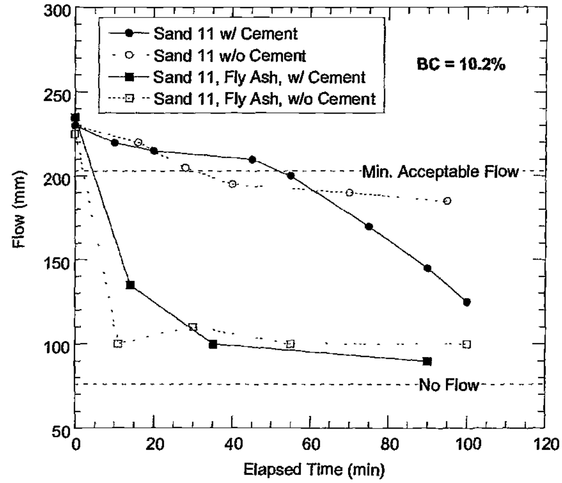

FIG. 8 —*Flow as a function of time for mixtures prepared with and without cement. One set of mixtures with fly ash (squares) and other set without fly ash (circles).*

Additional tests were conducted to determine if the source of foundry sand or the bentonite content affects the rate of flow loss. These tests were conducted with mixtures containing cement, but with and without fly ash fines. Flow as a function of time for the mixtures without fly ash fines is shown in Fig. 9. The flow loss is influenced by the source of the foundry sand, but it is not systematically related to bentonite content. For example, the foundry sands with high bentonite content (Sand 11 at 10.2 % and Sand 15 at 13.0 %) exhibited the smallest and greatest flow loss of the three sands that were tested. An absence of a relationship with bentonite content was also observed with mixtures prepared with fly ash fines [5]. However, in a manner similar to that shown in Fig. 8, the mixtures with fly ash fines exhibited appreciably greater rates of flow loss relative to those without fly ash fines.

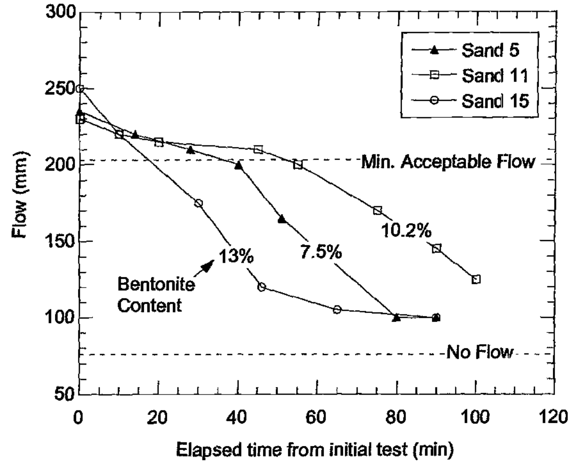

FIG. 9 —*Flow as a function of time for mixtures prepared without fly ash.*

Recovery of Initial Flow

The ability to maintain adequate flow or to recover flow loss was evaluated in two ways: adding additional water to elevate the initial flow and adding water just before placement (i.e., retempering water) to regain the original flow characteristics quickly. Both of these approaches can reduce the UCS. However, the effect on UCS was not evaluated.

Beginning with a higher initial flow was found to be ineffective [5]. Mixtures with high initial flow (275 mm) reached the minimum acceptable flow (205 mm) in essentially the same time (≈ 60 min) as mixtures prepared at the target flow (230 mm).

Tests to evaluate retempering were conducted by adding water incrementally at the end of a flow test (elapsed time ≈ 90–100 min) until a target flow of 230 mm ± 5 mm was achieved. The increase in water-solids ratio (W/S) required to achieve the target flow is shown in Fig. 10 as a function of bentonite content of the foundry sand. For mixtures containing fly ash, the increase in W/S varies appreciably with bentonite content, with the largest amount of retempering water required for intermediate (8–12 %) bentonite contents. Less retempering water was required for mixtures with foundry sands having high bentonite content (> 10 %) because these mixtures generally exhibited less flow loss than mixtures prepared with foundry sands having intermediate bentonite content. In contrast, the required increase in W/S was less sensitive to bentonite content for mixtures prepared without fly ash, although more retempering water was generally required for mixtures prepared with foundry sands having higher bentonite content. Most importantly, however, is that the mixtures with fly ash generally required more water than the mixtures without fly ash at the same bentonite content.

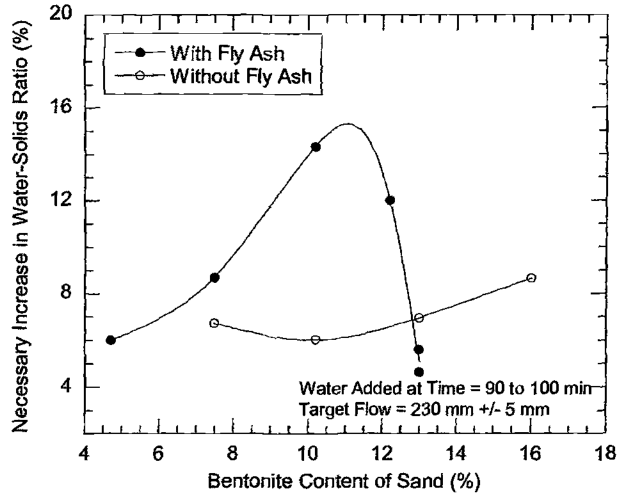

FIG. 10—*Increase in water-solids ratio (W/S) required to achieve target flow during retempering.*

Recommended Guidelines for Mixture

Based on the findings of this study, the following guidelines are given in Table 4 for mixtures prepared with foundry sands having bentonite contents ranging between 0–6 %, 6–10 %, and 10–13 %. These mixtures are intended to be excavatable and have a 28 d UCS between 0.3 and 1.0 MPa. They should be used as a starting point but should not be used in lieu of material specific design and testing. Different input components can change the flow, set time, strength, and other characteristics of the cured fill.

TABLE 4—*Recommended mixture for excavatable flowable fill.*

Bentonite Content of Foundry Sand (%)	Water (kg/m^3)	Foundry Sand (kg/m^3)	Cement (kg/m^3)	Fly Ash (kg/m^3)
6–10	475	1300	50	0
10–13	500	1225	45	0
0–6	475	1000–1250[a]	40[b]	150–400

Notes: [a]depends on the fly ash content, [b]depends on the pozzolanic index of the fly ash.

Summary and Conclusions

This study has shown that flowable fill mixtures containing foundry sand can provide suitable strength and flow, and that the composition of a suitable mixture depends on the bentonite content of the foundry sand. A key advantage of using foundry sands in lieu of natural sands in flowable fill is that the fly ash (or other source of fines) can be eliminated if bentonite content exceeds 6 %. Flowable fill mixtures without cementitious fly ash have several advantages over those with cementitious fly ash, including: (i) lower long-term strength gain (making the design of excavatable mixtures simpler and less risky), (ii) less flow loss, (iii) fewer components and fewer interactions between components that are difficult to characterize, and (iv) a larger fraction of foundry sand (the least expensive component in the mixture).

Testing a variety of mixtures showed that the UCS of flowable fill prepared with foundry sand is sensitive to the water-cement ratio, as has been observed by others, at least when the W/C spans a broad range (4–11). Mixtures with W/C < 6.5 generally have excessive UCS, whereas suitable UCS is generally associated with W/C > 6.5. Bentonite content does not affect the UCS systematically, although bentonite content does have an indirect effect in that foundry sands with more bentonite require more water to flow, which affects strength. The bentonite in foundry sand also can affect the long-term strength if the foundry sand has enough bentonite to preclude the need for fly ash. Long-term testing showed that mixtures with cementitious fly ash may gain significant strength beyond 28 d (complicating future excavation), whereas mixtures without cementitious fly ash gain little strength after 28 d. These tests also showed that the UCS after 28 d of curing can be reliably predicted from the UCS after 7 d of curing.

The only method identified in this study to control flow was to vary the amount of water in the mixture. The amount of water required to achieve adequate flow is a function of the bentonite content of the sand, regardless of whether sand is from a single foundry, a mixture prepared from several foundries, or a mixture of foundry and natural sands. In general, as the bentonite content increases, the required water content of the mixture increases correspondingly.

An analysis was also conducted to evaluate factors affecting flow loss. The most important factor affecting flow loss is the presence of cementitious fly ash in the mixture. Mixtures with cementitious fly ash exhibited much greater rates of flow loss. Thus, flow loss can be reduced appreciably by using a foundry sand with at least 6 % bentonite so that fly ash fines need not be added to the mixture. Mixtures prepared without cementitious fly ash also required less retempering water to recover flow after it dropped below an acceptable level.

Acknowledgments

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Properties of Controlled Low-Strength Materials Made with Wood Fly Ash

ABSTRACT: Controlled low-strength materials (CLSM) were made in the field using one source of wood fly ash as a major component. CLSM Mixtures S-1 and S-3 contained cement, wood fly ash (81 and 89 %, respectively, by mass of cementitious materials [*Cm*]), and sand; whereas, Mixture S-2 contained cement, wood fly ash (11 % of *Cm*), Class C coal fly ash (67 % of *Cm*), and sand. Mixtures S-1, S-2, and S-3 showed respective compressive strength values of 0.8, 0.3, and 0.6 MPa at 28 d, and 1.4, 14.4, and 1.0 MPa at one year. Combination of wood and coal fly ashes might have caused the drastic increase in the strength of Mixture S-2 at late ages. The respective water permeability values of Mixtures S-2 and S-3 decreased from 68 and 33 μm/s at 63 d to 6 and 12 μm/s at 227 d due to the improvement of microstructure of these CLSM mixtures.

KEYWORDS: bleedwater, Class C fly ash, compressive strength, flowable slurry, permeability, wood fly ash

Introduction

U.S. pulp and paper mills generate about one million dry ton of ash from burning wood/bark and one-half million dry ton of ash from burning fibrous residuals from mill wastewater treatment [21]. U.S. pulp and paper mills also generate about 1.2 million dry tons of ash from burning coal. NCASI has estimated that approximately one-third of the total ash is being utilized, while the remaining two-thirds are disposed of in landfills or lagoons. The large-scale disposal of wood ash is a major problem for the industry, mainly pulp mills, saw mills, and energy-generating plants that utilize wood and wood residue. The problem concerning the disposal of wood ash in landfills is accentuated by limited landfill space available, strict environmental regulations, and high costs. Co-firing wood residue with coal or other fuels leads to regulatory differentiation between ash generated from burning wood residue alone and ash generated from burning wood mixed with coal and/or other fuels. Theoretically, ash from wood residue combustion can be disposed of anywhere without any restrictions because it is considered a natural product (such as the ash produced from burning forests). On the other hand, ash produced by burning wood residue with coal must be disposed of in designated landfills, thereby increasing disposal costs and future liability.

Beneficial utilization options for wood ash with or without coal are essential for the industry. One of the possible uses of wood ash is in the production of Controlled Low-Strength Materials (CLSM), also widely known as flowable slurry. CLSM is a high-fluidity cementitious material that flows like a thick, viscous liquid, that self-levels without compacting, and that supports like

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a solid when hardened. The American Concrete Institute describes CLSM flowable slurry as a cementitious material that is in a flowable state at the time of placement and has a specified long-term compressive strength of 8.3 MPa or less [1]. A number of names, including flowable fill, unshrinkable fill, manufactured soil, controlled-density fill, and flowable mortar are being used to describe this material. CLSM is used primarily for non-structural and light-structural applications such as back-fills, sound insulating and isolation fills, pavement bases, conduit bedding, erosion control, and void filling. CLSM with higher strengths can be used for applications where future excavation is unlikely, such as structural fill under buildings. CLSM is an ideal backfill material. In deciding mixture proportions of CLSM, factors such as flowability, strength, and excavatability are evaluated. Permeability is also, for many uses, an important property of CLSM. Permeability is an indicator of the resistance the material offers against permeation of water, gases, and liquids. Permeability of CLSM depends on mixture proportions, properties of constituent materials, water-cementitious materials ratio (*w/cm*), and age.

Literature Review

Studies by Naik and his associates [10–15, 18–20, 22, 23] and by others [2, 6, 8, 9, 24] have evaluated the properties of different mixtures of CLSM such as density, strength, settlement, hydraulic conductivity, and shrinkage. Lai reported the compressive strength test results of flowable mortars made with high-volume coal ash [7]. He concluded that a 28 d compressive strength of about 1 MPa could be achieved with 6 % cement by mass with excellent flowability. Naik and Singh [13] and Ramme et al. [22] reported on excavatable CLSM mixtures made with or without used foundry sand and having strength between 0.3 to 0.7 MPa at the age of 28 d. Tikalsky et al. [27] also more recently reported that used foundry sand provides high-quality material for CLSM. Naik and Singh [14] reported on the water permeability of slurry materials (0.3–0.7 MPa) containing used foundry sand and fly ash as 0.03–0.74 µm/s. Horiguchi et al. [4] evaluated the potential use of off-specification coal fly ash plus non-standard bottom ash in CLSM and reported that CLSM with off-specification coal fly ash and non-standard bottom ash showed excellent performance. Horiguchi et al. [5] investigated compressive strength, flowability, and freezing and thawing of CLSM made with used foundry sand and bottom ash as fine aggregates. Based on the test results, they concluded that the frost heaving rate of CLSM with used foundry sand and bottom ash was less than 3 %, which is a relatively smaller value compared to other clay and fine-grained soil materials. Naik et al. [10] developed two types of CLSM utilizing post-consumer glass as aggregate and coal fly ash. One group of CLSM consisted of cement, fly ash, glass, and water; and another group of CLSM consisted of cement, sand, glass, and water. They concluded that all the flowable slurry mixtures developed satisfied the recommendations of the ACI Committee 229R-99 report [1]. Tikalsky et al. [26] evaluated CLSM containing clay-bonded and chemically-bonded used foundry sand and compared its properties in plastic and hardened states with those of CLSM mixtures containing uniformly graded crushed limestone sand. Test results showed that, as reported in the past, used foundry sand can be successfully used in CLSM. CLSM containing used foundry sand exhibited similar or better properties when compared with CLSM containing crushed limestone. Gassman et al. [3] examined the effects of prolonged mixing and re-tempering on the fluid-state and hardened-state properties of CLSM. The test results showed that extending the mixing time beyond 30 min decreased compressive strength and delayed the time of setting. Re-tempering did not affect the 28 d strength; however, it did affect the 91 d strength depending upon the mixing time.

Experimental Program

Materials

Type I portland cement conforming to ASTM Standard Specification for Portland Cement (C 150) was used in this investigation. Wood fly ash collected from a bag-house in a pulp mill in Wisconsin was used. Physical and chemical properties of the wood fly ash are given in Tables 1 and 2, respectively. ASTM standard specifications do not exist for wood fly ash. The nearest ASTM standard available is ASTM Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete (C 618). Wood ash is primarily generated from combustion of wood products; but at times coal is also used to balance the input heat generated with wood products. Therefore, properties of wood ash were compared with coal ash (even though ASTM C 618 for coal fly ash and natural pozzolans does not directly apply to this investigation). Physical and chemical properties of the wood ash did not conform to all the requirements of ASTM C 618 for coal fly ash. The wood ash met the following requirements of ASTM C 618 for Class F fly ash: (1) strength activity index with cement, (2) autoclave expansion, (3) uniformity in fineness and specific gravity, (4) amount of $SiO_2 + Al_2O_3 + Fe_2O_3$, (5) amount of SO_3, and (6) available alkalies. But the wood ash did not meet the following requirements of ASTM C 618 for Class F fly ash: (1) fineness, (2) water requirement, (3) loss on ignition, and (4) moisture content. However, when compared with the requirements of ASTM C 618 for Class N natural pozzolans, the wood fly ash met all the requirements with the exceptions of fineness and moisture content. One source of Class C fly ash meeting the standard physical and chemical requirements of ASTM C 618 was used. Its physical and chemical properties are reported in Tables 1 and 2, respectively. The Class C fly ash slightly exceeded the optional chemical requirement of ASTM C 618 for available alkalies (1.6 vs. 1.5 max). The fine aggregate used was natural sand having specific gravity of 2.67 and fineness modulus of 2.7. Its physical properties were determined per ASTM Standard Specification for Concrete Aggregates (C 33). It was obtained from a local ready-mixed concrete company and satisfied all requirements of ASTM C 33.

Mixture Proportions

Three series of CLSM mixtures (S-1, S-2, and S-3) were proportioned at a ready-mixed concrete plant. The volume of each mixture was seven cubic meters. Mixture proportions are given in Table 3. Series S-1 and S-3 CLSM mixtures contained cement, wood fly ash, and sand; whereas, Series S-2 CLSM mixtures also contained Class C fly ash besides cement, wood fly ash, and sand. Mixture proportions were based on past experience using different proportions of cement, wood fly ash, Class C coal fly ash, and sand. Proportions of cement, wood fly ash, and Class C fly ash in cementitious materials, as well as sand-cementitious materials ratios of the CLSM Mixtures are included in Table 3.

TABLE 1—*Physical properties of wood fly ash and Class C fly ash used vs. ASTM C 618.*

Test parameter	Wood Fly Ash Used	Class C Fly Ash Used	ASTM C 618 Requirements		
			Class N	Class F	Class C
Fineness, amount retained when wet-sieved on 45 μm (No.325) sieve, %	90 60*	10	34 max	34 max	34 max
Strength Activity Index with Cement, % of Control					
3 d	102*	110			
7 d	83*	111	75 min	75 min	75 min
28 d	79*	105	75 min	75 min	75 min
Water Requirement, % of Control	115*	95	115 max	105 max	105 max
Autoclave Expansion, %	-0.63*	0.08	0.80 max	0.80 max	0.80 max
Unit Weight, kg/m^3	1376	1083	...	...	...
Specific Gravity	2.60	2.58	...	...	...
Uniformity, variation from mean, %					
Fineness	0.6*	0.3	5 max	5 max	5 max
Specific Gravity	1.9	1.9	5 max	5 max	5 max

* When material finer than 150 μm (No. 100) sieve (25 % of the wood ash) was used.

TABLE 2—*Chemical properties of wood fly ash and Class C fly ash used vs. ASTM C 618.*

Analysis parameter	Wood Fly Ash Used	Class C Fly Ash Used	ASTM C 618 Requirements		
			Class N	Class F	Class C
Silicon Dioxide, SiO_2	61.4	38.5	...	...	...
Aluminum Oxide, Al_2O_3	6.2	20.4	...	...	...
Iron Oxide, Fe_2O_3	2.6	6.1	...	...	...
$SiO_2 + Al_2O_3 + Fe_2O_3$	70.2	65.1	70.0 min	70.0 min	50.0 min
Calcium Oxide, CaO	12.3	23.3	...	...	...
Magnesium Oxide, MgO	2.9	4.8	...	...	...
Titanium Oxide, TiO_2	0.57	1.4	...	...	...
Potassium Oxide, K_2O	3.3	0.66	...	...	...
Sodium Oxide, Na_2O	1.4	1.8	...	...	...
Sulfur Trioxide, SO_3	0.8	1.5	4.0 max	5.0 max	5.0 max
Loss on Ignition, LOI (750°C)	8.4	1.2	10.0 max	6.0 max[A]	6.0 max
Moisture Content	8.9–12.1	0.2	3.0 max	3.0 max	3.0 max
Available Alkalies, Na_2O (ASTM C 311)[B]	0.8	1.6	1.5 max	1.5 max	1.5 max

[A] According to ASTM C 618, up to 12 % loss on ignition may be approved by the user if either acceptable performance records or laboratory test results are made available.

[B] Optional requirement for the minimization of alkali-silica reaction.

TABLE 3—*Mixture proportions and fresh properties of CLSM mixtures.*

Mixture Number	S-1	S-2	S-3
Cement, C, kg/m^3	82.5	95.5	61.7
Wood Fly Ash, WFA, kg/m^3	344	47	509
Class C Coal Fly Ash, CFA, kg/m^3	0	286	0
Water, W, kg/m^3	294	307	402
SSD Fine Aggregate, S, kg/m^3	1281	1474	937
C/Cm^A	0.19	0.22	0.11
WFA/Cm^A	0.81	0.11	0.89
CFA/Cm^A	0	0.67	0
W/Cm^A	0.69	0.72	0.70
S/Cm^A	3.00	3.44	1.64
Air Temperature, °C	19	09	16
Fresh CLSM Temperature, °C	19	18	21
Flow, mm	90	165	140
Air Content, %	3.5	1.6	3.0
Unit Weight, kg/m^3	2002	2211	1910

^{A}Cm = C + WFA + CFA

Manufacturing Technique

All ingredients were batched and mixed at the facilities of the ready-mixed concrete plant. CLSM was manufactured in accordance with the recommendations of ACI 229R [1]. Cement, fine aggregate, wood fly ash, Class C fly ash, and water were automatically batched and added into a conventional ready-mixed concrete truck at the ready-mixed concrete plant. The wood fly ash was introduced into one of the bins typically used for aggregate, conveyed to scales for weighing, and then discharged into the ready-mixed concrete truck. Once all the materials were introduced, the material was mixed in the truck at a high-mixing speed until the mixture drum turned at least 70 revolutions. Then a representative sample of CLSM was obtained in accordance with ASTM Standard Practice for Sampling Freshly Mixed Controlled Low-Strength Material (D 5971). The sample was discharged onto a pan. Then fresh CLSM tests were performed, and test specimens were cast. Temperature, flow (or spread), air content, and unit weight were determined for each mixture before casting test specimens for compressive strength and water permeability measurements.

Preparation and Testing of Specimens

The temperature of the fresh slurry was measured in accordance with ASTM Standard Test Method for Temperature of Freshly Mixed Portland Cement Concrete (C 1064). Ambient air temperature was also measured and recorded. Flow/spread of fresh slurry was determined in accordance with ASTM Standard Test Method for Flow Consistency of Controlled Low Strength Material (CLSM) (D 6103). Air content of CLSM was determined in accordance with ASTM Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method (C 231). Unit weight of CLSM was determined in accordance with ASTM Standard Test Method for Unit Weight, Yield, Cement Content, and Air Content (Gravimetric) of Controlled Low Strength Material (CLSM) (D 6023). CLSM cylinders were prepared—one group for the determination of settlement and depth of bleedwater, and another group for the determination of compressive strength—in accordance with ASTM Standard Test Method for Preparation and Testing of Controlled Low Strength Material (CLSM) Test Cylinders (D 4832). The cylinders were cast in 150 × 300 mm cylindrical plastic molds. Settlement and depth of bleedwater were determined at 1-h and 22-h ages. Compressive strength was determined at the ages of 3, 7, 28, 91, 182, and 365 d in accordance with ASTM D 4832. The water permeability test specimens were cast in 100 × 125 mm cylindrical plastic molds. The water permeability of the slurry was determined at 63, 91, and 227 d in accordance with ASTM Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter (D 5084).

Test Results and Analysis

Plastic Properties

The properties of fresh flowable slurry materials examined were temperature, flow/spread, air content, unit weight, settlement, and bleedwater. Results of temperature, flow, air content, and unit weight of slurry Mixtures S-1, S-2 and S-3 are given in Table 3. The unit weight of the slurry mixtures was found to be in the range of 1910 to 2211 kg/m^3. Results of settlement measurements of CLSM mixtures are presented in Table 4. Cylinders of CLSM Mixtures S-1, S-2, and S-3 settled 3, 1.5, and 3 mm, respectively, at 1 h. The settlement values remained the same at 22 h. Bleedwater is given as the depth of water present at the top of 150 × 300 mm cylinder filled with CLSM. Bleedwater gives an indication of the cohesiveness of the CLSM mixture. Minimizing the amount of bleedwater is desirable to minimize the potential leaching of heavy-metal elements. Bleedwater test results are presented in Table 4. Bleedwater measurements for the slurry Mixtures S-1 showed that the depth of bleedwater was 3 mm at 1 h, but reduced to 1.5 mm at 22 h due to evaporation. Slurry Mixtures S-2 accumulated bleedwater of 1.5 mm at 1 h, and the depth of bleedwater was the same (1.5 mm) at 22 h. For slurry Mixture S-3, the depth of bleedwater was 3 mm at 1 h, and it remained the same (3 mm) at 22 h. It is not clear why Mixture S-1 lost bleedwater due to evaporation while Mixtures S-2 and S-3 did not lose bleedwater. CLSM Mixture S-2 containing Class C fly ash and the highest amount of sand showed the highest unit weight and lowest amount of settlement and bleedwater among the three CLSM mixtures.

TABLE 4—*Settlement and bleedwater for CLSM mixtures.*

Mixture	Settlement (mm)		Bleed Water (mm)	
Number	1 h	22 h	1 h	22 h
S-1	3	3	3	1.5
S-2	1.5	1.5	1.5	1.5
S-3	3	3	3	3

Compressive Strength

The compressive strength results of slurry mixtures are presented in Table 5 and Fig. 1. Compressive strength generally continued to increase with increase in age. This increase in strength with age indicates the pozzolanic reactions taking place due to wood and Class C fly ashes. Mixture S-1 and S-3 reached long-term compressive strengths of about 1.5 MPa and 1.0 MPa, respectively. These strengths are suitable for possible future excavation of CLSM using mechanical equipment [1]. Mixture S-2 containing wood fly ash combined with Class C fly ash showed a relatively low 28 d strength (0.28 MPa), but it exhibited a drastic increase in compressive strength at late ages and reached a 1-year strength of about 14.4 MPa. This could be due to the use of wood fly ash in combination with Class C fly ash. CLSM mixture made with Class C fly ash but without wood fly ash should be made in the future for comparison. Also, a higher amount of wood fly ash and a lower amount of Class C fly ash could be used in the future to manage the long-term strength of CLSM containing both wood and Class C fly ashes.

TABLE 5—*Compressive strength of CLSM mixtures.*

Mixture	Compressive Strength (MPa)					
Number	3 d	7 d	28 d	91 d	182 d	365 d
S-1	0.41	0.45	0.83	1.41	1.55	1.38
S-2	0.10	0.07	0.28	...	5.72	14.41
S-3	0.31	0.38	0.59	0.69	1.00	1.03

Water Permeability

A water permeability test was conducted for slurry Mixtures S-2 and S-3. Results at 63, 91, and 227 d are shown in Table 6 and Fig. 2. Generally, the water permeability decreased with the increase in age. In keeping with the drastic increase in compressive strength at late ages, permeability of CLSM Mixture S-2 decreased from 68 μm/s at 63 d to 6 μm/s at 227 d. Permeability of Mixture S-3 changed from 33 μm/s at 63 d to 12 μm/s at 227 d. The water permeability values of slurry mixtures decreased with the increase in age due to the improved microstructure of the CLSM matrix resulting from continuing pozzolanic reactions of wood fly ash and Class C fly ash.

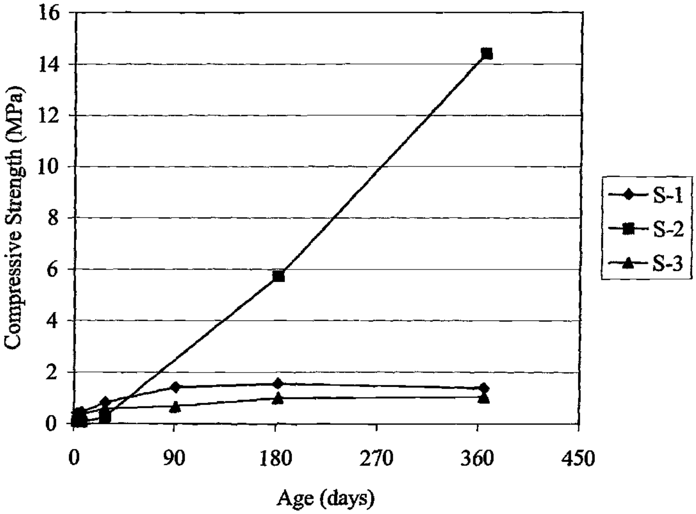

FIG. 1—*Compressive strength of CLSM mixtures.*

TABLE 6—*Average water permeability of CLSM mixtures.*

Mixture Number	Water Permeability (μm) 63 d	91 d	227 d
S-2	68	21	6
S-3	33	39	12

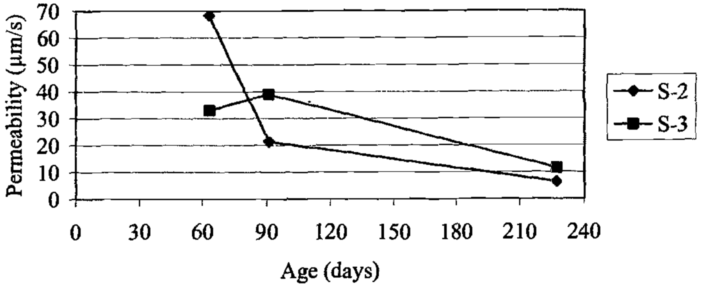

FIG. 2—*Average permeability of CLSM mixtures.*

Conclusions

The following are the general conclusions from this investigation:

1. The wood ash used did not conform to all ASTM C 618 requirements for coal fly ash. However, based on the test results, this wood fly ash can be used as a main component in flowable slurry because compressive strength and water permeability results indicate that slurry mixtures made with wood fly ash fully complied with the recommendations of ACI Committee 229R-99.
2. Compressive strength values for the slurry Mixtures S-1 and S-3, made with wood fly ash but without Class C coal ash, were 0.8 and 0.6 MPa at 28 d and 1.4 and 1.0 MPa at one year due to continuing pozzolanic reaction of wood fly ash. On the other hand, the slurry Mixture S-2 made with wood fly ash combined with Class C coal fly ash showed a 28 d strength of 0.3 MPa and a drastically increased one-year strength of 14.4 MPa.
3. The respective water permeability values for slurry Mixtures S-2 and S-3 were 68 and 33 μm/s at 63 d and 6 and 12 μm/s at 227 d. The water permeability of the slurry mixtures decreased with age due to the improved microstructure of CLSM matrix resulting from continuing pozzolanic reaction.

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Use of Botswana Fly Ash as Flowable Fill

REFERENCE: DeMars, K. A., Henderson, W. P., and Liu, M., "**Title of Paper,**"*Innovations in Controlled Low-Strength Material (Flowable Fill), ASTM STP 1459,*J. L. Hitch, A. K. Howard and W. P. Baas, Eds., ASTM International, West Conshohocken, PA, 2004.

ABSTRACT: In the present work high fly ash content flowable fill of Botswana fly ash has been investigated. The lime and cement in the proportion of 3%, 6%, 9%, 12%, and 15% and water equal to 125% of its liquid limit was mixed with fly ash to produce self leveling fill. The safe bearing capacity (S.B.C) of these fills was determined in the laboratory after 1, 2, 4, 7, and 15 days using drop test and the Dynamic Cone Penetration (DCP) test were determined in the field after 1, 7, and 28 days. The California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) of the fills were calculated from DCP values using empirical correlations. It was noted that there is no significant effect of lime or cement on seven days strength. The safe bearing capacity attained after seven days were approximately two to four times the safe bearing capacity of most well compacted earthen backfill materials. The CBR of the fills after seven days was found to be more than the requirement for the base and sub base for roads. The findings suggest that the high fly ash flowable fills of Botswana fly ash can successfully be used without any addition of lime or cement.

KEYWORDS: Botswana fly ash, flowable fill, safe bearing capacity, dynamic cone penetration resistance, california bearing ratio

Introduction

Flowable fill is a mixture of coal fly ash, water, and Portland cement that flows like a liquid, sets up like a solid, is self-leveling, and requires no compaction or vibration to achieve maximum density. It is designed to function in place of conventional backfill materials such as soil, or gravel and to minimize the common problems and restrictions generally associated with the placement of these materials. Flowable mixtures make up a class of engineering materials having characteristics and uses that overlap those of a broad range of traditional materials including compacted soil, soil-cement, and concrete. Consequently, flowable mixtures are proportioned, mixed, and delivered in a form that resembles a very workable concrete; and they provide for an in-place product that is equivalent to a high-quality compacted soil without the use of compaction equipment and related labour.

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The flowable character of these mixtures is derived from the spherical particle shape of fly ash or from a distribution of spherical and irregular particle shapes and sizes in fly ash and sand combinations when mixed with enough water to lubricate the particle surfaces.

Since high strength is not a requirement for a flowable fill, even a high Loss of Ignition (LOI) fly ash can be used. There are two basic types of flowable fill mixes that contain fly ash: high fly ash content mixes and low fly ash content mixes. The high fly ash content mixes typically contain nearly all fly ash, with a small percentage of Portland cement and enough water to make it flowable. Low fly ash mixes typically contain a high percentage of fine aggregate or filler material (usually sand), a low percentage of fly ash and Portland cement, and enough water to also make the mix flowable [1].

There are no specific requirements for the types of fly ash that may be used in flowable fill mixtures in Botswana. "Low lime" or Class F fly ash is well suited for use in high fly ash content mixes, but can also be used in low fly ash content mixes. "High lime" or Class C fly ash, because it is usually self hardening, is almost always used only in low fly ash content flowable mixes [2]. There is also a flowable fill product in which both Class F and Class C fly ash are used in varying mix proportions [2].

In Botswana more than 400 tons of fly ash is being produced everyday at Morupule Thermal Power Station, the only one in the country. More than 95% of this production is dumped as a waste in the form of slurry on the dumpsites while the remaining amount is being used by cement industries. This poses a serious environmental problem. Based on the amount of free lime present (about 6.5%), it is a class-F fly ash. The loss of ignition (LOI), determined by heating an ash sample to 850°C for 2 hrs using an open porcelain crucible, was found to be less than 1%. It is noted that LOI in Botswana fly ash is significantly low to enhance its self-hardening property even though the free lime content is not high. The limited work, done at the University of Botswana on local fly ash [3-5] has shown that both California Bearing Ratios (CBR) as well as Unconfined Compressive Strengths (UCS) of silty and sandy soils is significantly increased with the addition of fly ash alone as a stabilizer.

In the present investigation, effort has been made to explore the possibility of using local fly ash as a high fly ash content flowable fill. Fly ash-lime and fly ash-cement mixtures were prepared by adding lime and cement separately in the proportion of 3%, 6%, 9%, 12% and 15% of fly ash. Slurries of these mixtures were prepared by adding water equal to 125% of its liquid limits, which was sufficient to impart self-leveling flowability. These slurries were poured in metal trays and were allowed to set at room temperature. The safe bearing capacities (S.B.C.) of these mixtures were measured at an interval of 1, 2, 4, 8, and 15 days. Same slurries were poured in 150 mm diameter and 200 mm deep auger holes in the field and allowed to set under natural condition. The DCP of these fills were measured after 1, 7 and 28 days and were compared with the DCP values of natural ground and trenches filled by the contractors.

METHODOLOGY

Materials Used

Fly Ash

The fly ash used in this investigation was collected from the Morupule Thermal Power Station, Palapye. The fly ash used was well-graded non-plastic silt containing about 10% clay, 80% silt and 10% fine sand sized particles. Its liquid limit, as determined by cone penetrometer, was found to be 54% but the plastic limit could not be determined by rolling test. Its maximum dry density and optimum moisture content, corresponding to modified AASHTO compaction, were found to be 1310 kN/m^3 and 20% respectively. The chemical analyses of the fly ash (supplied by Morupule Power Station) are shown in Table 1.

TABLE 1— *Chemical composition of fly ash.*

Constituents	SiO_4	Al_2O_3	Fe_2O_3	TiO_2	Na_2O	CaO	K_2O	MgO	P_2O_5	Others
Proportion %	41.2	33.6	5.08	2.31	0.1	6.45	0.44	3.0	<0.05	> 7.77

Lime

The lime used was procured from the local supplier. It was a hydraulic lime of class B as per Bureau of Indian Standard (BIS): 712–1984 standard. This lime is a semi-hydraulic lime, which is used for mortars for masonry work. Its minimum compressive strength with lime sand mortar of proportion (1:3) by weight at the end of 14 days and 28 days should be 1.25 and 1.75 MPa respectively.

Portland Cement

The main raw materials used in the manufacture of Portland cement are limestone and shale, which are blended in specific proportions and fired at high temperatures to form cement clinker. A small quantity of gypsum is added to the cooled clinker, which is then ground to a fine powder known as – Portland cement. There are various types of Portland cement depending upon the composition of minor constituents. In the present investigation Portland limestone cement (II/A-L) was used.

Mixtures

The fly ash-lime and fly ash-cement mixtures were prepared by mixing lime and cement with fly ash in proportion of 3%, 6%, 9%, 12% and 15% of fly ash by mass. Slurries of these mixtures were prepared by mixing water equal to 125% of the respective liquid limits of the mixtures. The liquid limits of the mixtures are shown in Table 2. These slurries were used as flowable fills.

TABLE 2 — *Liquid limit of all the mixtures.*

Mixture - %	0 L	3 L	6 L	9 L	12 L	15 L	3 C	6 C	9 C	12 C	15 C
Liquid limit %	54	52	51	51	49	49	50	50	50	49	48

L – Lime; C - Cement

Laboratory Test

Safe Bearing Capacity

The safe bearing capacity of the flowable fills of all the mixtures was determined by dropping a circular plate (15 mm in diameter) carrying a weight from a known height. A dial gauge with a least count of 0.1 mm measured the amount of penetration. The assembly used shown in Fig. 1 was designed and assembled by the authors. The weights were changed according to the consistency and strength of the fills.

The kinetic energy of the mass after striking the mixture will be equal to the product of weight of the mass (W) and the height of fall (h). The penetration (S) of the mass in the mixture meets some resistance (R). To overcome the resistance from the mixture, mechanical work must be performed in driving the mass into the mixture, "i.e., R x S". The work energy relationship can be written as:

$$\tfrac{1}{2} M \times v^2 = R \times S$$

If the mass is a rigid body falling freely on the mixture with a velocity (v) and the final kinetic energy is zero, then

$$\tfrac{1}{2} M \times v^2 = W \times h$$

Hence $W \times h = R \times S$ i.e. $R = (W \times h)/S$

Value of R was taken as the safe bearing capacity of the fill.

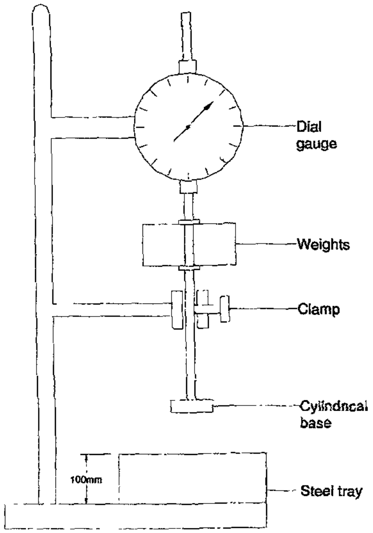

FIG. 1 — *Apparatus used to measure safe bearing capacity of the fill.*

Field Test

Dynamic Cone Penetration Resistance (DCP)

Engineers have used the methodology of Dynamic Cone Penetrometer for a number of years in Southern Africa as a non-destructive testing device to measure the in-situ bearing capacity of the pavements. The DCP instrument measures the penetration per blow into a pavement through each of different pavement layers. This penetration is a function of the in-situ shear strength of the material.

Research has shown that a good correlation exists between DCP measurements and the well-known California Bearing Ratio (CBR) of granular materials, as well as Unconfined Compressive Strength (UCS) of cemented materials [*6-8*].

In the present investigation the TRRL (Dynamic Cone Penetrometer A2465) was used. It uses a weight of 8 kg dropping through a height of 575 mm and a 60° cone having a diameter of 20 mm. The readings were taken after each blow and an average value of penetration in mm per blow was used to record DCP. The following empirical correlations were used to calculate CBR and UCS:

$\mathrm{Log}_{10}(\mathrm{CBR}) = 2.48 - 1.057\ \mathrm{Log}_{10}(\mathrm{mm/blow})$ - Kleyn & Van Heerden [*6*] (1)

$\mathrm{Log}_{10}(\mathrm{CBR}) = 2.48 - 1.057\ \mathrm{Log}_{10}(\mathrm{mm/blow})$ - TRRL [*7*] (2)

$\mathrm{UCS} = 15 \times (\mathrm{CBR})^{0.88}\ \mathrm{kPa}$ - TRRL [*8*] (3)

The DCP tests were performed in the field where the auger holes of 150 mm diameter and 200 mm depth were filled with the fills and allowed to set under natural climatic condition.

RESULTS AND DISCUSSIONS

Safe Bearing Capacity

The results of safe bearing capacity tests are shown in Figs. 2 and 3. It was noted that bearing capacity of all the mixtures increased with time. The measurements were possible only up to 15 days. After 28 days, the fills of all the mixtures were so hard that no appreciable dent could be recorded with the equipment used.

Fly ash – Lime

It is noted that initially the gain in S.B.C. is rapid up to first 7 days beyond which although it slows down, it continues to increase linearly even beyond 15 days. At the end of 7 days almost all the mixtures attained a value of 600 kPa or more, except for 9% lime for which it was 522 kPa. These values are approximately two to four times the bearing strength of most of the well-compacted earthen backfill materials [9]. As per South African Bureau of Standard [SABS 0161-1980] the presumed values of S.B.C. (submerged) of all soils are less than 500 kPa. It is interesting to note that within 24 hr a safe bearing capacity of 80 kPa is developed, which is high enough to allow most of the construction equipments to move without causing any significant damage.

There seems to be hardly any significant affect of lime on 7 days strength. The fly ash used can be considered as a well-graded silt containing 6.45% of lime. The lime present in fly ash seems to be sufficient to initiate pozzolanic hardening. This is in accordance with the findings of Koo [10], which have indicated that if the amount of unburnt carbon (LOI) is negligible, even a small quantity of free lime present in fly ash can initiate pozzolanic hardening. An addition of 3% of lime makes the total content of lime equal to 9.45%, which is close to the upper limit of the range of optimum lime content (3–10% depending upon the type of soil) and shows higher gain in strength after 15 days. This is in accordance with the findings of Tyagi [11], which suggests that the improvement in long-term strength is likely to be more at higher lime content.

Fly ash – Cement

The variation of S.B.C. with time for various proportions of cement is shown in Fig. 3. It may be noted that the variation of S.B.C. with time shows the same trend as that of lime. The gain is rapid up to first 7 days beyond which it increases linearly at a slower rate. The effect of cement is negligible up to 12%.

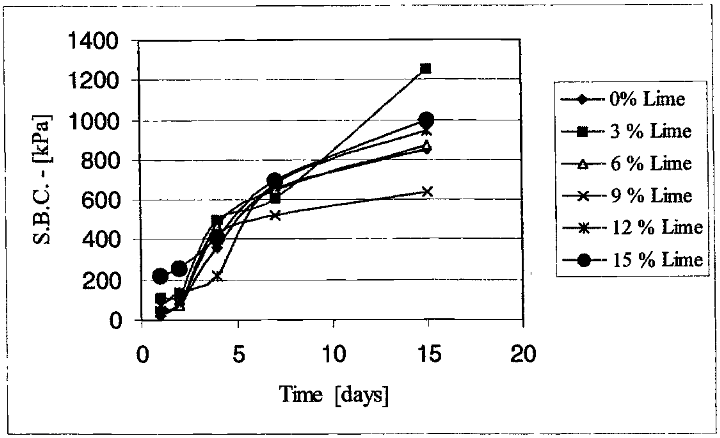

Fig. 2 — *Variation of S.B.C. with time for various fly ash – lime mixtures.*

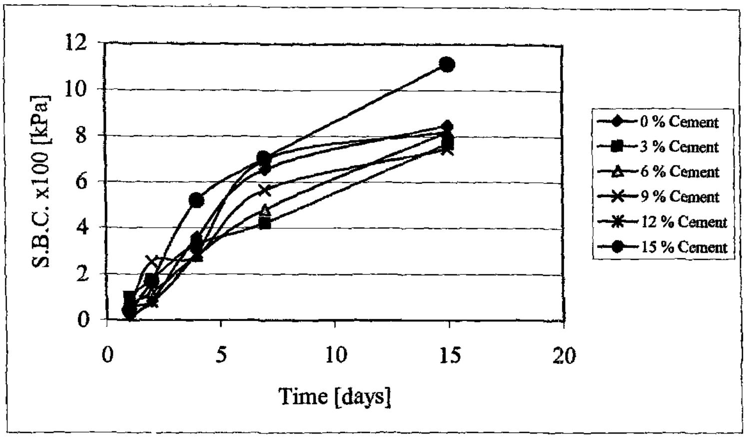

Fig. 3 — *Variation of S.B.C. with time for various fly ash – cement mixtures.*

Dynamic Cone Penetration Resistance (DCP)

The results of DCP tests on all the fills are plotted on a semi-log graph paper and shown in Figs. 4 and 5. The tests were conducted after a lapse of 1, 7, and 28 days. The variations as shown appear bilinear on the semi-log graph. The rate of decrease of DCP is very rapid within first 7 days after which it slows down. It is interesting to note that like S.B.C. the effect of lime appears to be insignificant within first 7 days. At the end of 28 days the effect of lime is significant only at 15%. In the case of fly ash-cement mixtures, the decrease in DCP follows the same trend as that of fly ash-lime mixture. The change in DCP is more or less proportional to the cement content unlike in fly ash-lime mixture where, the effect of lime is predominant only at 15%.

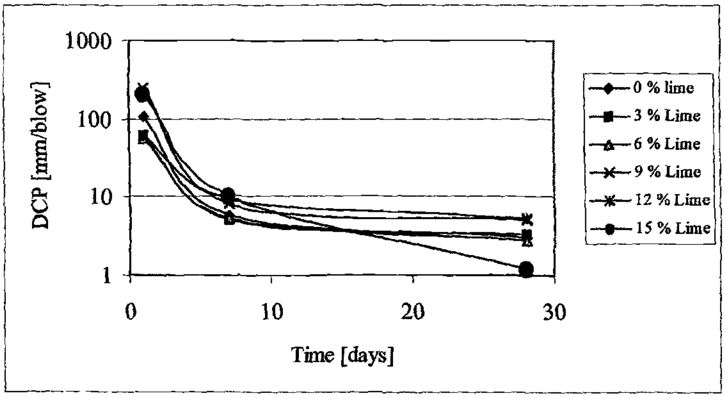

Fig. 4 — *Variation of DCP with time for various fly ash – lime mixtures.*

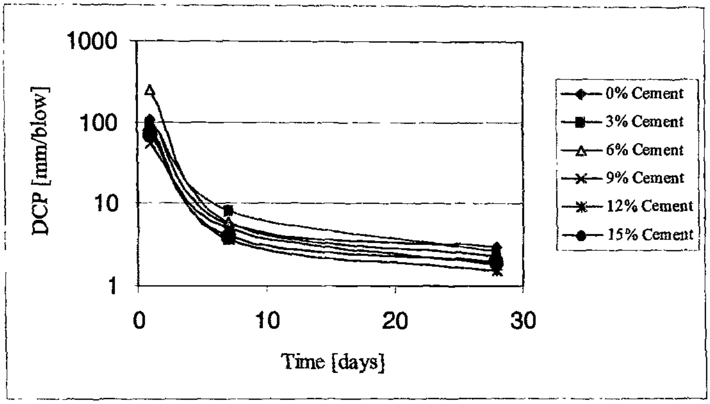

Fig. 5 — *Variation of DCP with time for various fly ash – cement mixtures.*

The CBR and UCS of all the fills were calculated using empirical correlations (1), (2), and (3) and are shown in Table 4.

From equations (1), (2) and (3) it is apparent that lower the magnitude of DCP, the higher the CBR and UCS. Similar trends are shown in Table 4. It is noted that both CBR and UCS increase with time. With the addition of lime up to 6%, there is a slight increase in CBR then it decreases up to 12% of lime and again it shows a sharp increase for 15% of lime. Similar inconsistency was observed in safe bearing capacity also. While with the addition of cement it shows a gradual increase up to 12% and then it decreases.

TABLE 4 — *DCP, CBR and UCS for the entire fill mixtures.*

Fill (Ash + L/C)	DCP- mm/blow (from field test)			TRRL, Road Note 8 [7]						Kleyn & Heerden [6]					
				CBR - % (eq.2)			UCS – kPa (eq. 3)			CBR - % (eq. 1)			UCS – kPa (eq. 3)		
	1 d	7 d	28 d	1d	7 d	28 d	1 d	7 d	28 d	1 d	7 d	28 d	1 d	7 d	28 d
0% L	109	5.67	3.0	2	48	95	29	452	825	1	47	105	15	444	901
3% L	60	5.0	3.2	4	55	88	51	510	771	2	55	97	28	510	840
6% L	56	5.3	2.75	4	52	104	51	477	893	2	51	117	28	477	991
9% L	244	8.2	5.0	1	33	55	15	325	510	0.4	29	55	7	290	510
12% L	61	9.3	5.3	4	29	53	51	290	494	2	25	52	28	255	485
15% L	209	10	1.17	1	27	256	15	273	1974	0.5	22	350	8	228	2599
3% C	97	8.3	2.67	2	32	107	28	317	916	1	29	122	15	290	1028
6% C	247	5.9	2.33	1	46	124	15	436	1043	0.4	44	145	7	419	1197
9% C	54	5.0	1.83	5	55	159	62	510	1298	3	55	198	39	510	1575
12% C	81	3.7	1.5	3	76	197	39	678	1568	2	80	255	28	709	1967
15% C	69	4.0	2.0	3	70	145	39	631	1197	2	73	176	28	654	1420

The lower value of CBR and UCS at 15% cement may be attributed to the fracturing of the fills during driving operation of the cone resulting into higher penetration and lower DCP. The DCP tests were also conducted on natural ground and on trenches filled recently and 2 years back by the contractors. The filling was done as per normal procedure used by most of the contractors. The results are shown in Table 5.

TABLE 5 —*DCP of natural ground and filled trenches.*

Location	G1	G2	G3	G4	G5	G6	G7	G8	G9	T1*	T2*	T3*	T4	T5	T6
DCP mm/blow	16	8.6	8	21	15.4	18.2	13	9.3	10	9	9	19	35	27	22
	Av. = 13.3									Av.=12.3			Av.= 28		

G – Ground; T*- Trenches filled 2 yrs back; T – Trenches filled recently

It is noted that 7 day DCP of fly ash fills without any lime or cement is 5.67, which is less than half of the average DCP of natural ground (13.3) and trenches filled about 2 years back (12.3). The recently filled trenches are much weaker than all of the 7 day fills (Av. DCP =28). It suggests that the use of flowable fills of Botswana fly ash, for ground and structural fills, could be a better proposition both in terms of economy and strength.

Conclusions

The laboratory and field tests conducted to evaluate the suitability of Botswana fly ash for flowable fills leads to the following conclusions:

1. The strength measured as safe bearing capacity; california bearing ratio and unconfined compressive strength increases with time.
2. The increase in strength is initially rapid up to 4 to 7 days and then slows down but continues to increase even beyond 28 days.
3. There seems to be no effect of lime on the safe bearing capacity up to 7 days, however, 28 days strength is better with 3% of lime.
4. The safe bearing capacity achieved after 7 days is about two to four times the bearing capacity of most well compacted earthen backfill materials.
5. The effect of cement proportion on safe bearing capacity is negligible up to 12%.The addition of lime up to 12% has no significant effect on CBR and UCS.
6. The CBR and UCS are significantly increased with the addition of cement and the maximum gain is observed with 12% of cement.
7. The 7 days strength of the fills is almost 2 times the strength of natural ground or 2 year- old backfilled trenches.
8. The use of high volume fly ash flowable fill with Botswana fly ash, without any addition of lime or cement, can be recommended for various purposes.

Acknowledgment

The authors would like to acknowledge Mr. Gilika of Botswana Power Corporation for his assistance in supplying the fly ash and Mr. J. Phale and Mr. T. Moreeng for their assistance in conducting all the tests.

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Case History: Stabilization Of The Sugar Creek Limestone Mine Using Dry Scrubber Ash

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REFERENCE: Moberly, R. L., Voss, L. B., and Mings, M.L., "**Case History: Stabilization of the Sugar Creek Limestone Mine Using Dry Scrubber Ash,**" Innovations ***in Controlled Low-Strength Material (Flowable Fill), ASTM STP 1459,*** J. L. Hitch, A. K. Howard, and W. P. Baas, Eds., ASTM International, West Conshohocken, PA, 2004.

ABSTRACT: Mine stabilization with coal combustion by-products such as fly ash is common throughout the United States. However, the use of the dry scrubber ash as opposed to fly ash has created some unique challenges in permitting and monitoring. The dry scrubber ash is a mixture of fly ash and residue from a dry scrubber unit designed to control air pollutants. The dry scrubber ash contains ammonia, and ventilation during mine stabilization can become a major issue. An abandoned room and pillar limestone mine in Sugar Creek, Missouri, which is owned by Lafarge North America, Inc. (Lafarge), is being backfilled using between 100 tons (90,700 kg) and 900 (816,300 kg) tons per day of dry scrubber ash slurry generated by two nearby power plants. Mixing the dry scrubber ash with water at the site creates the slurry. The slurry is injected into the mine through 8- to 10-inch (0.2 to 0.25 m) diameter cased boreholes drilled through as much as 175 feet (53.3 m) of soil and rock overburden. Because of previous subsidence, the Mine Safety and Health Administration (MSHA) refused permission to enter the majority of the mine and also did not allow construction equipment to be placed on top of the unstable portions of the mine. Planning and permitting for this project started in the mid 1990's. Prior to beginning injection activities, Lafarge obtained both Local and State permits for the dry scrubber ash project. The various permits required monitoring the extent of the underground areas stabilized, the progress in filling subsided areas, the volume of fly ash placed for stabilization, and potential environmental impacts (including ammonia emissions). Because of the restriction placed by MSHA on entering the majority of the mine, all observations of injection to date have been conducted via remote video photography or ultrasonic distance measuring sensor. The mine stabilization began on December 19, 2001. As of May 2003, approximately 165,000 tons (149.7 million kg) of dry scrubber ash slurry have been injected into the mine.

KEYWORDS: fly ash, stabilization, underground mining, coal combustion by-product, scrubber ash; ammonia

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Introduction

Mine stabilization with coal combustion by-products such as fly ash is common throughout the United States. There are many examples of where filling with fly ash has been used to stabilize portions of mines that have experienced dome outs or other types of failures. Mine filling has been successful in preventing larger scale mine collapse and restoring property.

The Kansas City area has a considerable number of underground mines that have been excavated for over 100 years. Many of these mines are no longer stable and, in some cases, are considered dangerous for any surface usage.

This case history provides an example of attempts to backfill an unstable mine and make the property both safe and usable for future development.

General Geology

Unconsolidated materials, including soils with origins including glacial, alluvial, colluvial, and residual, are the youngest geologic deposits in this area. These materials overly a series of sedimentary rock units of Pennsylvanian Age which have a total combined thickness of about 900 feet (274 m) in the Kansas City area. These geologic units represent a series of cyclic sequences of sedimentary deposition, probably caused by marine transgression and regression, which produced a series of repetitive thin beds of limestone and shale with occasional sandstone and coal beds. The rock units exposed in the majority of the Kansas City area include a series of formations and members assigned to the Kansas City Group of the Missourian Series. These units are illustrated on Figure 1.

Two units within the Kansas City Group, the Argentine Limestone Member of the Wyandotte Formation and the Bethany Falls Limestone Member of the Swope Formation, are the rock units typically mined in the Kansas City area. Both units exhibit a relatively thick sequence of limestone beds with a minimal amount of shale partings, and sufficient bed thickness to allow a roof beam that will support the mine opening. Layers of shale above the mined units are present to inhibit the infiltration of water into the mined space.

Structural features, or the lack thereof, have aided the mining activities in the Kansas City area. In general, the rock units in this area have a very gentle dip, typically about ½ degree downward to the northwest. Some exceptions do occur. Although several structural features are present, including joints, fractures, folds, and faults; they have had only a minimal impact on the mining and secondary development operations of these facilities.

Mining History

Surface mining was initiated at this site in the early 1900's to supply limestone for the cement plant that was constructed in Sugar Creek, Missouri (a suburb of Kansas City).

Limestone was originally quarried from the Iola Formation of the Kansas City Group (see Figure #1). This rock unit was exhausted in a short time and underground mining was initiated in the Bethany Falls Limestone. This mine was constructed using the "room and pillar" method of extraction where the rock was drilled and shot, leaving rooms with various dimensions. The pillars that were left in place to support the roof were also of various sizes.

The following provides a schematic of the subsurface conditions.

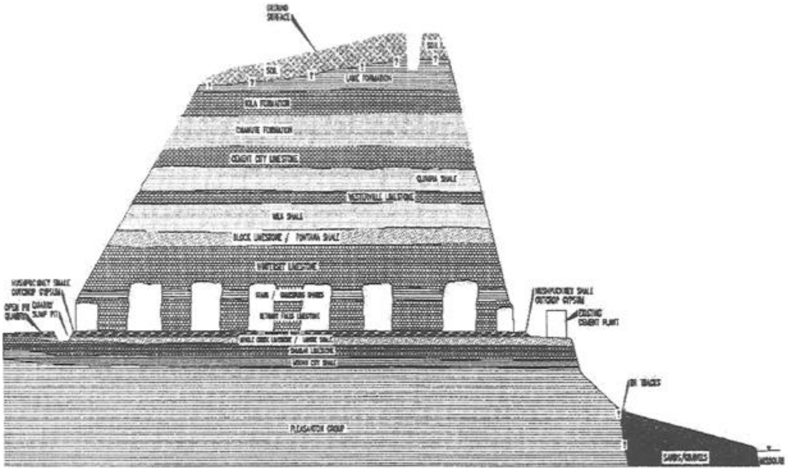

FIG. 1 — *Schmatic of geologic units.*

In the Bethany Falls Limestone mines in the Kansas City area, typical mines have been constructed with room sizes of about 40 to 50 feet (12.2 to 15.2 m) in dimension and floor to roof heights of 11 to 14 feet (3.3 to 4.3 m). Pillars remaining are typically on the order of 20 to 25 feet (6.1 to 7.6 m) in diameter. This provided a ratio of pillar diameter to room height of approximately 2:1, which was been found to be a stable configuration. In the early days of mining, pillars were left in a triangular or random pattern. About 50 years ago, the mining techniques changed, leaving pillars on a grid pattern, making the mine opening more conducive for secondary development, if desired.

The Sugar Creek mine did not follow the local practice of pillar spacing or sizing; many long irregular shaped pillars were left in place (see Figure 2). At some point in time, it was determined that both shale and limestone units above the Bethany Falls Limestone could also be used in the cement making process, and in some areas, the Stark/Galesburg Shales and portions of the Winterset Limestone overlying the Bethany Falls Limestone were removed. Where these additional units were removed is referred to as the "high tunnel" area. The high tunnel area created an unstable condition, partially due to a pillar diameter to room height ratios of about 1:1 (stable condition is about 2:1).

The low tunnel area, where only the Bethany Falls Limestone was removed, is relatively stable and is currently used for clinker storage and haul roads in some areas of the mine. The floor of the former mine, in most areas, is the top of the Hushpuckney Shale. Mining was discontinued in this area in the 1960s.

A series of mine collapses occurred at various times after mining was completed. Some of these failures resulted in major surface subsidence, as well as localized "dome-outs" within the interior of the mine. Legend has it that in the early 1990s, an equipment operator was doing some grading work above the mine. When he returned after his lunch break, he could not find his equipment and thought somebody had stolen it. On closer inspection, he found it was about 40-foot (12.2 m) deep in a new sinkhole. After this reported incident, MSHA declared the majority of the mine "off-limits" and stated that no one could enter this portion without completing specific entry requirements and notifying MSHA. In addition, no major equipment was allowed over this portion of the mine.

Within the former mine, small quantities of groundwater are found in the Hushpuckney Shale (the unit that forms the floor of most of the mine). Water moves through fractures in the shale and in some areas, seeps from the Hushpuckney at the face of the mine. The shale has an estimated hydraulic conductivity on the order of 1 x 10^{-7} cm/sec. The Hushpuckney is a relatively thin unit and is only a few feet thick in most areas beneath the mine. Thus, the volume is of water present in the Hushpuckney is small.

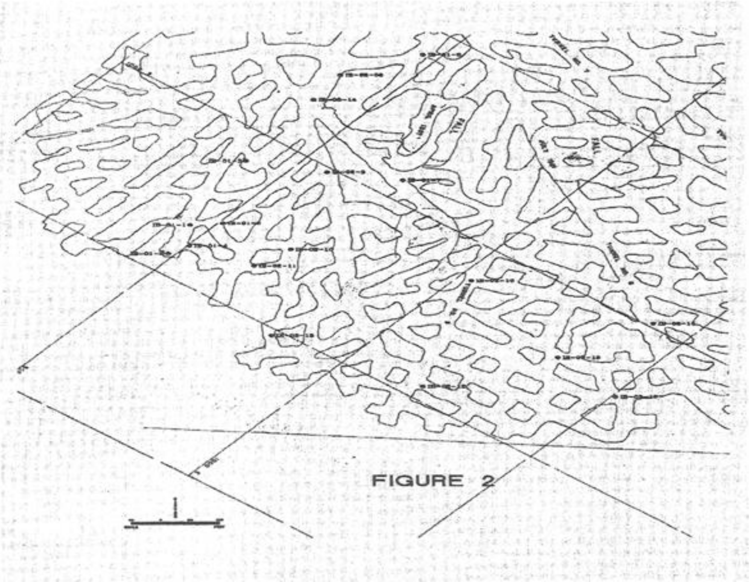

FIG. 2 – *Mine pillar map and injection boring location.*

Project History

In the early 1990s, a company called Mineral Solutions, Inc. (a subsidiary of Lafarge North America) evaluated the potential of using excess fly ash from several local fossil-fueled power plants for stabilizing the underground facilities at Sugar Creek. Initial planning and discussions with the City of Sugar Creek, Missouri and the Missouri Department of Natural Resources (MDNR) was initiated, and with favorable results of these initial discussions, additional planning and permitting was completed.

During the initial permitting process, a catastrophic explosion occurred at the power plant that was supposed to supply the majority of the fly ash for the mine backfilling project. The new air emissions systems installed at this power plant produced a dry scrubber ash utilizing ammonia in their process. The quality, quantity, and composition of the dry scrubber ash were not known at that time so significant modifications to the various permits were required. In addition, due to the potential emissions of ammonia, significant modification to the mine space, e.g., construction of bulkheads (see Figure 3) at portal road openings was required.

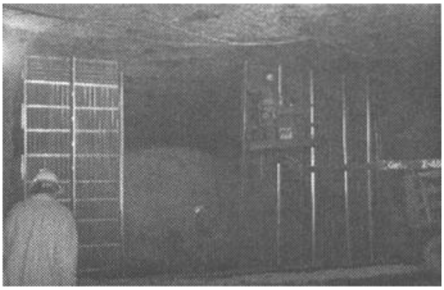

FIG. 3 — *Construction of bulkheads.*

Prior to startup of operations, Lafarge had to obtain the following permits for the fly ash injection project:

Special Use Permit from the City of Sugar Creek. This permit carries a term of 10 years and is accompanied by a set of relatively stringent conditions. The permit was granted in 2000 and thus will need to be renewed in 2010.

Underground Injection Control Permit from MDNR. This permit carries a term of 5 years and includes requirements for groundwater monitoring. The permit was renewed in 2000 and thus will need to be renewed in 2005, or before.

In addition, Lafarge maintains a **Beneficial Use Exemption** with the MDNR for the fly ash to be used for mine stabilization. Any changes to the type or source of the fly ash to be used to stabilize the mine will necessitate notifying MDNR, Solid Waste Management Program. A letter describing the dry scrubber ash expected from the rebuilt power plant was sent to the solid waste management program director on March 30, 2001.

As part of the overall project, a number of documents and plans were prepared. Included with these various documents were a Mine Stabilization Plan and a Quality Control Plan.

These Plans call for the following monitoring:

- The extent of the underground areas stabilized
- The progress in filling subsided areas
- The volume of fly ash placed for stabilization
- Potential environmental impacts

Safety considerations (and MSHA requirements) prevent access at mine level to observe filling and the construction of barriers. Consequently, the Mine Stabilization Plan called for observations to be made by lowering a camera through boreholes. Progress on filling mined space is also checked by using a tape to measure the depth to the top of the hardened fly ash. Placement of fly ash into surface depressions is monitored by comparing the volume of the depression to the volume of ash placed to verify that the slurry stays within the collapse.

To minimize the potential for environmental impacts, the following procedures were established:

- Quarterly (or more frequent) Toxicity Characteristic Leaching Procedure (TCLP) data are obtained and evaluated for all fly ash sources. The data is analyzed prior to any fly ash placement at the Sugar Creek site.
- Fly ash is to be rejected if it exceeds TCLP standards for metals.
- Fly ash placement must be in accordance with the Mine Stabilization Plan and the MDNR Underground Injection Permit.
- Groundwater samples are obtained semi-annually from two monitoring well clusters (2 wells each) located in the Missouri River alluvium. The Missouri River alluvium is the source of water for the City of Independence, Missouri. The Sugar Creek site is located less than 2 miles (3,218 m) upstream of the Independence well field but is outside of an area defined by the United States Geologic Survey (USGS) as the 100-year capture area for the Independence well field. Results are submitted to the Cities of Sugar Creek and Independence semi-annually. Results are reported to the MDNR at least annually.
- Because of the potential of ammonia emissions from the hydrated dry scrubber ash, a series of containment walls were constructed between mine pillars to seal off the area of proposed backfilling from areas of the mine that are still in use.

Monitoring for environmental impacts is performed in accordance with the conditions in the Special Use Permit issued by the City of Sugar Creek and in accordance with the Underground Injection Control permit issued to Lafarge by the MDNR.

An annual report on mine stabilization activities is prepared by Lafarge and submitted to the City of Sugar Creek. The report lists or discusses:

- The volume of fly ash placed
- The areas where fly ash was placed
- Areas where mine stabilization was completed
- The sources of the fly ash used
- The results of monitoring for environmental impact

Backfilling Operations

Mineral Solutions, Inc. operates the Mine Stabilization project at the Sugar Creek Facility. Filling of surface subsidences began in 1999 and underground injection of the dry scrubber ash began on December 19, 2001.

The activities associated with the backfilling operations of the Sugar Creek Mine can be broken down into several key components, including: site preparation; transportation; unloading; mixing; injection; and inspection. The following brief discussion provides a summary of each of these operations.

SITE PREPARATION– series of drill holes (see Figure 4) into the mine have been completed. These holes have ranged from about 95 to 175 feet (29 to 53 m) deep and are either 14- or 18-inch (0.36 or 0.46 m) diameter. An 8- or 10-inch (0.2 or 0.25 m) diameter, thick wall, PVC casing is installed in each drill hole and extends to within 1-foot (0.3 m) of the mine roof. After drilling and casing installation, each hole is videotaped to assist in an evaluation of the mine area in the vicinity of the drill hole.

Due to MSHA requirements, Boreholes must be drilled from a stable location, requiring placing the drill rig over a stable pillar or drilling an angle hole from a stable location either on or off of the mine. To reach some of these locations, construction of access roads was required. To date (May 2003), 18 boreholes have been drilled (see Figure 2). Several boreholes were drilled that did not encounter open mine space either due to mine collapse or encountering a mine pillar. Additional drill holes are planned in the near future.

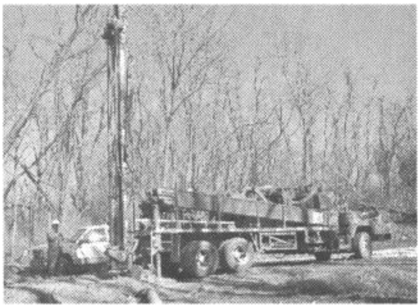

FIG. 4 —*Drilling injection borings.*

TRANSPORTATION – A number of pneumatic tractor-trailer tank trucks (see Figure 5) are utilized to transport the dry scrubber ash from nearby power plants in the Kansas City area to the mine site. Typically, a total of 3 trucks and 6 tanker/trailers are used on a daily basis. The total roundtrip time (loading, travel, unloading and return) is approximately 75 minutes. Each truck can transport about 35 tons (31,745 kg) of dry ash. On a typical day, 18 loads of ash are transported to the injection site.

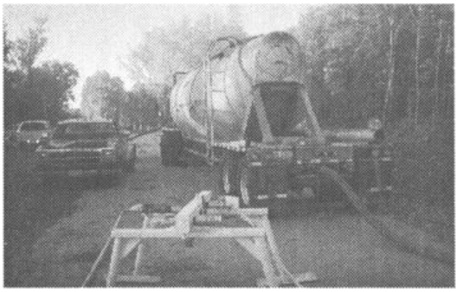

FIG. 5 – *Pneumatic trucks.*

UNLOADING – After the trailer is positioned, the ash is discharged to the unloading facilities via 8-inch hoses (see Figure 6).

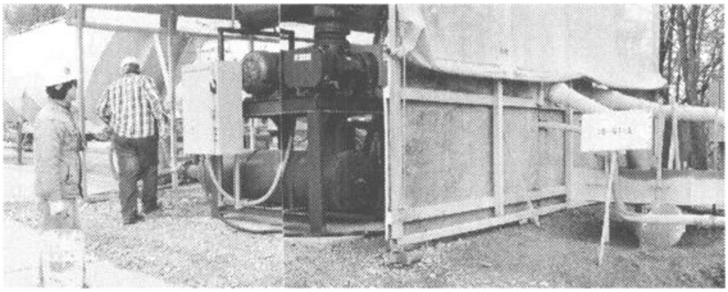

FIG. 6 – *Ash unloading facility.*

MIXING – a new 6-inch (0.15 m) water line has been constructed at the unloading facilities to supply the large volume of potable water needed for mixing purposes at the unloading facility. This water supply is from the nearby Independence, Missouri Water Department facilities. A mixing ratio of about 1 (ash) to 1.1+ (water) has been used to date to satisfy the mixing requirements and obtain the unconfined compressive strength required by the permits.

A proprietary slurry gun is used to mix the dry scrubber ash with locally obtained water for placement in surface subsidence areas (see Figure 7).

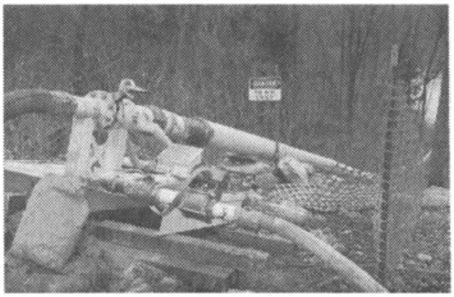

FIG. 7 — *Ash/water mixing gun.*

INJECTION— After mixing, the dry scrubber ash slurry is transported to the boreholes via 6-inch diameter PVC pipe and injected into the mine space (see Figure 8).

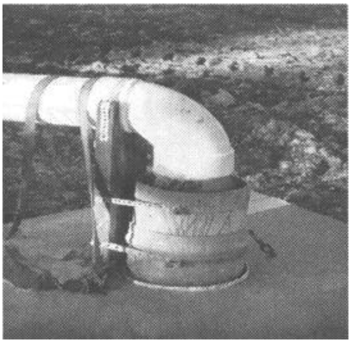

FIG. 8 — *Borehole injection.*

INSPECTION – After the dry scrubber ash is mixed and injected into pre-drilled injection holes, the depth of solidified ash is measured on a daily basis and occasionally check by lowering a video camera through the injection hole and into the mine (see Figure 9). When an accumulation of solidified ash is identified, the measurement frequency is increased. When substantial buildup has occurred near the injection hole, the operation is moved to a new location and injection is reinitiated.

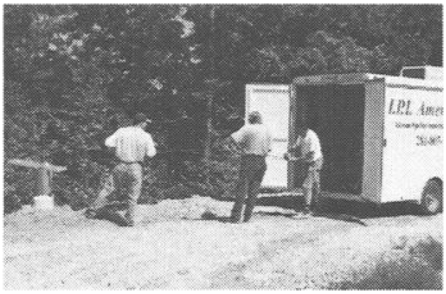

FIG. 9 – *Video inspection.*

TESTING—The dry scrubber ash is tested for fineness, ammonia, and strength. TCLP tests are performed in accordance with the project Quality Assurance Plan. In addition, the underground area that is accessible is inspected on a weekly basis and selected locations are tested for ammonia emissions on a daily basis.

Results and Conclusions

As of May 2003, approximately 165,000 tons (149.7 million kg) of dry scrubber ash, mixed with about 380 million gallons (1,438 million liters) of potable water have been used to stabilize portions of the former Sugar Creek Mine. At the time of this writing, analysis of the initial areas to be stabilized was being made to see if the void space had been filled. If any void spaces are found, additional boreholes are drilled to allow for continued injection.

Calculations indicate the former Sugar Creek Mine will be backfilled and stabilized in approximately 17–20 years.

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Section II: Engineering Property Analysis

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Rapid Set, High-Early Strength, Non-Excavatable Flowable Fill

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ABSTRACT: A high-flow, rapid-set, non-excavatable CLSM mixture called ZOOM was developed for applications where time was critical using normal concrete component materials. The following criteria were established for the ZOOM mixture:

- Pass the ASTM D 6024 in 6 h or less regardless of subgrade moisture conditions
- Little or no bleeding or shrinkage
- Flow as per ASTM D 6103 greater than 222 mm
- Greater than 207 kPa compressive strength as per ASTM D 4832 in 24 h
- Be able to perform using a wide variety of Tennessee aggregates

The development of the ZOOM mixture began in the laboratory in May 2002 using Ohio River Sand (ORS). Subsequently, the mixture proportions were adjusted to produce the desired plastic and hardened properties with other Tennessee fine aggregates. Three successful field demonstrations using different fine aggregates were held across Tennessee in the fall of 2002. ZOOM CLSM met compressive strength development and time of suitability for load application performance criteria at every field demonstration. Plastic properties were adequate but failed to meet the established criteria on two occasions. Fine aggregate properties such as gradation and angularity were found to dictate mixture proportions required to achieve flow, air content, and bleeding characteristics. Average air temperature and CLSM air content were found to be important to time of suitability for load application. The research effort was co-sponsored by the Tennessee Department of Transportation and the Tennessee Ready Mixed Concrete Association

KEYWORDS: controlled low-strength material, air content, flow consistency, ball drop apparatus, compressive strength, fine aggregate, angularity, particle shape, gradation

Introduction

The Tennessee Department of Transportation (TDOT) Division of Materials & Tests saw a need for a rapid set, non-excavatable Controlled Low-Strength Material (CLSM) for applications where time was critical. CLSM initial set can occur in two ways: dewatering and chemical reactions. The research team decided that the CLSM should initially harden due to chemical reactions rather than by bleeding (dewatering) in case of unfavorable placement conditions. The new CLSM needed not only to set and gain compressive strength rapidly but also to have a very fluid consistency while plastic. The new CLSM mixture was named ZOOM to reflect the rapid set and strength gain.

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The opinions, findings, and conclusions expressed here are those of the authors and not necessarily those of the Tennessee Department of Transportation or the Tennessee Ready Mixed Concrete Association

Research Significance

The development of a high flow, rapid set CLSM mixture will allow the TDOT Materials and Tests Division additional flexibility to respond to highway situations requiring a working platform or structural fill that is self-compacting, sets rapidly, and gains strength quickly. Examples of such situations would be an emergency subgrade or base repair where the pavement must be opened to traffic as soon as possible or a trench excavation across a heavily trafficked roadway.

Research Objectives

Tennessee Technological University (TTU) researchers established the criteria shown below for the ZOOM CLSM mixture:

- Must pass the Standard Test Method for Ball Drop on Controlled Low Strength Material (CLSM) to Determine Suitability for Load Application (ASTM D 6024) in 6 h or less, regardless of subgrade moisture conditions or permeability.
- Must have little or no bleeding or shrinkage.
- Must flow as per Standard Test Method for Flow Consistency of Controlled Low Strength Material (CLSM) (ASTM D 6103) greater than 222 mm.
- Must have greater than 207 kPa compressive strength as per Standard Test Method for Preparation and Testing of Controlled Low Strength Material (CLSM) Test Cylinders (ASTM D 4832) in 24 h.
- Must be able to perform using a wide variety of Tennessee aggregates.

Materials

Aggregates

The research team obtained crushed limestone screenings, Ohio River sand, limestone manufactured sand, and crushed sandstone sand from Middle and East Tennessee aggregate producers. The specific gravity and absorption of each aggregate are shown in Table 1. Fine aggregate specific gravity and absorption were determined in accordance with Standard Method of Test for Specific Gravity and Absorption of Fine Aggregates (AASHTO T 84-00). The grading of the aggregates is shown in Fig. 1. Gradations were determined in accordance with Standard Method of Test for Fine and Coarse Aggregates (AASHTO T 27-99) and Standard Method of Test for Materials Finer than 75-um (No. 200 Sieve) in Mineral Aggregates by Washing (AASHTO T 11-96). Uncompacted void values, determined in accordance with Standard Method of Test for Uncompacted Void Content of Fine Aggregate (AASHTO T 304-96), are shown in Fig. 2.

TABLE 1—*ZOOM CLSM aggregate specific gravities and absorptions.*

Aggregate	Apparent Specific Gravity	Bulk Specific Gravity (Dry)	Bulk Specific Gravity (SSD)	Absorption, %
Ohio River Sand (Control)	2.645	2.583	2.607	0.93
Manufactured Limestone Sand	2.676	2.588	2.621	1.27
Limestone Screenings	2.760	2.676	2.708	1.11
Crushed Sandstone	2.658	2.611	2.628	0.65

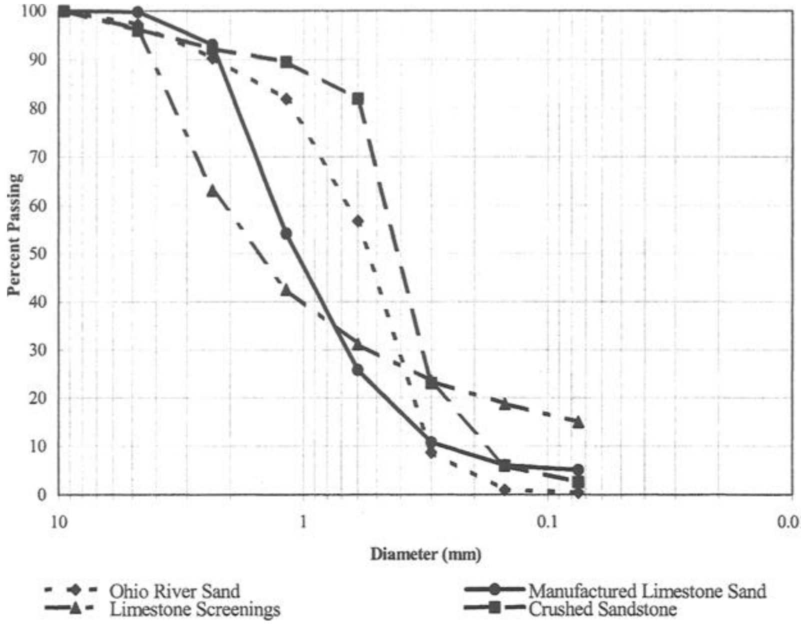

FIG. 1—*CLSM fine aggregate gradation comparison.*

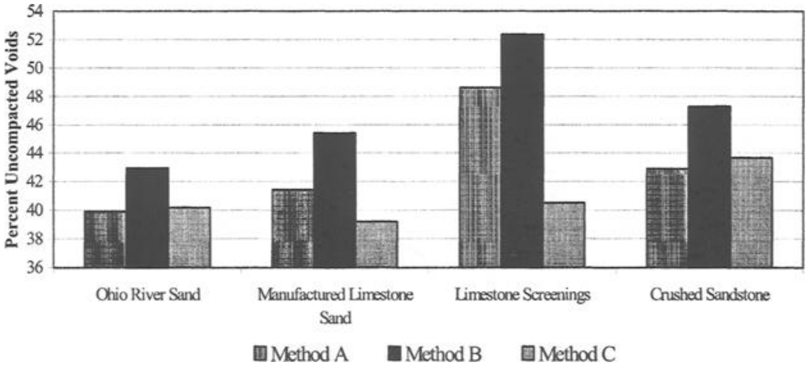

FIG. 2—*Comparison of CLSM Fine Aggregate Angularity Values (AASHTO T 304).*

Other Materials

Type I Portland Cement meeting Standard Specification for Portland Cement Standards (ASTM C 150) was selected. Local tap water was also used for all laboratory mixtures. An air-entraining admixture, conforming to Standard Specification for Air-Entraining Admixtures for Concrete (ASTM C 260-97), was used in all laboratory ZOOM batches. A commercially available powder-form CLSM air generator was used for ZOOM field batches. A commercially available high-range water reducer and a water-reducing accelerator conforming to Standard Specification for Chemical Admixtures for Concrete (ASTM C 494) Types F and E, respectively, were used in field and laboratory mixtures.

Commercially available, single-use cardboard molds (100 × 200 mm), reported by the manufacturer to be in compliance with Standard Specification for Molds for Forming Concrete Test Cylinders Vertically (ASTM C 470), were used for all compressive strength samples. Commercially available, wet-suit neoprene pads in Practice for Use of Unbonded Caps in Determination of Compressive Strength of Hardened Concrete Cylinders (ASTM C 1231) rigid retainers were used for capping all compressive strength specimens. To obtain the same thickness as the approved neoprene, two layers of the softer neoprene were required.

Procedure

The initial ZOOM mixture was proportioned by trial batches in the laboratory at Tennessee Technological University (TTU) with Ohio River Sand fine aggregate. All batches were mixed in a 0.57 m^3 capacity electric mixer. Mixing was conducted in accordance with Standard Test Method for Preparation and Testing of Controlled Low Strength Material (CLSM) Test Cylinders (ASTM D 4832-95). The initial ZOOM mixture proportions are shown in Table 2.

TABLE 2—*Initial ZOOM CLSM mixture proportions.*

Component	Amount
Type I Portland Cement	178 kg/m^3
Water	188 kg/m^3
Ohio River Sand (SSD)	1439 kg/m^3
Air-Entraining Agent	2.71 liters/m^3
High-Range Water Reducer	1.16 liters/m^3
Accelerator	8.70 liters/m^3

Plastic property tests were conducted on all batches. Unit weight and air content (gravimetric) tests were performed in accordance with Standard Test Method for Unit Weight, Yield, Cement Content and Air Content (Gravimetric) of Controlled Low Strength Material (ASTM D 6023-96). Determination of flow was performed in accordance with Standard Test Method for Flow Consistency of Controlled Low Strength Material (ASTM D 6103-97).

Compressive strength tests were performed in accordance with Standard Test Method for Preparation and Testing of Controlled Low Strength Material (CLSM) Test Cylinders (ASTM D 4832-95) with the exceptions recommended by Sauter and Crouch [3].

Initial Results

The initial plastic properties for ZOOM CLSM mixtures with all fine aggregates are shown in Table 3. Equal volumes of other fine aggregates were substituted for Ohio River Sand in the control mixture and absorption water quantity adjustments were made for other fine aggregates. All four ZOOM CLSM mixtures failed to comply with the total requirements. However, the 6 mm flow deficiency of the Ohio River Sand mixture and the 1.4 percent excess air content of the manufactured limestone sand mixture were not considered serious enough to affect performance. However, the limestone screenings and crushed sandstone mixtures had greater difficulties meeting the desired properties. Table 4 shows a comparison of the critical fine aggregate properties for ZOOM CLSM. Information from Tables 3 and 4 were analyzed to determine how the mixture deficiencies could be addressed.

TABLE 3—*Initial ZOOM CLSM plastic properties.*

...	Requirements	Ohio River Sand	Manufactured Limestone Sand	Limestone Screenings	Crushed Sandstone
Flow, mm	222 minimum	216	248	Shear (No Flow)	165
Bleed Time, min	Little or None	4.5	No Bleeding	No Bleeding	No Bleeding
Shrinkage	Little or None	Minimal	No Shrinkage	No Shrinkage	No Shrinkage
Air Content, %	20-30 preferred	25.7	31.1	16.6	30.4
Unit Weight, kg/m^3	None	1674	1636	1950	1589
Problems	...	Flow	None	Flow & Air	Flow
Possible Solutions	...	Best Combination Available	...	Increase air volume & paste fluidity	Increase paste fluidity

TABLE 4—*ZOOM CLSM aggregate property summary.*

Aggregate	% Passing #200	FM	C_u	T 304 U_s	T 304 U_m	T 304 U_r
Ohio River Sand (Control)	0.4	2.64	2.10	39.92	42.97	40.19
Manufactured Limestone Sand	5.1	3.10	5.93	41.41	45.43	39.22
Limestone Screenings	15.0	3.25	29.33	48.61	52.38	40.52
Crushed Sandstone	2.6	2.11	2.56	42.90	47.27	43.67

Mixture Deficiencies and Adjustments

Limestone Screenings

The air content of the limestone screenings ZOOM CLSM was approximately 9 % less than that of ZOOM CLSM with control aggregate due to a much higher fines content (15 % vs. 0.4 %). Several factors reduced the flow of the limestone screenings ZOOM CLSM mixture to zero. First, the high fines content (15 % vs. 0.4 %) was probably the most important factor in reducing flow. Second, the particle shape (U_s = 48.61 and U_m = 52.38) of the limestone screenings approached a flat and elongate condition. ACI 221-96 [1] cited the work of Gray and Bell [2], who recommended a maximum U_m of 53 percent to avoid flat and elongate conditions. Third, the denser gradation (C_u = 29.33 vs. C_u = 2.10 for the control aggregate) made obtaining adequate flow more difficult. Finally, and perhaps least importantly, a higher FM (3.25) indicates a much coarser gradation than ORS (FM = 2.64). Coarser particles are harder to mobilize. Bleeding was not a problem due to the high fines content and denser gradation.

Crushed Sandstone

Flow was 51 mm less than the flow of ZOOM CLSM with the control aggregate. The angularity of the crushed sandstone particles (U_s = 42.90 and U_m = 47.27) compared to the control aggregate (U_s = 39.92 and U_m = 41.41) was certainly a major factor. In addition, the crushed sandstone had a much finer gradation as indicated by the comparison of fineness modulii (FM = 2.11 for crushed sandstone compared to FM = 2.64 for the control aggregate). The finer aggregate required more paste to coat and mobilize the particles. Bleeding did not occur with the initial substitution of crushed sandstone for the control aggregate. However, flow concerns required more paste to mobilize aggregate. Unfortunately the gradation (U_r = 43.67) is much more open than the control aggregate gradation (U_r = 40.19). This would lead to bleeding problems during mixture proportion adjustment. Further, plastic cohesion problems resulted from 58.9 % of aggregate passing the No. 30 sieve and being retained on the No. 50 sieve.

Adjustments

The adjustments and revised proportions for the limestone screenings and crushed sandstone mixtures are shown in Table 5. Plastic properties for the adjusted mixture proportion limestone screenings and crushed sandstone mixtures are shown in Table 6. The research team was not able to satisfy both flow and bleeding requirements for the crushed sandstone ZOOM CLSM. However, flow was increased to 184 mm without bleeding by increasing the high-range water reducer.

TABLE 5—*ZOOM CLSM adjusted laboratory mixture proportions.*

Component	Limestone Screenings	Crushed Sandstone
Type I Portland Cement	208 kg/m^3 Control + 30kg/m^3	178 kg/m^3
Water	223 kg/m^3 Control +34 kg/m^3	188 kg/m^3
Fine Aggregate (SSD)	1386 kg/m^3	1460 kg/m^3
Air-Entraining Agent	4.06 liters/m^3 Control + 1.16 liters/m^3	2.71 liters/m^3
High-Range Water Reducer	1.74 liters/m^3 Control + 0.58 liters/m^3	3.52 liters/m^3 Control + 2.36 liters/m^3
Accelerator	8.70 liters/m^3	8.70 liters/m^3

TABLE 6—*ZOOM CLSM plastic properties using adjusted mixture proportions.*

Property	Limestone Screenings	Crushed Sandstone	Requirement
Flow, mm	241	184	222 minimum
Bleed Time, min	No Bleeding	No Bleeding	Little or No Bleeding
Shrinkage	No Shrinkage	No Shrinkage	Little or No Shrinkage
Air Content, %	22.0	26.4	20-30 Preferred
Unit Weight, kg/m^3	1770	1677	None
Meet Requirements?	Yes	No, Low Flow	...

Field Demonstration Results and Analysis

Field demonstrations of ZOOM CLSM were held in Nashville, Knoxville, and Algood, Tennessee using local fine aggregate(s). Each field demonstration consisted of one or more trench placements (approximately 0.9 m wide, 1.07 m deep, and 2.74 m long) using the local fine aggregate(s). Plastic testing of the ZOOM CLSM was conducted at each location, and currently available information was distributed to present government and industry personnel.

Comparisons of compressive strength development for field demonstrations and laboratory ZOOM CLSM mixtures are shown in Figs. 3 and 4. Figures 5–7 show comparison of flow, air content and time to pass the ball drop test, respectively. Compressive strength specimens were not fabricated at ready mix producer's facility in Nashville. Ball drop test data is not available for the limestone screenings ZOOM CLSM due to excessive water in the trench precluding ball drop testing.

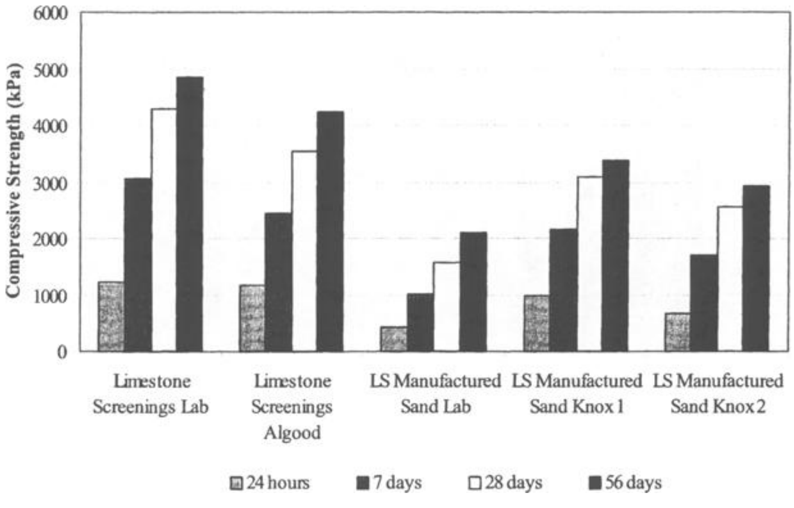

FIG. 3—*Comparison of lab and field compressive strength development for LS screenings and LS manufactured sand mixtures.*

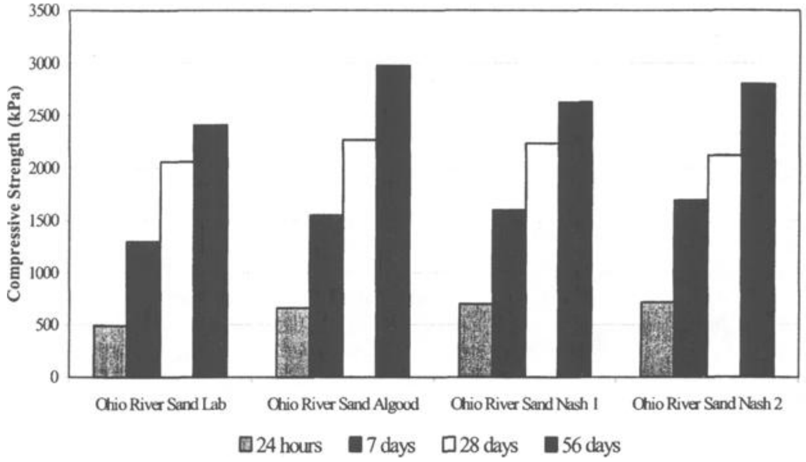

FIG. 4—*Comparison of lab and field compressive strength development for Ohio River sand mixtures.*

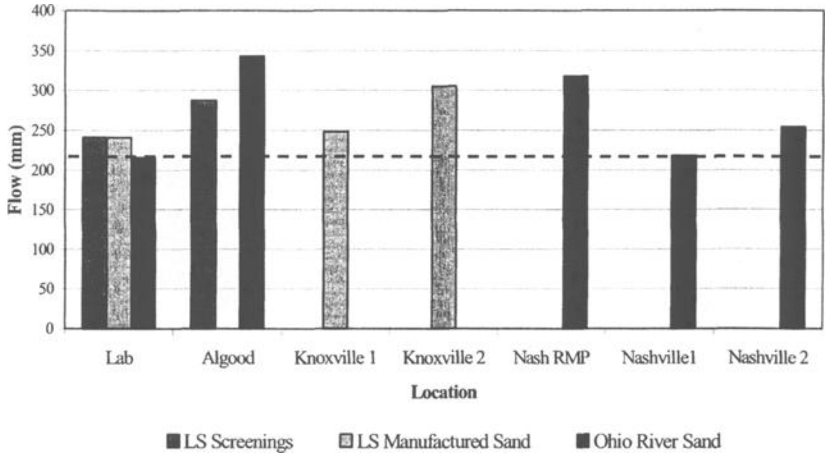

FIG. 5—*Comparison of flow values.*

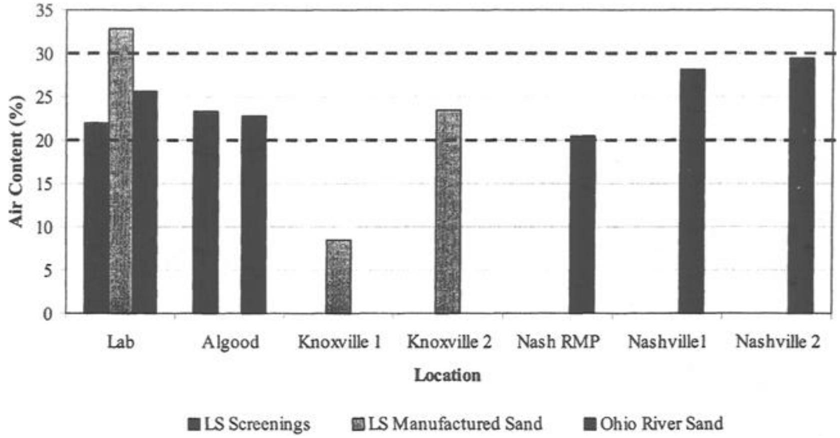

FIG. 6—*Comparison of air contents.*

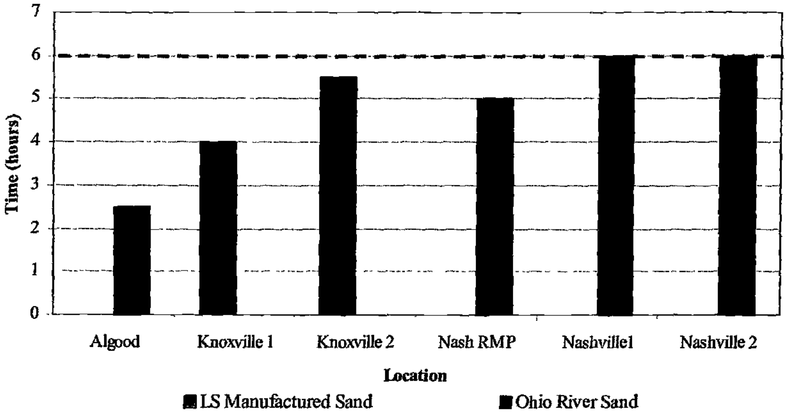

FIG. 7—*Comparison of times to pass ASTM ball drop.*

ZOOM CLSM met compressive strength development and time of set performance criteria at every field demonstration. However, ZOOM CLSM made with the Ohio River sand control aggregate failed to achieve the desired flow for Nashville Number 1 Trench. The flow was greater than 200 mm but less than 222 mm. Limestone manufactured sand ZOOM CLSM mixtures failed to fall within the desired air content range for Knoxville Number 1 Trench. The lower air content did not adversely affect the other mixture properties enough to cause a failure in compressive strength, set time, or flow.

The effect of average air temperature divided by air content on the time to pass the ball drop test is shown in Fig. 8. The data for Knoxville Trench 1 is not included in Fig. 8 due to the unusually low air content of 8.5 %. The coefficient of determination was 0.6185, indicating a possible relationship. However, only five data points were available for the correlation. Further, ZOOM CLSM mixture temperature over time would have been superior to average air temperature, unfortunately those data were not available. Finally, two key factors for time to pass ball drop did not vary in the available data: Portland cement content and accelerator dosage.

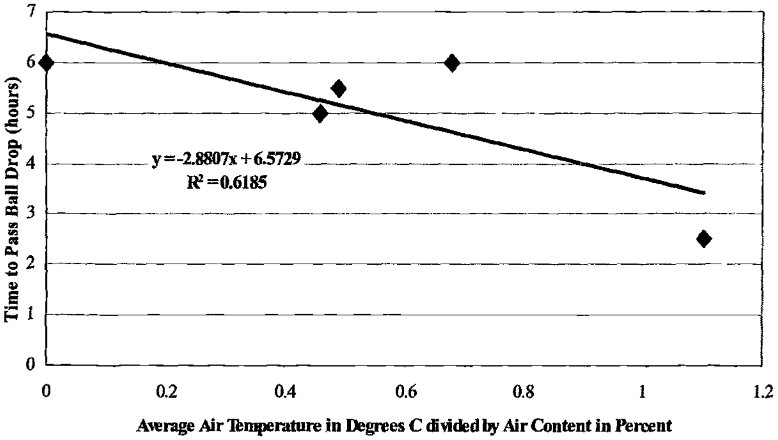

FIG. 8—*Effect of average air temperature and air content on time to pass ball drop test.*

Conclusions

The following conclusions can be drawn from the limited data available in this study:

- A rapid-set non-excavatable CLSM for applications where time was a critical factor can be produced with a wide variety of Tennessee fine aggregates.
- Fine aggregate properties, such as gradation and angularity, dictate mixture proportions required to achieve flow, air content, and bleeding characteristics of CLSM.
- Average air temperature was directly proportional to time of suitability for load application.
- CLSM air content was inversely proportional to time of suitability for load application.

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Methods for Field and Laboratory Measurement of Flowability and Setting Time of Controlled Low-Strength Materials

ABSTRACT: Flow consistency and setting time are two important properties of controlled low-strength materials (CLSM). This paper describes and evaluates several standard and non-standard methods to measure these properties. Several mixtures with a range of water-to-binder ratios were investigated through a series of field and laboratory experiments. A linear relationship was observed between the flowability measured by the flow cylinder method (ASTM D 6103) and the inverted slump cone method. Pocket penetrometer and Torvane measurements were compared to the Kelly Ball method (ASTM D 6024) for estimating sufficient bearing capacity. Pocket penetrometer resistance correlates well, but its capacity was often exceeded. Volume stability should be controlled to avoid softening of the surface and subsequent delays in measured hardening time.

KEYWORDS: controlled low-strength material, flowable fill, flowability, setting, hardening, compressive strength

Introduction

Controlled low-strength material (CLSM) is a self-leveling, self-compacted, cementitious material used primarily as a backfill instead of compacted earth. By definition, it must not exceed a compressive strength of 8.3 MPa (1200 psi), although it is often proportioned to develop strengths much less than the limit [1]. CLSM is a flowable mixture of cement, fly ash, sand, water, and, sometimes, chemical admixtures. Common applications include backfilling, void filling, utility bedding, and bridge approaches. High flowability, rapid setting time, and low long-term strengths are often desired properties of CLSM; however, each CLSM application requires certain material properties for the desired performance. For example, high early strength and higher ultimate strength are more important than high flowability when CLSM is used for a bridge approach, whereas high flowability and low strength are more desirable properties for utility bedding.

There has been a considerable increase in the use of CLSM in place of compacted earth in recent years, however, the development of quality control and quality assurance procedures lags behind. CLSM suffers a lack of consistency in the field due, in part, to prolonged mixing times experienced during construction delays and the addition of excess water prior to discharge. It is

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important, therefore, to develop and evaluate test standards to assess properties such as flowability, mixture stability and uniformity, readiness to accept loads, and future excavatability of field-mixed CLSM so that the desired performance of CLSM is achieved.

This paper presents results from a field and laboratory program to evaluate methodology for testing flowability and setting (and hardening) time of CLSM. Several non-standard methods are introduced and compared to ASTM standard methods.

Background

Methods to Measure Flow Consistency

Flowability is the property that governs the self-leveling ability of CLSM. Flowability is quantified by its fluid, or flow, consistency. Since plastic CLSM has a consistency that can range between plastic concrete and cement grout, its flowability can be assessed using concrete and grout test methodology. Methods of determining flowability are summarized in Table 1 and include the open-ended flow cylinder test (ASTM D 6103), the standard concrete slump cone method (ASTM C 143), and the flow cone method (ASTM C 939). ASTM D 6103 is the only method developed specifically for measuring the flow consistency of CLSM. The flow cone is best used for neat cement grouts but can also be used for CLSM mixtures with aggregates less than 6 mm (0.25 in.); however, the funnel tends to clog even when used for standard CLSM mixtures containing fine aggregate. The slump cone is primarily used for conventional concrete, which is stiffer than CLSM.

TABLE 1—*Summary of test procedures for determining flow consistency.*

Standard	Test Volume mL (in^3)	Measurements	Applications
ASTM D 6103 [open-ended flow cylinder]	663 (42.4)	Used to measure the spread diameter	Used for CLSM
ASTM C 143 [slump cone]	2361 (151)	Used to measure slump	Used for concrete and cement-based grouts
ASTM C 939 [flow cone]	1725 (110)	Determines the time of efflux of grout through a flow cone	Used for neat grouts, CLSM mixtures with aggregate less than 6 mm (0.25 in.)

It is important to use a clean, leveled surface to check the flow consistency, since an uneven surface, as is often encountered in the field, can lead to an inaccurate measurement. Since no standard testing method is currently available to test the flow consistency of CLSM in the field, a field-portable flow table was designed and constructed as shown in Fig. 1. The rectangular flow table is made of wood and has dimensions of 625 mm × 600 mm (25 in. × 24 in.). The surface is constructed of a melamine resin-coated laminate that is smooth and nonporous. The flow table has two levels attached on opposite sides, and it has adjustable foot screws attached below each of the four corners of the table. By adjusting the screws and checking the levels, a smooth leveled surface can be provided on uneven ground.

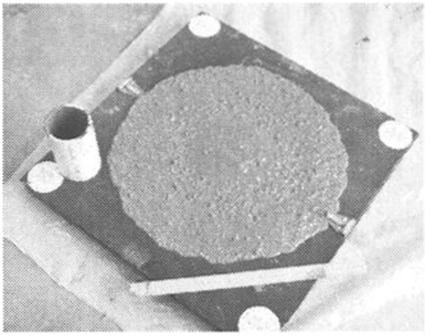


FIG. 1—*Wooden flow table for ASTM D 6103 flowability measurements.*

FIG. 2—*Flowability measurements using an inverted slump cone.*

The flow cylinder standard specifies the use of a 75 mm × 150 mm (3 in. × 6 in.) open-ended cylinder to measure the diameter of spread in two perpendicular directions. The average diameter of spread gives the flow consistency of the mixture. A spread diameter of 200 to 300 mm (8 to 12 in.) is considered flowable and acceptable for most applications. One limitation of the flow cylinder test is that it uses a smaller volume of material than the other two tests listed in Table 1.

The slump cone test (ASTM C 143) is specified for concrete but can also be used to check the consistency of CLSM. However, there is currently no standard procedure. The slump of conventional concrete should be 50–100 mm (2–4 in.), depending on the application. For CLSM, a standard correlation between slump and flow consistency is yet to be developed. One limitation of the slump cone test method is that high flow mixtures create high slumps, which may be difficult to measure in the field [3]. A variation of the traditional slump cone method is the inverted slump cone method. In the inverted slump cone test, the cone is inverted, and the material flows out of the smaller diameter end of the cone as shown in Fig. 2. Spread diameter is measured instead of slump. Because the spread diameters often exceed the dimensions of the flow table, this test should be performed on a clean ground surface in accordance with ASTM C 143.

Methods to Measure Time of Set

Time of set is the time when a CLSM transitions from a fluid to a hardened state. Typically, CLSM mixtures will set in less than 24 h but may not offer a competent load-bearing surface for up to 2 to 3 weeks [7]. Thus it is important to differentiate between time of set and the time when the material has sufficient strength to support construction loads. High early strengths are desired in some CLSM applications, such as bridge approaches, to minimize downtime for construction.

The Kelly Ball apparatus (ASTM D 6024) is the standard for determining when a CLSM surface is ready for load application. The field test specifies dropping a metallic 15 kg spherical ball from a height of 100 mm (4 in.) five times. A surface indentation diameter less than 75 mm (3 in.) suggests that the surface is ready to accept loads. This method was developed based on common practice for a contractor to stomp on the surface and assess the load bearing capacity based on the indentation created. If the CLSM surface has hardened, the surface will remain free of water, whereas a non-hardened surface will result in pumping of excess water on the surface after the impact. Thus, the shortcomings of the Kelly Ball include difficulties in measuring the indentation diameter when the CLSM surface is inundated with water from bleeding, precipitation, or runoff. In addition, the ball impact may splash water from the CLSM surface onto the operator and immediate surroundings [4].

The pocket penetrometer and Torvane are simple, hand-held geotechnical tools commonly used to assess the consistency of cohesive soils. Terminology used to describe the consistency of clay and corresponding ranges of unconfined compressive strength are shown in Table 2. Based on their simple operation and range of measurable strengths, both devices can be used to obtain the setting time of CLSM and to quantify strength gain with time in the laboratory or field.

TABLE 2—*General relationship of consistency and unconfined compression strength of clays [9].*

Consistency	Unconfined Compression Strength, q_u	
	tons/ft^2	kN/m^2
Very Soft	0–0.25	0–25
Soft	0.25–0.5	25–50
Medium	0.5–1	50–100
Stiff	1–2	100–200
Very Stiff	2–4	200–400
Hard	>4	>400

The pocket penetrometer is a spring-operated device used to measure compressive strength of cohesive soil by pushing a ground and polished 6 mm (0.25 in.) diameter loading piston into the soil to a depth of 6 mm (0.25 in.). Compressive stress in kN/m^2 (or tons/ft^2) is indicated by reading a scale on the piston barrel. The method has been used by Gassman et al. [2] and Pierce [5] to determine the setting time of CLSM and cement grouts. Similarly, the Torvane is used to estimate the shear strength of cohesive soils. The Torvane test consists of pushing a multi-bladed vane into undisturbed soil and rotating it to determine the torsional force required to cause a cylindrical volume of soil to be sheared by the vane. The torsional force is then related to the undrained shear strength of the soil, which is equal to half of the unconfined compressive strength.

These two tools can be used in both the laboratory and field to obtain strength measurements on the surface of a CLSM fill. They can also be used to estimate the setting time for CLSM mixtures by simply recording the time of initial resistance to either tool. For high bleeding mixtures, the formation of a weaker layer at the top may underestimate the strength measured from these tools. Measurements should be taken at several locations on the fill surface to account for possible variability. The major limitation with using these tools is that they do not provide strength measurement with depth. However, there are other geotechnical penetrometers and devices for obtaining measurements at depth.

Methods to Measure Strength

The strength of CLSM is almost always assessed using the unconfined compressive strength test (ASTM D 4832). Cylinders cast from CLSM are moist-cured and strength is commonly evaluated at ages of 28 and 56 d. In many applications, low long-term strengths of CLSM are required to ensure future excavatability of the material. According to ACI [1], CLSM with an ultimate unconfined compressive strength less than 345 kPa (50 psi) is excavatable by hand. CLSM with an ultimate unconfined compressive strength up to 2070 kPa (300 psi) can be excavated using heavy equipment. It should be noted that these limits are somewhat arbitrary and depend on the mixture proportions.

Experimental Program

The experimental program is the product of a field study of CLSM placement for bridge approach construction. As part of the field study, the authors observed local practice of placing CLSM at several bridge sites for the South Carolina Department of Transportation (SCDOT). Figure 3 shows the filling of a bridge approach with dimensions of 7.6 m × 1.7 m × 1.7 m. At each site, material was sampled from at least two mixing trucks and tested for flowability, bleeding, and setting time using a pocket penetrometer. Remaining material was collected in 75 mm × 150 mm (3 in. × 6 in.) plastic cylinders for unconfined compressive strength tests. Cylinders were covered and left on site for 24 h before being transported to the laboratory for curing and testing.

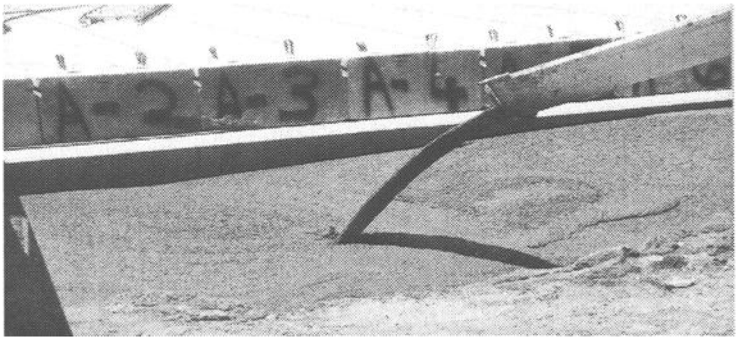


FIG. 3—*CLSM placement at a bridge approach in Aiken, South Carolina.*

Three important observations from these site visits are noted as follows:

1. Often the material was not sufficiently flowable to be self-leveling. Concrete vibrators and shovels were then required to distribute and level the CLSM after placement. While this is not a significant concern when filling a large void space such as a bridge approach, it becomes an issue if material of the same consistency is used to fill much smaller spaces, such as pipe bedding in a trench.
2. Often water was added to the mixing trucks on site, thereby changing the water content and flowability of the CLSM. Even though one standard mixture was specified at all sites, the flowability varied significantly as a result of variable water

contents. Due to the extra water added to increase flowability, the design strength may not be achieved if more than 20 % extra water was added [2].

3. According to SCDOT personnel, setting times are often prolonged such that construction is delayed.

Based on these field experiences, a laboratory program was orchestrated to: (1) study the fluid- and hardened-state properties of the standard mixtures specified by the SCDOT, (2) investigate the effect of increasing water content of these standard mixtures, and (3) develop simple field tests to measure flowability and setting time for quality control.

Laboratory Program

The laboratory program was conducted in two phases. The first phase concentrated on strength measurements, and the second phase focused on flowability and setting time. Lab mixtures were composed of ordinary portland cement, Class F fly ash, local sand conforming to ASTM C 33, and tap water at room temperature. Mixture proportions were changed solely by increasing the water content (such that the mass of dry ingredients remained the same). Water-to-binder (w/b) ratios of 0.69 to 1.14 were produced, where binder refers to the combined mass of cement and fly ash (or cementitious materials). Materials were blended in a 0.16-m^3 (4.5-ft^3) electric concrete mixer that was rotated at an inclination of 45° to ensure efficient mixing.

Phase 1—In the first phase, six mixtures were proportioned with increasing w/b ratios as designated in Table 3. Mixture proportions with w/b ratios of 0.69 and 0.82 represent SCDOT standard mixtures [8] and serve as the control mixtures. Four more mixtures were produced by increasing the water content to achieve w/b ratios of 0.97, 1.00, 1.05, and 1.14. Flowability, bleeding, air content, and unit weight were measured immediately after mixing. Flowability tests were performed using the flow cylinder method in accordance with ASTM D 6103. These tests were conducted on the flow table described earlier. Tests for volume stability or bleeding (ASTM C 940) were done by placing 800 mL of material in a 1000 mL graduated cylinder and measuring the volume of bleed water that accumulated on the surface. Air content was measured in accordance with ASTM C 231; unit weight was also determined as part of each test for air content.

The remaining material was sampled in 75 × 150 mm (3 × 6 in.) plastic cylinders for unconfined compression tests at 3, 7, 14, 28, 56, and 90 d. Twenty-five cylinders were collected per batch to ensure that a minimum of three cylinders were available per test age. Specimens were moist-cured in a closed container for 7 d, after which they were demolded and transferred to a curing room. They were not immersed in a limewater bath to avoid possible leaching and strength deterioration [6]. At each test age, three specimens were weighed and sulfur-capped prior to testing in unconfined compression (ASTM D 4832). For mixtures at higher w/b ratios, testing at early ages (3 and 7 d) was difficult because some specimens were too fragile for capping and testing. Compression tests were conducted with a low-load capacity machine designed to test cohesive soil specimens.

TABLE 3—*Mixture proportions for experimental program.*

Mixture Designation	w/b[1]	Cement kg (lb.), %[2]	Class F Fly ash kg (lb.), %[2]	Sand kg (lb.), %[2]	Water Liters (gal.), %[2]
Standard SCDOT less flowable mixture	0.69	2 (4.4), 1.4	24.1 (52.8), 16.7	100 (220), 69.4	18 (4.7), 12.5
Standard SCDOT more flowable mixture	0.82	2 (4.4), 1.3	24.1 (52.8), 16.3	100 (220), 67.9	21.4 (5.6), 14.5

[1] Four additional mixtures were made with w/b ratios of 0.97, 1.00, 1.05, and 1.14 by increasing the mass of water.

[2] Represents percent composition by mass.

Phase 2—In the second phase, five of the six mixtures (w/b = 0.69, 0.82, 0.97, 1.05, 1.14) were batched again and tested for: (1) variability in flow consistency as measured by the flow cylinder (three tests per batch); (2) flow consistency as measured by inverted slump cone; and (3) setting time and early hardening as measured by a Kelly Ball, pocket penetrometer, and Torvane.

To measure setting time and hardening, material from each mixture was placed in two 0.05-m^3 (1.7-ft^3) plastic containers. One container was kept covered to allow bleed water to accumulate on the surface without evaporating. The other container was left uncovered. The purpose of these two containers was to determine the influence of surface condition ("wet" or "dry") on the measurement of setting time and hardening. Kelly Ball tests were performed according to ASTM D 6024 in both containers. Three tests (at three different times) were performed in each container. The first tests were conducted at approximately 24 h, when the CLSM had set and hardened sufficiently to bear the impact. The Kelly Ball was supported on two rectangular wooden blocks as shown in Fig. 4. It is raised 100 mm (4 in.) and released five consecutive times on the surface to produce a spherical indentation. The closed container was tested with bleed water present, which usually splashed onto the operator after each impact. The operator wore goggles for eye protection. Prior to testing in the open container, any remaining bleed water was removed with a small plastic syringe. Removing the bleed water facilitated safer and easier testing.

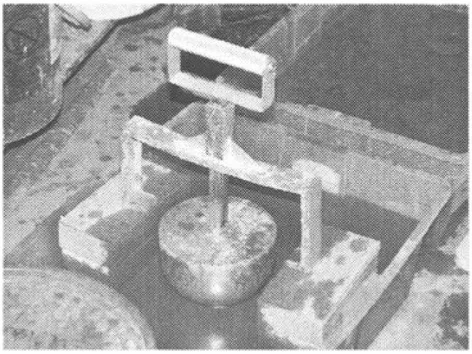


FIG. 4—*Kelly Ball to measure hardening of lab-mixed CLSM.*

Pocket penetrometer and Torvane measurements were taken in the same two containers at the same times as the Kelly Ball tests. This was done to obtain correlations between these tools and the Kelly Ball to predict setting and hardening times. Resistance was measured at four different locations using each tool in each container. An average value of resistance was calculated for the pocket penetrometer and Torvane. The smallest measurable resistance is 25 kN/m^2 (0.25 $tons/ft^2$)

for the pocket penetrometer and 5 kN/m^2 for a standard Torvane. Maximum capacity is 400 kN/m^2 and 100 kN/m^2, respectively. In a number of tests, the material surface was hard enough to exceed the capacity of these tools, such that further measurements were not possible. This will be discussed in more detail in the experimental results.

Experimental Results

Fluid-State (Plastic) Properties

Table 4 summarizes results for flowability, bleeding, air content, and fluid density for the six laboratory mixtures. These results demonstrate expected trends with increasing water content. Recall that the only variable in the mixture proportions is water content; the aggregate and binder contents are equal for each mixture. As expected, flowability and bleeding increase with a corresponding increase in w/b ratio. The two mixtures produced with the least amount of water (w/b $\leq$ 0.82) were relatively stable and bled less than 3 %. Mixtures with w/b > 1 were less stable and had higher bleeding ranging from 3.9–5.7 %. With all six mixtures, most of the bleed water accumulated during the first hour after mixing. Mixtures with w/b > 1 experienced rapid bleeding in the first 15 min. All mixtures stabilized (with no further bleeding) after 3 h. As water content increases, the excess water occupies void space within the matrix such that the measured air content decreases from 6.6 to 0.4 %. The only property that is not influenced by water content is the fluid density, which for all mixtures falls in the range of 1984–2032 kg/m^3 (124–127 pcf).

TABLE 4—*Fluid-state results from the laboratory program.*

w/b	Flow Consistency ASTM D 6103 mm	Bleeding ASTM C 940 %	Air Content ASTM C 231 %	Fluid Density kg/m^3 (pcf)
0.69	112.5	1.3	6.6	1984 (124)
0.82	151	2.6	5.2	2029 (126)
0.97	237.5	3.7	1.2	2032 (127)
1.00	250	3.9	0.8	2032 (127)
1.05	284	4.4	0.6	1984 (124)
1.14	336	5.7	0.4	1984 (124)

Figure 5 illustrates the trend and variation of flowability as measured with a flow cylinder. The values given in Table 4 for flowability represent the average values of multiple batches of mixtures produced at each w/b ratio. Data shown in Fig. 5 represent values measured from each batch. From this figure it can be seen that flowability increases with w/b ratio, and that good flow characteristics (> 200 mm) can be achieved consistently at w/b > 1. The latter observation is consistent with published literature [2, 10]. More importantly, Fig. 5 illustrates the variability in flow measurements for each w/b ratio. When increasing the w/b ratio, the variability in flow measurements increases. This implies that material properties are less consistent and thus less controllable at higher water contents. So volume stability becomes particularly important if flow consistency is used as a measure of quality control. These observations suggest that bleeding should be routinely measured in the field to ensure the mixture is stable. If it is not feasible to conduct a complete test because of the required time, then the test should be conducted for at least 15 min to determine if rapid bleeding occurs, suggesting the material is unstable. In addition, more than one flowability test should be performed per batch of CLSM to get a correct estimate of the flow characteristics.

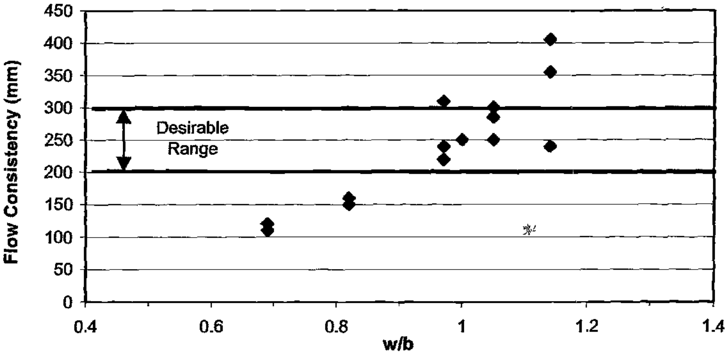


FIG. 5—*Flow consistency of six mixtures as measured from flow cylinder (ASTM D 6103).*

In addition to the flow cylinder method, flow consistency measurements using an inverted slump cone were recorded for three field mixtures and six laboratory mixtures. Figure 6 compares the flow consistency measured from these two methods. Based on these data, a linear relationship exists between the flow consistency from both procedures with excellent correlation statistics ($R^2 = 0.97$). The relationship can be expressed as:

$$\text{Flow}_{\text{inverted slump}}\ (\text{mm}) = 2.9 \times \text{Flow}_{\text{cylinder}}\ (\text{mm}) - 120 \qquad (1)$$

From the above relationship, an optimum flow range of 200 to 300 mm (8 to 12 in.) from the flow cylinder test can be considered equivalent to a flow range of 475 to 750 mm (19 to 30 in.) from an inverted slump cone test. This correlation can be used as a general guide for evaluating flow consistency measurements from an inverted slump cone, where CLSM with a flow range of 475 to 750 mm can be considered to have good flow characteristics. However, the flow cylinder test (ASTM D 6103) is still recommended until further data are acquired to standardize the inverted slump cone method.

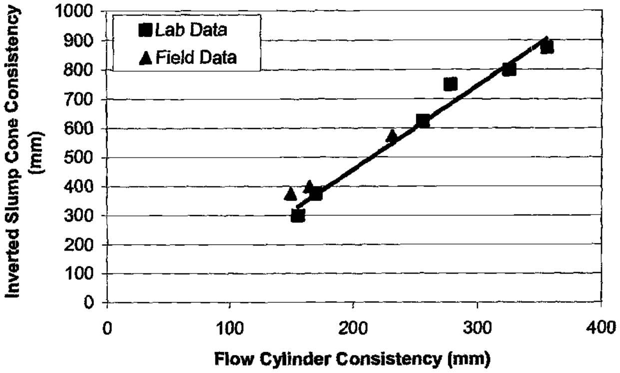


FIG. 6—*Correlation between measurements from flow cylinder and inverted slump cone.*

Hardened-State (In-Service) Properties

Setting time and early hardening were evaluated for five mixtures using a Kelly Ball, pocket penetrometer, and Torvane. Table 5 shows the results of Kelly Ball indentations recorded at three different times for each mixture in closed and open containers. The time of first measurement was targeted at 24 h, but actual measurements occurred between 18 and 27 h. The first set of indentations always measured more than the required 75 mm diameter, suggesting that none of the mixtures was suitable for load application per ASTM D 6024. However, all mixtures had clearly set, since the material offered sufficient resistance to the dropping of the Kelly Ball. The pocket penetrometer and Torvane also recorded measurable resistance to indicate that setting time was reached prior to the first Kelly Ball measurement. In fact, pocket penetrometer values were consistent with those of a stiff to very stiff clay. The time of second and third Kelly Ball measurements was adjusted for each mixture in an effort to record an indentation diameter less than or equal to 75 mm. However, for all but the first mixture (w/b = 0.69), the third and final measurement still exceeded the required 75 mm. It is interesting to note that the difference in measured indentation for the first mixture is almost negligible from 44 to 68 h, which raises the question of what time should be considered suitable for load application. If a 78 mm diameter indentation is deemed acceptable, then construction can begin 24 h sooner. Similarly, the mixture with w/b = 0.97 yields an 80 mm indentation at 72 h, which may in fact be sufficient to bear the load. Unfortunately, there was not enough undisturbed material to perform a fourth test to determine when, in fact, a 75 mm indentation was reached.

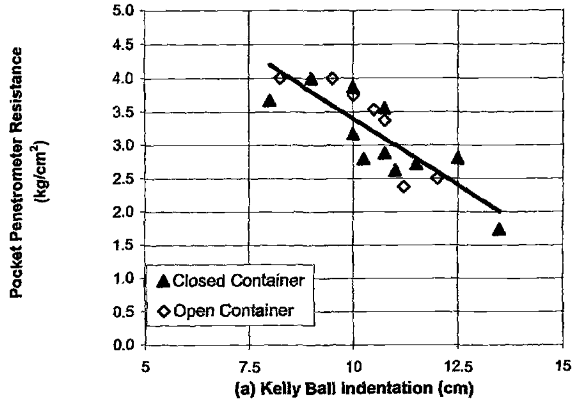
From Table 5, it can be observed that material placed in a closed container consistently yielded larger indentation diameters, suggesting that there is a softening effect due to the presence of accumulated bleed water. This effect delays the time to achieve the required 75 mm indentation diameter. The test procedure was more convenient to perform with the open container since there was no bleed water, and thus splashing of water did not occur. The severity of water splashing from the closed container increased with an increase in w/b ratio.

TABLE 5—*Kelly Ball indentation diameters in open and closed containers.*

w/b	Time h	Indentation Diam. in Closed Container with Bleed Water mm (in.)	Indentation Diam. in Open Container with Bleed Water Removed[1] mm (in.)	Approx. Time after which CLSM is Suitable for Load Application h
0.69	21	90 (3.6)	82 (3.3)	44 – 68
	44	78 (3.1)	78 (3.1)	
	68	75 (3.0)	72 (2.9)	
0.82	21	108 (4.3)	105 (4.2)	>48
	28	102 (4.1)	100 (4.0)	
	48	100 (4.0)	80 (3.2)	
0.97	27	125 (5.0)	107 (4.3)	≥72
	49	100 (4.0)	95 (3.8)	
	72	80 (3.2)	80 (3.2)	
1.05	24	115 (4.6)	120 (4.8)	>71
	48	102 (4.1)	95 (3.8)	
	71	100 (4.0)	87 (3.5)	
1.14	18	135 (5.4)	115 (4.6)	>92
	45	110 (4.4)	100 (4.0)	
	92	107 (4.3)	80 (3.2)	

[1] Bleed water was removed from the open container immediately before the first reading (18–27 h).

Figures 7*a* and 7*b* compare the measured resistance from a pocket penetrometer and Torvane to the Kelly Ball indentation diameter. Best-fit linear relationships between surface resistance and surface indentation diameter are illustrated on these two figures with solid lines. In Fig. 7*a*, measurements in both open and closed containers follow the same linear trend. This observation suggests that pocket penetrometer measurements can be correlated to indentation diameter, regardless of CLSM surface conditions. On the other hand, the Torvane measurements seem to be influenced by surface conditions, particularly when the indentation diameter is less than 100 mm. For example, the Torvane resistance equivalent to an indentation diameter of approximately 75 mm in closed containers is 20-25 kN/m^2 (0.20-0.25 kg/cm^2). The equivalent resistance in open containers is much higher on average, with a maximum measurement of 45 kN/m^2 (although some measurements exceeded the Torvane capacity of 100 kN/m^2). There is clearly more scatter with the Torvane measurements than with the pocket penetrometer. However, if closed container measurements are considered separately, the Torvane data follow a linear trend, as shown by the dashed line in Fig. 7*b*. No obvious trend exists for the open container measurements.



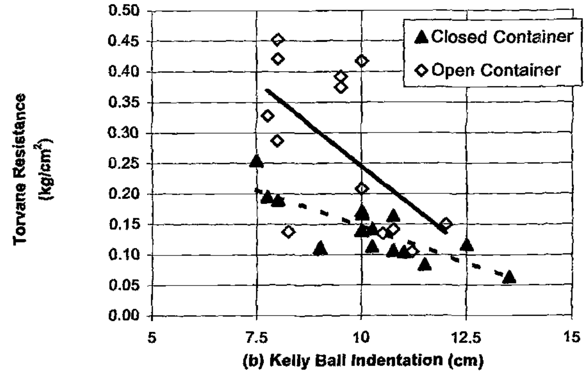


FIG. 7—*Comparison of Kelly Ball indentations to (a) pocket penetrometer and (b) Torvane.*

To evaluate the potential of either a pocket penetrometer or Torvane to estimate the time required for suitable load bearing capacity, their readings were compared to the final indentation diameters as shown in Table 6. For all but two measurements, the pocket penetrometer exceeded its capacity (400 kN/m^2 or 4.0 kg/cm^2) as indentation diameter approached 75 mm. It should be noted that a measurement exceeding 400 kN/m^2 corresponds to hard clay, which can be considered an excellent load bearing soil. Even though the pocket penetrometer correlates well with the Kelly Ball (see Fig. 7*a*), its capacity is too low to provide a measurement when the indentation reaches 75 mm. Although a field penetrometer was not tested in this study, these findings suggest that a higher-capacity penetrometer might be a suitable tool for estimating time required for load application. Similarly, the Torvane exceeded its capacity (100 kN/m^2 or 1.0 kg/cm^2) on three of the five mixtures when tested in an open container. Its lower capacity and higher degree of measurement scatter (see Fig. 7*b*) suggest that the Torvane is a less suitable tool for CLSM than a penetrometer.

TABLE 6—*Pocket penetrometer and Torvane resistance corresponding to final Kelly Ball readings.*

w/b	Time H		Kelly Ball mm (in.)		Pocket Penetrometer kN/m²		Torvane kN/m²	
	Closed Container	Open Container	Closed Container	Open Container	Closed Container	Open Container	Closed Container	Open Container
0.69	68	68	75 (3.0)	72 (2.9)	> 400	> 400	26	> 100
0.82	48	48	100 (4.0)	80 (3.2)	400	> 400	17	28
0.97	72	72	80 (3.2)	80 (3.2)	370	> 400	19	45
1.05	71	71	100 (4.0)	87 (3.5)	> 400	> 400	17	> 100
1.14	92	92	107 (4.3)	80 (3.2)	> 400	> 400	17	> 100

Multiple specimens from six mixtures were tested in unconfined compression at 3, 7, 14, 28, 56, and 90 d. Figure 8 shows the increase in compressive strength with curing age for each w/b ratio. The first observation is that strength tends to decrease at each age with an increase in w/b ratio, as expected. At 3 d, all but one mixture (w/b = 1.14) have reached a strength of at least 100 kPa, which is equivalent to stiff clay. By 7 d, strengths range from 100 to 330 kPa, depending on the w/b ratio. Secondly, the trends in strength gain with age are generally as expected. It is worth noting that substantial strength gains were observed between 28 and 90 d. In some cases, strengths measured at 90 d are more than twice that measured at 28 d. This finding is important when considering the long-term performance and excavatability requirements of CLSM mixtures. In all cases, 90 d strengths are still sufficiently low to be considered excavatable by mechanical means. If 28 d strengths are used as the basis for predicting future excavatability, all but the strongest mixture (574 kPa for w/b = 0.69) fall below the maximum 28 d limit of 406 kPa suggested by Webb et al. [10]. It should also be noted that curing conditions might not be as favorable in the field, thus tempering the potential strength gain.

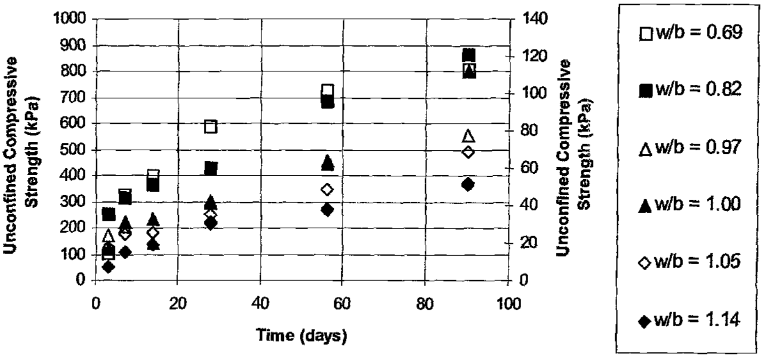


FIG. 8—*Unconfined compressive strength for six mixtures.*

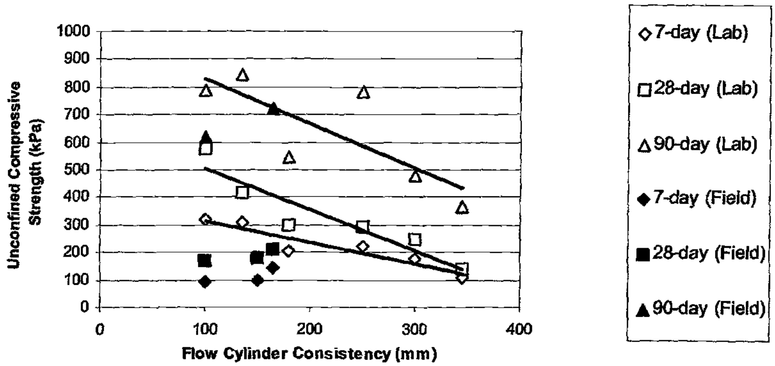


FIG. 9—*Unconfined compressive strength as a function of flow consistency.*

Finally, Fig. 9 compares the average compressive strength for cylinders collected in the field and lab to the average flowability of that mixture per ASTM D 6103. The purpose of making this comparison is to determine if flowability can be used to estimate or predict material strength. In general, there is a trend of achieving a lower strength with a more flowable material, where only the water content has been changed. This trend can be seen with the three solid trend lines, which represent the best linear fits for the laboratory strength data collected at 7, 28, and 90 d. Interestingly, the trends are reasonably consistent with 7 d and 28 d strengths, but the correlation is not as strong with 90 d strengths. It is also significant that the field data do not fit the trends well. Strengths measured at 7 and 28 d from field mixtures are substantially less than what would be predicted by the lab-based trend lines. The reasons for this discrepancy are unclear and suggest that this flowability-strength relationship needs to be studied further.

Conclusions

Three main conclusions can be drawn from this research:

1. The inverted slump cone method appears to be an acceptable alternative to the flow cylinder method (ASTM D 6103) for measuring flowability. There is a direct, linear correlation between the spread diameters measured by each method. Based on this relationship, high flowability mixtures should produce an inverted slump cone spread diameter of 475 to 750 mm.
2. Pocket penetrometer resistance correlates well with indentation diameter produced by the Kelly Ball method (ASTM D 6024), but its capacity is insufficient to determine when CLSM is ready to accept load. A high-capacity (> 400 kN/m^2) field penetrometer, such as a Proctor or mortar penetrometer, may be a better alternative to measure setting and hardening time.
3. Volume stability (bleeding) should be controlled and therefore must be checked in the field. CLSM that is not properly proportioned and contains excess water can exhibit

variable flow consistency, softening of the surface and subsequent delays in measured hardening time, and reduced compressive strength.

Acknowledgments

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Long Term Study of 23 Excavatable Tennessee Flowable Fill Mixtures

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ABSTRACT: Twenty-three different EFF mixtures were placed in trenches simulating utility cuts during March through May of 2001. All EFF mixtures were tested for flow, unit weight, gravimetric air content, suitability for load application, and compressive strength development over time. The trenches were excavated in March 2003. Excavation difficulty was correlated with laboratory compressive strength for non-air-entrained mixtures. Bearing capacity estimates with the dynamic cone penetration apparatus were determined for all trenches. Nine EFF mixtures were used to assess the impact of Portland cement content and ASTM C 618 Class F fly ash content. Portland cement contents of 17.8, 26.7, and 35.6 kg/m^3 and ASTM C 618 Class F fly ash contents of 178, 219.5, and 261 kg/m^3 were used to evaluate the impact of component proportions. Proportions for the EFF mixtures were chosen using Kentucky Transportation Cabinet and Tennessee Ready Mixed Concrete Association (TRMCA) recommendations as well as a previous Tennessee Technological University research mixture. Six EFF mixtures were used to assess the impact of Portland cement content and high-unburned carbon fly ash content. Portland cement contents of 26.7 and 35.6 kg/m^3 and high-unburned carbon fly ash contents of 219.5, 261, and 302.5 kg/m^3 were used to evaluate the impact of component proportions. The influence of aggregate type on EFF mixtures was evaluated by using five different aggregate types in the EFF mixture recommended by TRMCA (26.7 kg/m^3 Portland cement and 219.5 kg/m^3 ASTM C 618 Class F fly ash). In addition, four comparison EFF mixtures were also used in the study (1 Tennessee Department of Transportation (TDOT) and 3 air-entrained EFF mixtures).

KEYWORDS: controlled low-strength material, compressive strength, backfill, excavatability, ball drop apparatus, flow consistency, air content, innovations in controlled low-strength material (flowable fill)

Introduction

Excavatable flowable fill (EFF) is a blend of Portland cement, fine aggregate, water, and admixtures. EFF is delivered in a ready mix truck, but EFF is not concrete. EFF was developed

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to serve as an alternate backfill for roadway utility cuts. The three primary advantages of EFF are:

1. Improved worker safety—requires no compaction, therefore workers spend less time in the utility trench
2. No in-service settlement—utility cut patches do not sink or produce roadway hazards
3. Can be removed with conventional excavating equipment—no jack hammering

Unlike Portland cement concrete (PCC), higher compressive strength is not beneficial for EFF. PCC requires a minimum strength to perform properly in structures. EFF requires both a minimum and maximum strength to perform properly. Minimum strength recommendations are to assure that EFF has adequate bearing capacity and does not settle (deform) excessively under load. Maximum strength recommendations are to assure that EFF can be removed with conventional excavating equipment.

Research Significance

EFF mixture design requires a new mindset. The "stronger is better" idea does not work with EFF. Several well-meaning designers have produced "EFF" mixtures, which are not excavatable, using the "stronger is better" idea. The paste portion of the mixture (Portland cement, water, and admixtures) is critical to EFF performance. Proper paste proportions allow EFF mixtures to be fluid, develop adequate early strength, and yet not become so strong that it cannot be excavated later. The primary purpose of the project is to increase specifying agency confidence in EFF by providing data on excavatability and the impact of component materials on EFF engineering properties.

Research Objectives

The objectives of the proposed research are as follows:

1. To determine the long-term excavatability of flowable fill mixtures containing various quantities of Portland cement and Class F fly ash as per Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan For Use as a Mineral Admixture in Concrete (ASTM C 618) under field conditions and to correlate the findings with compressive strength development in the laboratory.
2. To determine the long-term excavatability of flowable fill mixtures containing various quantities of Portland cement and high unburned carbon fly ash under field conditions and to correlate the findings with compressive strength development in the laboratory.
3. To determine if varying aggregate type significantly influences the results of objective 1.

EFF Mixtures

Nine EFF mixtures (see Table 1) were used to assess the impact of Class F Fly Ash and Portland cement content. Proportions for the EFF mixtures were chosen using Kentucky Transportation Cabinet [3] and Tennessee Ready Mixed Concrete Association (TRMCA) recommendations as well as a previous Tennessee Technological University capping research mixture [4]. Portland cement contents ranged from 17.8 to 35.6 kg/m^3. Class F fly ash contents ranged from 178 to 261 kg/m^3. The fine aggregate used was Ohio River sand.

Six EFF mixtures (see Table 2) were used to assess the impact of Portland cement content and high-unburned carbon (loss-on-ignition greater than five percent) fly ash content. Portland cement contents of 26.7 and 35.6 kg/m^3 and high-unburned carbon fly ash contents of 219.5, 261, and 302.6 kg/m^3 were used to evaluate the impact of component proportions. The fine aggregate used was Ohio River sand.

The influence of aggregate type on EFF mixtures was evaluated by using five different aggregate types in the TRMCA EFF mixture (see Tables 3 and 4). Two additional aggregate variable mixtures were planned:

- Trench 20 oily foundry sand
- Trench 21 clayey foundry sand

TABLE 1—*EFF mixtures with Type I PC, Class F fly ash, and Ohio River sand.*

Mixture	Date Placed	PC (kg/m^3)	Fly Ash (kg/m^3)	Water (kg/m^3)	Aggregate (kg/m^3)	Flow (mm)	Ball Drop (h)
1 KTC	3/12/01	17.8	178	326.3	1780	0	22
2	3/12/01	17.8	219.5	297.2	1519	0	21
3	3/12/01	17.8	261	291.3	1488	241	21
4	3/12/01	26.7	178	302.6	1544	267	20
5 TRMCA	3/12/01	26.7	219.5	296.1	1514	279	19
6	5/14/01	26.7	261	290.7	1483	279	20
7	5/16/01	35.6	178	301.4	1540	0	19
8	5/16/01	35.6	219.5	296.7	1506	0	18
9 TTU CAP	5/16/01	35.6	261	295.5	1481	457	19

TABLE 2—*EFF mixtures with Type I PC, high unburned carbon fly ash, and Ohio River sand.*

Mixture	Date Placed	PC (kg/m^3)	Fly Ash (kg/m^3)	Water (kg/m^3)	Aggregate (kg/m^3)	Flow (mm)	Ball Drop (h)
10	5/15/01	26.7	219.5	305.5	1600.1	0.0	19
11	5/15/01	35.6	219.5	301.9	1542.6	215.9	18
12	5/15/01	26.7	261.0	296.7	1516.9	355.6	71
13	5/15/01	35.6	261.0	293.1	1518.7	393.7	66
14	5/15/01	26.7	302.6	285.3	1499.2	381.0	69
15	5/15/01	35.6	302.6	284.2	1495.0	406.4	66

TABLE 3—*Aggregate variables for TRMCA (26.7 PC/219.5 F ash) EFF mixture.*

Mixture Number / Fine Aggregate	Date Placed	Water (kg/m^3)	Aggregate (kg/m^3)	Flow (mm)	Ball Drop (h)
5 Ohio River Sand	3/12/01	296.0	1514.1	279.4	19
16 Limestone Manufactured Sand	5/14/01	296.0	1514.1	279.4	48
17 Crushed Sandstone	5/14/01	351.8	1401.3	0.0	22
18 Masonry Sand	5/14/01	380.3	1299.3	317.5	44
19 Limestone Screenings	5/14/01	265.7	1549.0	266.7	23
20 Oily Foundry Sand*					
21 Clayey Foundry Sand*					

*Not placed.

TABLE 4—*Variable aggregate specifications.*

Aggregate Type	Specification
Crushed sandstone	TDOT PCC Fine Aggregate – near ASTM C 33
Manufactured Limestone Sand	TDOT PCC Fine Aggregate – near ASTM C 33
Masonry Sand (high silica dredged sand)	Near ASTM C 144
Limestone Screenings	AASHTO M43 Size Number 10 [1]
Oily Foundry Sand*	None
Clayey Foundry Sand*	None

*Not placed.

Oily foundry sand aggregate was not available at the time of trench placement. Clayey foundry sand contained such large metal fragments that local ready mix producers would not allow it in their mixers. Therefore, neither of the trenches was placed. Four additional comparison EFF mixtures (see Table 5) were also used in the study.

TABLE 5—*EFF comparison mixtures.*

Mixture	Date Placed	PC (kg/m^3)	Fly Ash (kg/m^3)	Water (kg/m^3)	Agg. (kg/m^3)	Flow (mm)	Air (%)	Ball Drop (h)
22 TDOT	5/14/01	59.3	148.3	296.7	1661.1*	0	...	21
23 MB AE 90	5/15/01	59.3	0	201.7	1446.9*	222.3	28.3	46
24 WRG Darafill	5/15/01	59.3	0	160.2	1374.1*	158.8	24.3	20
25 MBT Rheofill	5/15/01	47.5	0	222.7	1483.8**	184.2	25.9	67

*Ohio River sand.

**Limestone Manufactured sand.

Procedure

Approximately 4.21 m^3 of each EFF mixture were delivered to the TTU campus in a ready mix truck. About 4.08 m^3 of each mixture were placed in a 0.9 m deep, 0.9 m wide, 4.9 m long trench simulating a utility cut. The remainder of the mixture was used to cast compressive strength cylinders and conduct plastic property tests.

Each mixture was sampled near the middle of the batch in accordance with Standard Practice for Sampling Freshly Mixed Controlled Low Strength Material (ASTM D 5791). The consistency of each mixture was determined as per Standard Test Method for Flow Consistency of Controlled Low Strength Material (CLSM)(ASTM D 6103). The unit weight and air content of each mixture were determined in accordance with Standard Test Method for Unit Weight, Yield, Cement Content, and Air Content (Gravimetric) of Controlled Low Strength Material (CLSM)(ASTM D 6023). Flow values and air contents (for air-entrained mixtures only) are shown in Tables 1–3 and 5. Fifty 102 mm diameter, 204 mm height, compressive strength cylinders of each mixture were cast in accordance with Standard Test Method for Preparation and Testing of Soil-Cement Slurry Test Cylinders (ASTM D 4832-95), with the following exceptions:

- Cardboard molds were used instead of plastic due to stripping difficulties with CLSM in plastic molds.
- CLSMs were not mounded on top of the cylinders in the plastic state and removed after hardening with a wire brush due to the high potential for cylinder damage.

Three compressive strength cylinders were tested at each time shown in Table 6, providing that sufficient cylinders survived transportation and mold stripping. The compressive strength testing was conducted in accordance with ASTM D 4832-95, with the following exception:

- Compressive strength cylinders were capped with wet-suit neoprene in rigid retaining caps as described in Sauter and Crouch [4].

TABLE 6—*Testing times.*

Days	7	28	63	98	140	182	238	301	364	455	546	637	728
Weeks	1	4	9	14	20	26	34	43	52	65	78	91	104
Years						0.5			1	1.25	1.5	1.75	2

The EFF trenches were tested for suitability for load application at approximately 6 h after placement and subsequently every 2 to 4 h during regular work hours until each mixture passed the test or 4 d elapsed. The test was conducted as prescribed in Standard Test Method for Ball Drop on Controlled Low Strength Material (CLSM) To Determine Suitability for Load Application (ASTM D 6024). The time each trench passed ASTM 6024 is shown in Tables 1–3 and 5.

Two Dynamic Cone Penetrometer (DCP) tests [2] were conducted on each trench on Monday, 10 March 2003. Several attempts were made to push Shelby Tubes and obtain compressive strength samples; however, no viable samples were recovered. Two attempts to excavate the EFF in each trench with a Case 580E backhoe were made on Tuesday, 11 March 2003. The backhoe operator provided a 1–10 (10 being the most difficult) estimate of excavation difficulty for each trench. Trenches containing mixtures 1–5 were two years old at the time of testing and excavation; the remainder of the trenches was approximately 22 months old.

Results

The average values of 28 d, maximum obtained, and current compressive strengths (637 or 728 d), along with average DCP test results and excavation difficulty ratings are shown Tables 7–10. Excavation difficulty is a function of equipment used. The case 580E used in this project was chosen based on availability. The operator deemed all EFF mixtures excavatable; however, excavation difficulty varied considerably.

TABLE 7—*Strength and excavatability results for EFF mixtures with Type I PC, Class F fly ash, and Ohio River sand.*

Mixture	28 d Compressive Strength (kPa)	Maximum Compressive Strength (kPa)	Current (637 or 728 d) Compressive Strength (kPa)	Dynamic Cone Penetrometer (kPa)	Case 580E Excavation Difficulty Rating
1 KTC	41.4	68.9	48.3*	240	1
2	68.9	103.4	82.7*	>480	3
3	89.6	151.7	117.2*	>480	4
4	137.9	330.9	330.9*	>480	7
5 TRMCA	117.2	282.7	199.9*	360	7
6	137.9	468.8	468.8**	>480	8
7	117.2	682.6	330.9**	>480	7
8	186.2	620.5	455.1**	430	8
9 TTU Cap	275.8	999.7	882.5**	>480	9

*637 d, **728 d.

TABLE 8—*Strength and excavatability results for EFF mixtures with Type I PC, high unburned carbon fly ash, and Ohio River sand.*

Mixture	28 d Compressive Strength (kPa)	Maximum Compressive Strength (kPa)	Current (637 d) Compressive Strength (kPa)	Dynamic Cone Penetrometer (kPa)	Case 580E Excavation Difficulty Rating
10	234.4	648.1	579.2	360	7
11	282.7	992.8	696.4	>480	9
12	137.9	206.8	179.3	155	4
13	213.7	572.3	441.3	165	3
14	199.9	468.8	399.9	155	3
15	199.9	944.6	910.1	>480	6

TABLE 9—*Strength and excavatability results for aggregate variables for TRMCA EFF mixture.*

Mixture	28 d Compressive Strength (kPa)	Maximum Compressive Strength (kPa)	Current (637 d) Compressive Strength (kPa)	Dynamic Cone Penetrometer (kPa)	Case 580E Excavation Difficulty Rating
5 Ohio River Sand	117.2	282.7	199.9	360	7
16 Limestone Manufactured Sand	337.8	730.8	524.0	215	9
17 Crushed Sandstone	165.5	868.7	648.1	>480	8
18 Masonry Sand	330.9	779.7	717.1	380	7
19 Limestone Screenings	399.9	923.9	820.5	310	9

TABLE 10—*Strength and excavatability results for EFF comparison mixtures.*

Mixture	28 d Compressive Strength (kPa)	Maximum Compressive Strength (kPa)	Current (637 d) Compressive Strength (kPa)	Dynamic Cone Penetrometer (kPa)	Case 580E Excavation Difficulty Rating
22 TDOT	275.8	1385.8	1096.3	>480	10
23 MB AE 90	110.3	268.9	199.9	130	3
24 WRG Darafill	248.2	537.8	379.2	275	6
25 MBT Rheofill	117.2	317.2	282.7	95	4

Analysis of Results

Figure 1 shows a correlation between ASTM D 6103 flow and cementitious materials content of the PC-ash mixtures. Although the coefficient of determination is rather low (0.5017), it is interesting to note that for EFF mixtures with a cementitious materials content greater than 246.2 kg/m^3, 88.9 % of them had a flow greater than 204 mm. However, for EFF mixtures with a cementitious material content less than or equal to 246.2 kg/m^3, only 44.4 % had a flow greater than 204 mm.

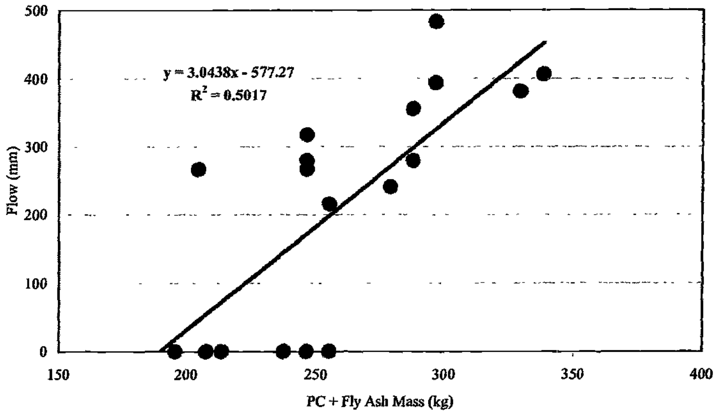

FIG. 1—*Flow vs. cementitious materials content for PC-ash mixtures.*

Time to pass the ASTM D 6024 Ball Drop Test for the PC-ash mixtures did not correlate well with mixture composition. There were two facts indicating that time to pass the ball drop may be proportional to cementitious materials content of the PC-ash mixtures:

- 8 of 10 mixtures with cementitious materials content less than or equal to 246.2 kg/m^3 passed the ball drop in less than 24 h.
- 3 of 4 mixtures with cementitious materials content greater than or equal to 296.7 kg/m^3 took more than 60 h to pass the ball drop.

The authors thought it was likely that high cementitious materials content inhibited bleeding of the EFF mixtures thus retarding dewatering and subsequent stiffening. No correlation to time to pass the ball drop test was attempted with the limited number of air-entrained EFF mixtures.

Figure 2 shows a correlation between 28 d compressive strength and PC mass cubed multiplied by fly ash mass for Class F fly ash and Ohio River sand mixtures. The R^2 of 0.8198 indicates a fairly strong relationship. Figure 3 shows maximum compressive strength vs. PC mass^2 multiplied by fly ash content for Class F fly ash and Ohio River sand mixtures. The excellent fit (R^2 = 0.9687) of the linear trend line shows mathematically what the industry personnel have intuitively known for some time—EFF potential compressive strength is directly proportional to cementitious materials content. PC content of the PC-Class F fly ash EFF mixtures is more influential for early compressive strength development (28 d) than for maximum compressive strength as indicated by the cubic and squared PC mass relationships. Similar correlations for PC-High Unburned Carbon Ash were very poor, indicating no relationships.

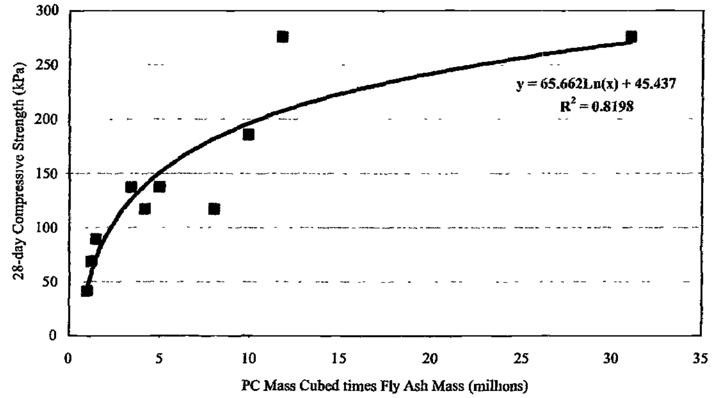

FIG. 2—*Comparison of 28 d compressive strength and cementitious materials content for Class F fly ash and Ohio River sand mixture.*

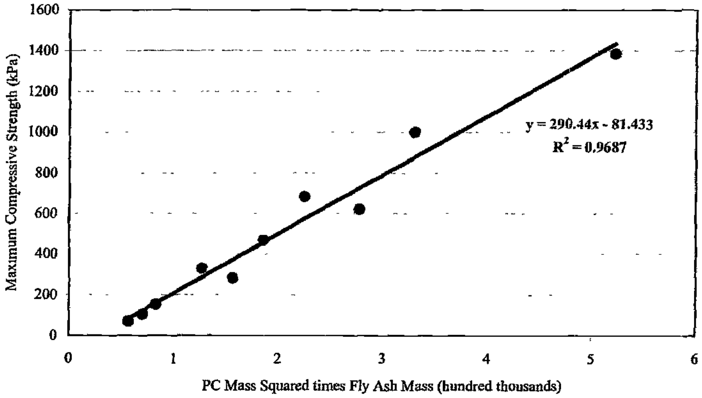

FIG. 3—*Comparison of maximum compressive strength and cementitious materials content for Class F fly ash and Ohio River sand mixtures.*

Substitution of variable aggregates for Ohio River sand into the TRMCA EFF mixture yielded few useful observations. Flow of all the mixtures was similar except for the crushed sandstone mixture. The locally available crushed sandstone often has more than 55 % of the particles by weight between the No. 30 and No. 50 sieves, leading to a very open gradation prone to bleeding and segregation. No viable explanation could be developed for the difference in time to pass the ball drop. Although excavation difficulties for all the aggregate variable mixtures were similar, compressive strengths and DCP results varied widely.

Figure 4 shows correlations between current compressive strengths at the time of excavation and Case 580E backhoe excavation difficulty. Good relationships were obtained for PC-Class F fly ash mixtures with all aggregate types included and for air-entrained mixtures. Only three air-entrained mixtures were available for correlation. Air-entrained mixtures are easier to excavate than non-air-entrained mixtures at the same compressive strength. A poor correlation was obtained with PC-high unburned carbon ash mixtures, indicating no relationship. DCP data did not correlate well, with mixture composition or excavation difficulty possibly due to the upper limit on DCP results.

The importance of cementitious materials content to flow and time to pass the ball drop, along with the correlations shown in Figs. 2 and 3, suggest that the cementitious materials content of a PC-Class F fly ash EFF mixture is extremely important to mixture performance. Unfortunately, it appears that compressive strength cementitious materials relationships are aggregate dependent.

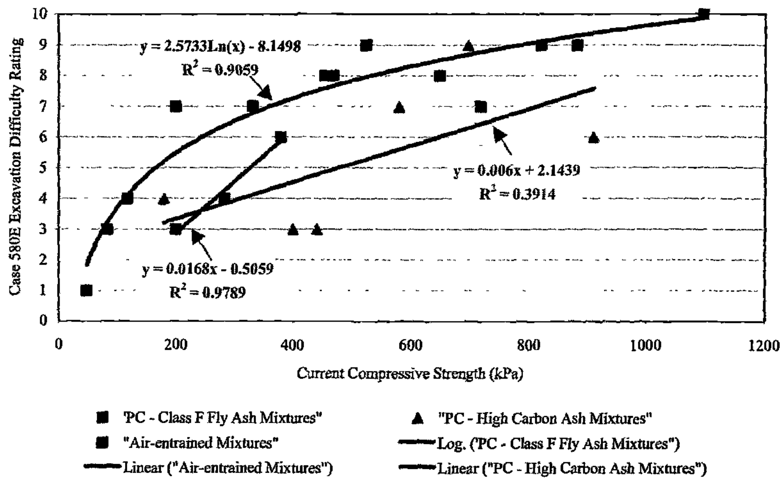

FIG. 4—*Excavation difficulty vs. current compressive strength.*

Conclusions

The following conclusions can be drawn from the limited data available:

- Non-air-entrained PC-Ash EFF mixtures with cementitious materials contents greater than 246.2 kg/m^3 have a much higher probability of achieving an ASTM D 6103 flow greater than 204 mm than similar EFF mixtures with lower cementitious materials contents.
- Non-air-entrained PC-Ash EFF mixtures with cementitious materials contents less than or equal to 246.2 kg/m^3 have a much higher probability of passing the ASTM D 6024 ball drop test in less than 24 h than similar EFF mixtures with cementitious materials contents greater than 296.7 kg/m^3.
- There appears to be a good relationship between 28 d compressive strength and PC mass^3 multiplied by fly ash mass for non-air-entrained PC-Class F fly ash EFF mixtures. Unfortunately, the relationship appears to be aggregate-dependent.
- There appears to be an excellent relationship between maximum (potential) compressive strength and PC mass^2 multiplied by fly ash mass for non-air-entrained PC-Class F fly ash EFF mixtures. Unfortunately, the relationship appears to be aggregate-dependent.
- Although the PC content of non-air-entrained PC-Class F fly ash EFF mixtures is very important to both early compressive strength development and maximum (potential) compressive strength, PC content appears to be more important to early compressive strength development.
- There appears to be a strong relationship between compressive strength of non-air-entrained PC-Class F fly ash EFF mixtures and excavation difficulty.
- There appears to be an excellent relationship between compressive strength of air-entrained EFF mixtures and excavation difficulty. Further, air-entrained EFF mixtures are easier to excavate at the same compressive strength than non-air-entrained PC-Class F fly ash EFF mixtures.

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Thermally Insulating Foundations and Ground Slabs Using Highly-Foamed Concrete

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ABSTRACT: Foamed concrete, comprising a cementitious paste or mortar together with preformed foam, has many attractive properties, perhaps the most useful being its excellent thermal insulation properties, and therefore it can be classified as controlled thermal fill (CTF). Although widely used as a simple backfill, foamed concrete can be designed easily for particular densities (800–1600 kg/m^3), flow characteristics (100–300 mm spread), strength (typically less than 10 MPa), and thermal insulation performance (0.2–0.6 W/mK). These properties make it an ideal material for house construction, in particular, for enhancing the thermal efficiency of the foundations and ground slab. This paper examines the performance of a range of foamed concretes for trench fill foundations and ground slabs in terms of thermal performance and main engineering, permeation, and durability properties. The consonant advantages of using fly ash (low-lime, fine, and coarse) technology will also be discussed.

KEYWORDS: foamed concrete, thermal insulation, housing foundations, ground slab, fine low-lime fly ash, coarse low-lime fly ash, engineering, permeation, durability properties

Nomenclature

AB	Aircrete blocks
ACEC	Aggressive Chemical Environment Class
DPC/DPM	Damp-proof course/damp-proof membrane
FA_{coarse}	Coarse low-lime fly ash
FA_{fine}	Fine low-lime fly ash
FC	Foamed concrete
PC	Portland cement
U-value	Thermal transmittance, W/m^{2}K
w/cm	Water/cementitious material ratio
λ_{ind}	Thermal conductivity, W/mK (Note: this is an indicative value, as the test equipment has not been calibrated against a national standard. However, first party calibration of the test equipment was carried out using materials of known values.)

Introduction

Controlled low-strength materials (CLSM) have been used worldwide for a number of years, particularly as controlled density fill [4], due to their flowability and removability (if required), the latter resulting from relatively low compressive strengths (less than 8 MPa at 28 d [2]). In addition to the traditional CLSM, another construction material

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with a broad range of applications and similar properties to those above is foamed concrete.

Foamed concrete (FC), also known as cellular concrete, is a highly aerated paste/mortar with air contents greater than 20 % by volume [18] and can be considered a type of Controlled Thermal Fill (CTF). It is produced with the addition of a designed quantity of preformed foam to a cementitious paste or mortar (base mix) and has been widely used in void filling, highway reinstatements, and soil stabilization applications. The flowing and self-compacting properties, low densities (typically between 800 and 1600 kg/m^3, although it is possible to go down to 400 kg/m^3), light weight, and excellent thermal insulating capacity (typically <0.5 W/mK as a result of its closed-cell microstructure) make foamed concrete an attractive material for construction [3]. Foamed concrete therefore has great potential for enhancing the thermal efficiency of building elements with reduced load-bearing requirements.

This paper considers the use of foamed concrete in thermally insulating trench fill foundations and ground slabs for low-rise housing. Many countries recognize the need to reduce fossil fuel emissions and energy consumed in heating/cooling dwellings. In the UK, the thermal transmittance (U-value) requirement for ground slabs has been reduced from 0.45 W/m^{2}K to 0.25 W/m^{2}K (in accordance with guidance on Conservation of Fuel and Power in Dwellings in the UK Building Regulations BRAD L1). Faced with this considerable increase in thermal performance requirements the house builders must meet, the Concrete Technology Unit at the University of Dundee decided to investigate the use of foamed concrete to assist the house builders. High strength is not required for house foundations; indeed the strength of foamed concrete used has a number of advantages, including reduced unit cost, improved sustainability (due to reduced PC demand), and ability to retrofit pipework and services, if required.

In this study it was decided to confine the research work to foamed concretes that could be obtained readily from ready mixed concrete suppliers, i.e., a range of plastic densities of 1000, 1200, and 1400 kg/m^3 (i.e., air content between 40 % and 60 %). In addition, the use of fine and coarse low-lime bituminous fly ashes as 30 % (by mass) replacement of Portland cement and 50–100 % replacement (by mass) of sand fines respectively was considered a means of enhancing FC properties. The suitability of foamed concrete as CTF for trench fill foundations was assessed in terms of compressive strength, capillary sorption, resistance to aggressive chemical environments (ACE), and freeze/thaw (F/T) cycles. In addition, the thermal conductivity and drying shrinkage strains were examined to evaluate foamed concrete performance in ground slabs.

Use for Foamed Concrete in Housing Construction

There have been a number of small-scale trials of foamed concrete in house construction [15], but it was decided in this study to utilize a conventional type of construction familiar to UK house builders. The type of construction envisaged is for FC trench fill foundations and ground-supported slab, as shown schematically in Fig. 1, comprising in-situ production of foamed concrete, which is poured directly in the trench without any requirement for compaction. At the next shift, the two inner courses of wall blocks can be constructed, which provide a permanent form for the slab. Granular fill, sand blinding, damp proof membrane, and any additional thermal insulation are incorporated as required.

When comparing the proposed construction method with the most common current practice in the UK, comprising aircrete block (AB) foundation wall and suspended inverted concrete T-beam and AB slab with significant amounts of additional slab polystyrene insulation, the flowing and self-compacting properties of FC reduce construction time by simplifying workmanship requirements, thereby enhancing site productivity and cost effectiveness of construction. In addition, safety on site is improved, as no man-entry is required in the trench. Moreover, the FC configuration is monolithic that ensures no cold joints, in comparison with the mortar bed joints present in the AB foundation wall and composite slab. Finally, depending on the performance of foamed concrete in the aggressive chemical environment tested, the proposed construction may be appropriate for housing built on previously used [brownfield] sites.

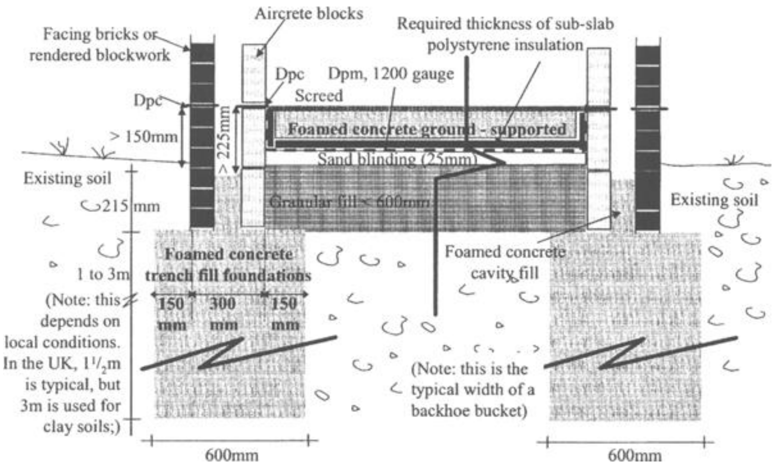

FIG. 1—*Section drawing of proposed foamed concrete trench fill foundations and ground slab typical of UK house building construction [8].*

Materials and Mix Proportions

The materials used in this study included:

- *Portland cement (PC)* conforming to BS EN Specification for Portland cement (BS 12/BS EN 197-1 CEM1) -42.5N, ASTM C 150-94 Type I.
- *Fine fly ash (FA_{fine})* with a 45μm sieve (No.325 ASTM) retention of 7.5 % and conforming to BS Specification for Pulverized-Fuel Ash for Use with PC (BS 3892-1 / BS EN 450), ASTM C 618-94a Class F.
- *Coarse fly ash (FA_{coarse})* with a 45μm sieve (No.325 ASTM) retention of 26.5 % and conforming to BS Specification for Pulverized-Fuel Ash to be Used as a Type I addition (BS 3892-2, ASTM C 618-94a Class F).

- *Natural sand* conforming to BS Specification for Aggregates for Concrete (BS EN 12620), with particles greater than 2.36mm removed.
- *Surfactant* (commercial synthetic foaming agent).

The mix proportions of the foamed concretes examined, derived using the method described by Giannakou and Jones [8], are summarized in Table 1. The cementitious material (PC, FA_{fine}) content and water/cementitious material ratio (w/cm) in this study were kept constant throughout at 300 kg/m^3 and 0.50 respectively.

TABLE 1—*Mix constituent proportions of foamed concrete mixes.*

Plas. Dens. kg/m^3	Cement Cont., kg/m^3		Fines Content, kg/m^3		Total Water Content[a], kg/m^3	Calc. Foam Content[b], kg/m^3	Calc. Air Content, %
	PC	FA_{fine}	Sand	FA_{coarse}			
1000	300	0	550	0	150	24.9	55
			220	220	260	20.9	46
			0	365	335	18.5	41
	210	90	550	0	150	24.1	53
			220	220	260	20.4	45
			0	365	335	18.0	40
1200	300	0	750	0	150	21.1	47
			300	300	300	16.1	36
			0	500	400	12.8	28
	210	90	750	0	150	20.6	46
			300	300	300	15.6	35
			0	500	400	12.3	27
1400	300	0	950	0	150	17.7	39
			380	380	340	11.4	25
			0	635	470	7.2	16
	210	90	950	0	150	17.2	38
			380	380	340	10.9	24
			0	635	470	6.7	15

[a] The FA_{coarse} quantity was taken into account in the w/cm to ensure that sufficient free water was present in the mix to wet the large surface area of the fine particles. In addition, the w/cm ratio was chosen to ensure spread values greater than 150mm.

[b] Foam density 50 kg/m^3.

Preparation of Laboratory Foamed Concrete Specimens

The preformed foam was produced in a dry system generator from a 6 % aqueous surfactant solution, which was expanded to a 50 kg/m^3 density. This was immediately added to the base mix and combined in a liner type mixer (although folding action is considered more suitable for combining the base mix and foam) until uniform consistency was achieved. A plastic density within ± 50 kg/m^3 of the design value was used as a target. The specimens were cast in steel molds lined with kitchen cling film to prevent interaction of the foamed concrete with the mould oil and then covered with cling film for 24 h. Following demolding, the specimens were sealed-cured at 20°C and 55% RH until testing.

Foamed Concrete Trench Fill Foundations

The suitability of foamed concrete as CTF for trench fill foundations was assessed in terms of compressive strength, capillary sorption, resistance to aggressive chemical environments (ACE), and freeze/thaw (F/T) cycles, as described in the following sections.

Compressive Strength

Compressive strength was measured on 100mm cube specimens in accordance with the BS Method for Determination of Compressive Strength of Test Specimens (BS EN 12390-3). The values obtained following 56 d of sealed-curing are given in Fig. 2.

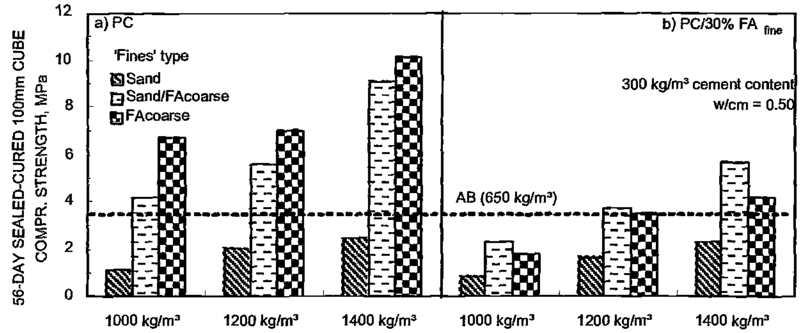

FIG. 2—*Influence of density and mix constituents on 56 d sealed-cured 100 mm cube compressive strengths.*

The strengths ranged from 1–10 MPa, with the highest values obtained on 1400 kg/m^3 concretes, due to the reduced volume of air, and on those with the greater FA$_{coarse}$ content, in line with observations of De Rose and Morris [6], Kearsley [11], and Ramamurthy and Narayanan [17]. Indeed, strength increased substantially when sand was either partially (50 %) or fully replaced with FA$_{coarse}$, with values on the PC mixes up to 4 and 7 times higher, respectively, as a result of the greater binding capacity. However, the strengths of the PC/30 % FA$_{fine}$ mixes were up to 80 % lower than the corresponding PC mixes, with the greatest strength loss observed on the FA$_{coarse}$ mixes, and with those using all sand as the fines phase exhibiting same strength as the corresponding PC concretes after 56 d. The fines type achieving optimum strengths was the blend of sand and FA$_{coarse}$, probably due to a more suitable calcium/silica (Ca/Si) ratio, with sufficient lime ($Ca(OH)_2$) to react with pozzolanic phases in the FA. Overall, the majority of concretes with 50 % FA$_{coarse}$ or 100 % FA$_{coarse}$ achieved 56 d strengths exceeding that of the aircrete block (3.5 MPa).

Capillary Sorption

Given that house foundations can be subjected to attack by deleterious agents (e.g., sulfates and acids) migrating through soil in the ground water, the resistance of (unsaturated) foamed concrete to capillary flow was examined using a one-dimensional sorptivity test [14]. Sorptivity measurements were made on 100 mm sealed-cured cubes, oven-dried at 30°C to constant weight, using the method developed by Hall [9]. The specimens were placed on mesh in a container filled with water to a height of 5mm above the base of the specimen, and the change in weight was measured at designated time intervals. The indices determined for the range of foamed concretes tested are given in Fig. 3.

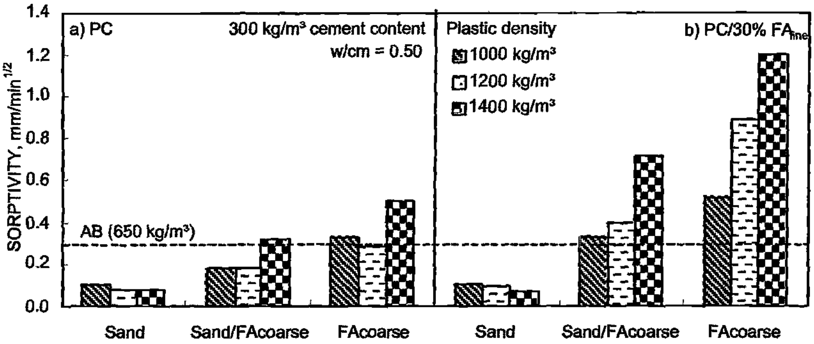

FIG. 3—*Sorptivity indices of 1000, 1200, and 1400 kg/m³ foamed concretes.*

The sorptivities ranged between 0.1 and 1.2 mm/min$^{1/2}$, with values for the sand/FA$_{\text{coarse}}$ and FA$_{\text{coarse}}$ fines mixes reducing with decreasing density. The lowest sorptivity was with the PC/30 % FA$_{\text{fine}}$ concretes. Assuming closed-cell bubble structure, the entrained air voids would be expected to obstruct the flow of water in the same way as coarse aggregate particles [13] and, hence, sorption would occur through the paste/mortar phase. As a result, the greater volume of sorbing paste/mortar at the higher densities would be expected to lead to higher sorptivity.

For a given plastic density, the sorptivity ranking in terms of fines type was sand, sand/FA$_{\text{coarse}}$ and FA$_{\text{coarse}}$ in increasing order of magnitude. More specifically, at any given density, the indices calculated for PC concretes with sand/FA$_{\text{coarse}}$ and FA$_{\text{coarse}}$ fines were up to 4.3 and 6.8 times greater, respectively, than those of corresponding sand mixes, while the equivalent increases in sorptivity noted on PC/30 % FA$_{\text{fine}}$ concretes were up to 10.3 and 17.4 times, respectively. These differences in performance of fines types were most notable at the higher densities. The increasing sorptivities with increasing FA$_{\text{coarse}}$ contents, which correspond to greater total amounts of fines (i.e., <125 μm) in the concretes, are probably due to a denser microstructure of the solid phase (higher strength concrete), thereby resulting in greater capillary attraction.

Resistance to Aggressive Chemical Environments

The resistance of the foamed concrete to aggressive chemical attack was measured in terms of length and strength change on 75 × 75 × 225 mm prisms and 100 mm cubes, respectively. These were subjected to a sulfate solution (comprising 30 % Gypsum ($CaSO_4 \cdot 2H_2O$) and 70 % Epsomite ($MgSO_4 \cdot 7H_2O$)) of Design Sulfate Class 4 and ACEC 4 (4.5 g/*l* SO_4), as defined in BRE Special Digest for Concrete in Aggressive Ground (BRE SD 1). The results obtained after six months exposure are summarized in Table 2.

TABLE 2—*Influence of aggressive chemical environment on linear expansion and 100 mm cube strengths.*

Plas. Dens. kg/m³	Cement Type	Fines Type	Resultant Deterioration of Test Samples		
			6 Month Expansion in DS4 solution, % of water storage	6 Month Cube Strength, % change[a]	
				H_2O	DS4
1000	PC	Sand	80.3	-25.8	-34.8
		Sand/FA_{coarse}	76.8	+14.8	+7.6
		FA_{coarse}	66.4	+58.2	-9.0
1400	PC	Sand	99.1	-42.7	-50.9
		Sand/FA_{coarse}	90.1	+122.0	+66.9
		FA_{coarse}	77.5	+86.4	+69.6
1000	PC/ 30 % FA_{fine}	Sand	310.0	-5.9	-5.9
		FA_{coarse}	130.0	+505.5	+439.0
Aircrete Blocks (AB)			109.0	...	...

[a] With respect to 56 d sealed-cured 100 mm cube compressive strength.

The differences in swelling and length expansion between the 1000 and 1400 kg/m³ plastic density foamed concretes were minimal (up to 200 μstrain difference) after six months of exposure, with slightly higher values on the 1000 kg/m³ specimens. For a given density and cement combination, the length expansion of the different fines concretes was very similar, and therefore no performance ranking could be established. In addition, the overall expansions were small (less than 600 μstrain) and, given the lack of visual physical damage and minimal differences in expansion between the reference (H_2O) and DS4 exposures, they suggest that the expansions noted within the first six months cannot be attributed to sulfate reactions and by-products. The expansions measured on both the sand and FA_{coarse} aggregate foamed concretes with 30 % FA_{fine} in DS4 solution were very similar to those of the equivalent PC specimens throughout the exposure period. The result trends on the AB specimens suggest that the expansion noted on the aircrete blocks is similar to that of foamed concrete.

The six month compressive strength measurements of 100 mm cubes immersed in the reference (H_2O) and DS4 solutions, summarized in Table 2, showed slight reductions in strengths of all sand fines concretes subjected to both the DS4 solution and water, in comparison with strengths recorded on corresponding 56 d sealed-cured specimens. On the other hand, all sand/FA_{coarse} and FA_{coarse} exhibited increases in strength in both exposures due to the ongoing hydration from pozzolanic reaction.

Resistance to Freezing and Thawing

The ranges of foamed concretes examined were subjected to three daily cycles of alternate freezing (-10°C) and thawing (+5°C), broadly in line with Procedure B of the ASTM Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing (C 666-97). The damage assessment was carried out in terms of length expansion and compressive strength on 75 × 75 × 225 mm prisms and 100 mm cubes, respectively, and the measurements obtained at the end of the 100 d exposure period (300 cycles) are summarized in Table 3.

TABLE 3—*Influence of alternate freeze/thaw cycles on linear expansion and 100 mm cube strengths of 1000 and 1400 kg/m^3 foamed concretes.*[a]

Plas. Dens. kg/m^3	Cement Type	Fines Type	Resultant Deterioration of Test Samples	
			Expansion After 100 days, μstrain	Strength of F/T Specimens, % of 56 d reference[c] strength
1000	PC	Sand	460	83.5
		Sand/FA$_{coarse}$	446	107.6
		FA$_{coarse}$	295	97.0
1400	PC	Sand	278 at 63 d[b]	77.8
		Sand/FA$_{coarse}$	219	132.8
		FA$_{coarse}$	350 at 56 d[b]	118.4
1000	PC/ 30 % FA$_{fine}$	Sand	480	82.4
		FA$_{coarse}$	330	372.2
Aircrete Blocks (AB)			92 at 84 d[b]	48.6

[a] Specimens were sealed-cured for 28 d prior to exposure in freezing and thawing cycles.

[b] Test stopped as specimens had fractured.

[c] Sealed-cured specimens.

Overall, the 1000 kg/m^3 density test specimens exhibited greater expansion than the corresponding 1400 kg/m^3 concretes, probably due to the more significant ingress of water in the coarse porous interconnected microstructure. However, the larger volume of pores of the 1000 kg/m^3 seemed to be able to accommodate the expansive forces more efficiently than the 1400 kg/m^3 concretes, since the sand and FA$_{coarse}$ specimens of the latter density and the AB prisms failed prior to completion of the exposure period.

The freeze/thaw resistance of the PC/30 % FA$_{fine}$ foamed concretes for both sand and FA$_{coarse}$ fines types was similar to that of PC foamed concretes. The ultimate length expansion measurements on the PC/30 % FA$_{fine}$ and PC mixes were 480 and 460 μstrain for the sand and 330 and 295 μstrain for the FA$_{coarse}$ concretes. Although the linear expansion of aircrete blocks in F/T cycles was smaller than that of the foamed concrete specimens, both AB specimens cracked and failed before completion of the exposure, and these also exhibited the highest strength loss, compared to reference cube strength values.

As expected from the results given above, the alternate freezing and thawing cycles resulted in corresponding strength loss for the majority of foamed concretes. In general, the performance ranking in length expansions and strength loss was also reflected in the weight of material that had spalled, crumbled, or broken off by the end of the exposure.

Foamed Concrete Ground Slabs

The suitability of foamed concrete as CTF for ground-supported slabs was assessed in terms of thermal conductivity and drying shrinkage strains, as described in the following sections.

Indicative Thermal Conductivity

Thermal conductivity (λ) is an inherent property (i.e., independent of testing conditions) of a house building material and defines the rate at which heat passes through it, with low values reflecting greater insulating ability. Indicative thermal conductivity was measured on 290 mm square slabs of 50 mm thickness, which were sealed-cured for 28 d, oven-dried at 30°C (to prevent damage caused to the foamed concrete microstructure at higher temperatures) until weight was constant, and then placed in a desiccator for 24 h. These were then placed in the apparatus shown in Fig. 4, with self-adhesive insulating foam tape attached firmly around its perimeter and three Type K thermocouples secured with masking tape on either side of the specimen surface. Following placement of the specimen in the apparatus, 24 h were allowed before testing was initiated to allow for steady rate heat transfer to be achieved.

The apparatus developed at Dundee University was based on guidelines given in BS 874: Part 3.2: 1990 Determining Thermal Insulating Properties Using the Calibrated Hot-Box Method. The apparatus was an insulated hot-box with a 15W heat source and a plywood baffle to enhance uniform distribution/transfer of heat through conduction and to minimize that through radiation. A refrigerating unit was added downstream and maintained at a constant low temperature to increase the differential on either side of the specimen and to simulate the range of values to which ground-supported slabs are typically exposed. Calibration of the equipment was carried out with an aircrete block and a normal weight concrete specimen, and it was found that the thermal conductivity values quoted for the aircrete block and normal weight concrete samples were obtained at 30°C, the setting for the heated side and the maximum setting for the refrigerating unit. As a result, this combination of settings was maintained for the testing of foamed concrete and benchmark products, with three sets of readings of the counter on the thermostat and temperatures on all Type K thermocouples taken within 24 h.

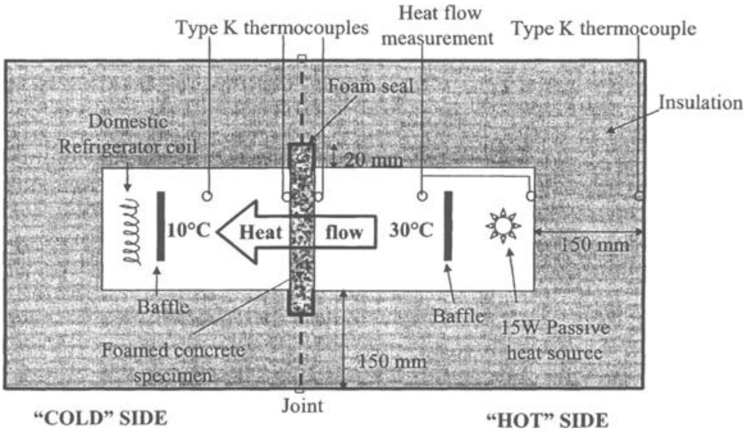

FIG. 4—*Schematic layout of thermal conductivity test equipment.*

λ_{ind} (W/mK) was calculated, as an average or means of three repeat tests on the same sample, from Eq 1 [6]:

$$\lambda_{ind} = (Q\,D) / (A\,\Delta T) \tag{1}$$

where, Q = time rate of heat flow
D = test specimen thickness, m
A = exposed area of test specimen, m^2
ΔT = temperature differential between "hot" and "cold" side of specimen, °K

The thermal conductivities (λ_{ind}) measured are given in Table 4. As expected, lower λ_{ind} were obtained with the lower density test specimens, due to the large bubble phase. The influence of cement type on λ_{ind} was also significant. The values for PC concretes ranged between 0.36 and 0.55 W/mK, which are within the range reported in the literature [1, 5, 18], but in comparison, corresponding λ_{ind} for PC/30 % FA_{fine} were 12–38% lower. This is probably due to the lower particle density and cenospheric morphology of FA_{fine} [10]. A similar effect was noted with the comparative thermal performance of the different fines types. The sand/FA_{coarse} and FA_{coarse} mixes resulted in lower λ_{ind} values than all the sand test specimens (up to 17 and 31 % lower, respectively). The lowest recorded value was 0.22 W/mK for the 1000 kg/m^3 density PC/FA_{fine} test specimen, which approximates to the thermal performance of typical aircrete blocks (0.19 W/mK) at 650 kg/m^3 density.

Unlike with other properties (e.g., compressive strength, drying shrinkage, sorptivity), where a simultaneous replacement of PC with FA_{fine} and sand with FA_{coarse} was used, resulting in either no benefit or an adverse effect, thermal conductivity was improved.

Effect on U-Value

The effect of the different λ_{ind} values on the U-value of a typical house ground slab/foundation element is also shown in Table 4. The U-value calculation was carried out in accordance with the BS EN ISO Calculation Method for Thermal Performance of Buildings—Heat Transfer via the Ground (BS EN ISO 13370). In this case, it was assumed that a typical element would consist of a 600 mm wide by 1.5 m deep strip foundation overlaid by a 150 mm ground-supported slab (see Fig. 1).

TABLE 4—*Thermal conductivities (λ_{ind}) of the range of foamed concretes examined.*

Plastic Density, kg/m^3	Cement Type	Fines Type	Measured Thermal Conductivity, W/mK	Example of a Typical House Ground Slab/Foundation U-value[a], W/m^{2}K
1000	PC	Sand	0.40	0.49
		Sand/FA_{coarse}	0.43	0.51
		FA_{coarse}	0.36	0.47
1000	PC/ 30 % FA_{fine}	Sand	0.29	0.42
		Sand/FA_{coarse}	0.28	0.41
		FA_{coarse}	0.22	0.36
1200	PC	Sand	0.53	0.56
		Sand/FA_{coarse}	0.46	0.52
		FA_{coarse}	0.41	0.50
1200	PC/ 30 % FA_{fine}	Sand	0.43	0.51
		Sand/FA_{coarse}	0.36	0.47
		FA_{coarse}	0.30	0.43
1400	PC	Sand	0.47	0.53
		Sand/FA_{coarse}	0.56	0.57
		FA_{coarse}	0.40	0.49
1400	PC/ 30 % FA_{fine}	Sand	0.59	0.58
		Sand/FA_{coarse}	0.49	0.54
		FA_{coarse}	0.41	0.50

[a] Calculation was carried out for 150 mm thick slab, 600 mm and 1500 mm foundation width and depth respectively (assuming a perimeter to area ratio of 0.7).

It can be seen that even the lowest λ_{ind} value concrete would still require additional sub-slab insulation (e.g., polystyrene with λ_{ind} of 0.027 W/mK) to achieve the UK maximum U-value of 0.25 W/m^{2}K. However, this is three times lower than would be required for a normal weight concrete slab.

Drying Shrinkage

50 × 50 × 200 mm prisms were used to measure drying shrinkage, which were stored at 20°C and 55 % RH. Length change (to ±0.002 mm, compared to initial length after demolding at 24 h) was monitored weekly. The influence of cement type and fines type for the 1000 kg/m^3 plastic density concretes is shown in Fig. 5.

It can be seen that in most cases, drying shrinkage strain levels off after approximately three weeks of storage, as also observed by McGovern [16]. The 60 d values of 680–3500 μstrain are in line with observations from other studies [6,7,12]. As might be expected, the presence of sand reduced the relative shrinking ability of the concrete. For a given fines type, drying shrinkage strains decreased up to 70 %, with 30% replacement of PC with FA$_{fine}$, with a lower proportion of cement, and hence, with a reduced volume of shrinkable paste.

At higher densities, for the same cement content and w/cm ratio, the air is effectively replaced by fines. The shrinkage strains observed at 1200 and 1400 kg/m^3, however, were only slightly lower (down to 2000 μstrain). These trends can perhaps be attributed to changes in the microstructure, suggesting that the bubbles themselves appear to provide some degree of volume stability. However, this has not been quantified, and clearly, further work has to be carried out to determine the effect of each of the two phases (paste/mortar and air) on foamed concrete properties.

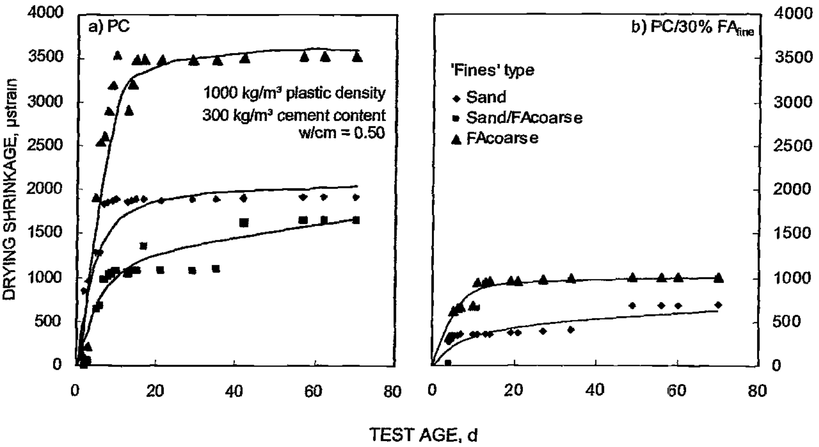

FIG. 5—*Drying shrinkage strain development of 1000 kg/m^3 PC and PC/30 % FA$_{fine}$ foamed concretes.*

Conclusions

This study has demonstrated that foamed concrete potentially can be used as Controlled Thermal Fill (CTF), for the construction of thermally insulating trench fill foundations and ground-supported slabs for housing. This could be extremely beneficial in temperate and cold climates.

Indeed, as regards suitability of the material for foundations, the compressive strengths of the PC foamed concretes with 50 % and 100 % FA_{coarse}, throughout the density range examined, were between 1 and 10 MPa (which are sufficient for this application and allow re-excavation for pipework and services), within a typical range of strengths for CLSM. The sorptivity to water of the foamed concretes with sand or 50 % FA_{coarse} were extremely low. In addition, foamed concrete was essentially unaffected by sulfate attack after 6 months exposure, with similarly good resistance to freeze/thaw attack, even in saturating conditions.

The thermal insulating capacity of foamed concrete (λ_{ind} of 0.22 W/mK with FA_{fine}), coupled with the ability to have a monolithic construction with the foundation, which minimizes risk of cold bridges, means that low elemental U-value can be achieved (e.g., for the UK requirement of 0.25 W/m^{2}K, the requirement for polystyrene insulation is three times smaller than that for normal weight concrete). The 30 % replacement of PC with FA_{fine} reduced drying shrinkage strains by up to 70 %.

The use of both fine and coarse low-lime bituminous fly ashes as PC and sand replacement materials, respectively, enhanced foamed concrete properties significantly. This was particularly so for drying shrinkage (with a 30 % FA_{fine} cement content). A partial (50 %) or full replacement of sand with FA_{coarse} fly ash improved the thermal insulating capacity of the foamed concrete. However, the simultaneous replacement of PC with FA_{fine} and sand with FA_{coarse} should be avoided for house construction applications, as this produced excessively low strengths and significantly greater sorptivity.

Overall, the proposed foundation and ground slab configuration with foamed concrete has the potential of improving cost effectiveness of housing construction in terms of time (simplified construction and enhanced productivity) and material (widely available from ready-mix plants, minimal workmanship requirements) and improved site safety. In addition, given the properties examined, there appears to be potential for use of the material in walls and slabs of basements and also in buildings on potentially contaminated (brownfield) sites.

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Section III: Pipeline Applications

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Field Demonstration Test on Construction and Strength of Flexible Pipe Drainage System Using Flowable Fill

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ABSTRACT: A team at Ohio University recently completed a research project related to flowable fill. The main objective of the project was to evaluate the feasibility of constructing an economical drainage pipe system using a flexible thermoplastic pipe and flowable fill. The project tasks were divided into three phases (laboratory characterization tests, field demonstration tests, and engineering analysis). This technical paper summarizes mainly data obtained during one of the Phase 2 field demonstration tests conducted at the load frame site, utilizing a corrugated HDPE pipe, flowable fill, and a variety of sensors. The test results confirmed many previously cited advantages of using flowable fill as pipe backfill material and also showed that some potential problems could be overcome easily. Finite element analysis simulated the field performance of the flexible pipe-flowable fill system reasonably well. In summary, it was concluded that it was quite feasible to construct a sound subsurface drainage system using flexible pipe and flowable fill.

KEYWORDS: controlled low-strength material, flowable fill, flexible pipe, field test, performance, strength, drainage pipe

Introduction

This paper reports some findings that the authors made during their research project on Controlled Low Strength Material-Controlled Density Fill (CLSM-CDF) for the Ohio Department of Transportation (ODOT). The main objective of the research project was to evaluate the feasibility of constructing an economical drainage pipe system using a flexible thermoplastic pipe and flowable fill. The project was driven by the facts that: 1) large diameter thermoplastic pipe products are used at an increasing rate to construct short-span bridges in Ohio, which has a relatively large region characterized with abrasive low-pH surface drainage flow from surface mines; and 2) CLSM has been reported to possess several advantages over conventional soil as backfill material for thermoplastic pipes. The project activities were divided into three phases — laboratory characterization of CLSM (Phase 1), field demonstration tests (Phase 2), and engineering analysis (Phase 3). Further details of the project can be found in the final report by Masada et al. [3].

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Background

It has been reported by the American Concrete Institute [1] and others [2] that CLSM possesses advantages over conventional soil as a pipe backfill material. The advantages of CLSM cited by the ACI and Brewer [1,2] are listed below:

- CLSM mix design can be adjusted so that its modulus can reach a higher level than the soil fill.
- CLSM can envelope the pipe completely and provide an ideal installation condition (i.e., perfect haunching).
- Trench width can be reduced when using CLSM because there is no need for a compactor on each side of the pipe.
- It is possible that the use of CLSM can result in less concern for worker safety during the pipe installation.
- CLSM fill can be colored for easy detection of the underground pipeline during future excavation.

Despite these advantages, the use of CLSM is still not common in most construction projects. This may be due to the fact that there are some potential concerns associated with the use of CLSM, especially in thermoplastic pipe installation projects. The concerns include pipe floatation, strength performance (initial strength gain, long-term excavatability), generation of high hydration heat, and the cost and availability of CLSM. Another reason for the lack of CLSM use in general construction work may be due to a shortage of scientific data available on the field performance of CLSM as pipe backfill. The cost and availability of CLSM also play a role in determining its popularity in many regions. In some municipalities, it is specified that CLSM be used in certain types of construction work. A comprehensive field demonstration study is needed to verify these advantages, to prove that the concerns are unfounded or can be overcome easily, and to promote CLSM use in buried pipeline construction.

Laboratory Characterization

An extensive characterization test was carried out in the laboratory to determine engineering properties of ODOT Item 613 (low strength mortar) as a function of time. Table 1 lists the three low-strength mortar mix designs addressed under Item 613. ODOT requires that the LOI (loss on ignition) be less than 3 % for fly ash.

TABLE 1—*ODOT low-strength mortar mix designs (after Item 613).*

Amount per m^3 (yd^3)	Type 1 CLSM Mix	Type 2 CLSM Mix	Type 3 CLSM Mix
Portland Cement	30 kg (50 lb)	59 kg (100 lb)	0
Class C Fly Ash	0	0	297 kg (500 lb)
Class F Fly Ash	148 kg (250 lb)	0	891 kg (1,500 lb)
Fine Aggregate	1,726 kg (2,910 lb)	1,436 kg (2,420 lb)	0
Water	297 kg (500 lb)	125 to 210 kg (210 to 300 lb)	504 kg (850 lb)
Air-Entrainment Agent	...	Yes	...

The basic material characterization test program consisted of:

- Unit weight (Standard Test Method for Unit Weight, Yield, Cement Content and Air Content of Controlled Low Strength Material; ASTM D-6023)
- Flowability test (Standard Test Method for Flow Consistency of Controlled Low Strength Material; ASTM D-6103)
- Time for hardening (Time of Setting of Concrete Mixtures by Penetration Resistance; ASTM C-403)
- Unconfined compression strength (Standard Test Method for Compressive Strength of Cylindrical Concrete Specimen; ASTM C-39)

The advanced material characterization test program consisted of:

- One-dimensional (1-D) compression test
- Direct shear test (*Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions: ASTM D-3080*)
- Triaxial compression test (*Standard Test Method for Consolidated Undrained Triaxial Compression Test for Soils; ASTM D-4767*)
- Resilient modulus test (*Method of Test for Resilient Modulus of Unbound Granular Base/Subbase Materials and Subgrade Soils; AASHTO T-294*)

Tables 2 and 3 summarize the results obtained from the laboratory test programs. The 1-D compression tests were performed using a 102 mm (4 in.) diameter mold. Axial strain was increased up to about 12 % in each test. Vertical stress levels involved in the direct shear tests were 67.6 and 101.4 kPa (9.8 and 14.7 psi). All of the mixes behaved like a dense silty sand, experiencing volume expansion prior to shearing. The triaxial compression tests were conducted under the chamber pressure of 17.2, 34.5, and 51.7 kPa (2.5, 5.0, and 7.5 psi). Some differences in the results between the direct shear and triaxial compression tests may be due to the fact that the test specimens failed in a more natural manner in the triaxial compression set-up. The resilient modulus tests were performed by subjecting each specimen to chamber pressure of 17.2, 34.5, 51.7, and 68.9kPa (2.5, 5.0, 7.5, and 10 psi). The deviatoric stress values ranged from 17.2 to 103.4 kPa (2.5 to 15 psi). Based on the laboratory test results, Type 1 mix was ruled out for the subsequent field demonstration tests.

Field Demonstration Test

One of the field demonstration tests was conducted at the ORITE load frame site between 13 July and 17 July 2000. The site was located in a plateau region and consisted of relatively stiff glacial till (CL; A-7-6), underlain by sedimentary rock. A standard 6.1 m (20 ft) length, 762 mm (30 in.) inside diameter, HDPE pipe was selected as the test pipe and instrumented with sensors (fiber optic strain gages, electrical resistance strain gages, miniature-scale vibrating-wire pressure cells, and linear potentiometers) before backfilling. The pipe wall was corrugated outside (108 mm pitch by 59 mm depth) (to develop moment of inertia) and smoothly lined inside (to increase hydraulic capacity). The hydraulic liner was only 1.5 mm (0.06 in.) thick and represented only 15 % of the wall area per unit length. Engineering properties of the test pipe and the native soil are listed later in Table 7.

TABLE 2—*Basic test results on flowable fill (laboratory study).*

		Type 1 CLSM Mix	Type 2 CLSM Mix	Type 3 CLSM Mix
Unit Weight (kN/m^3)		20.6 (131.1 pcf)	18.3 (116.8 pcf)	16.0 (101.8 pcf)
Flowability		251 mm (9.9 in.)	178 mm (7.0 in.)	340 mm (13.4 in.)
Penetration Resistance (PR) in MPa	1.4	2–3 d	Less than 1 d	Less than 1 d
	2.8	3–4 d	1–2 d	2–2.5 d
	4.1	8–9 d	2–d	7–8 d
	6.9	10–11 d	3–4 d	Never reached
Unconfined Compress. Strength (UCS) in kPa @:	2 h	NP	NP	102.0 (14.8 psi)
	1 d	NP	34.5 (5.0 psi)	NT
	2 d	20.7 (3.0 psi)	67.6 (9.8 psi)	286.1 (41.5 psi)
	4 d	66.2 (9.6 psi)	NT	306.1 (44.4 psi)
	7 d	69.6 (10.1 psi)	124.1 (18.0 psi)	NT
	14 d	94.5 (13.7 d)	NT	NT
	28 d	125.5 (18.2 psi)	237.9 (34.5 psi)	284.8 (41.3 psi)
	90 d	148.9 (21.6 psi)	242.0 (35.1 psi)	343.4 (49.8 psi)
	1 year	131.0 (19.0 psi)	244.8 (35.5 psi)	331.0 (48.0 psi)
Removability Modulus		0.67 (< 1.0) – O.K.	0.78 (< 1.0) – O.K.	0.69 (< 1.0) – O.K.

NP = Not Possible. NT = Not Taken.

TABLE 3—*Advanced test results on flowable fill (laboratory study).*

		Type 1 CLSM Mix	Type 2 CLSM Mix	Type 3 CLSM Mix
1-D Compr. M_S in MPa @:	2 h	0.5 ksi @ ε of 2 %. 1.8 ksi @ ε of 4 %. 3.3 ksi @ ε of 5 %.	0.5 ksi @ ε of 2 %. 1.1 ksi @ ε of 4 %. 1.4 ksi @ ε of 5 %.	0.1 ksi @ ε of 2 %. 0.1 ksi @ ε of 4 %. 0.8 ksi @ ε of 5 %.
	1 d	2.8 ksi @ ε of 2 %. 6.0 ksi @ ε of 4 %. 8.2 ksi @ ε of 5 %.	4.9 ksi @ ε of 2 %. 6.4 ksi @ ε of 4 %. 7.1 ksi @ ε of 5 %.	1.8 ksi @ ε of 2 %. 1.4 ksi @ ε of 4 %. 1.5 ksi @ ε of 5 %.
	2 d	3.4 ksi @ ε of 2 %. 5.9 ksi @ ε of 4 %. 8.0 ksi @ ε of 5 %.	5.5 ksi @ ε of 2 %. 9.2 ksi @ ε of 4 %. 11.0 ksi @ ε of 5 %.	1.9 ksi @ ε of 2 %. 1.7 ksi @ ε of 4 %. 1.7 ksi @ ε of 5 %.
Direct Shear Test Results @:	2 h	$\phi = 29^\circ$ $c = 0.8$ psi	$\phi = 28^\circ$ $c = 0.3$ psi	$\phi = 26^\circ$ $c = 0.0$ psi
	1 d	$\phi = 34^\circ$ $c = 4.3$ psi	$\phi = 29^\circ$ $c = 3.8$ psi	$\phi = 25^\circ$ $c = 9.8$ psi
	2 d	$\phi = 34^\circ$ $c = 3.8$ psi	$\phi = 20^\circ$ $c = 8.0$ psi	$\phi = 21^\circ$ $c = 12.$ psi
Triaxial Compr. Test Results @:	1 d	$\phi = 24^\circ$ $c = 2.8$ psi	$\phi = 21^\circ$ $c = 1.1$ psi	$\phi = 23^\circ$ $c = 2.0$ psi
	2 d	$\phi = 38^\circ$ $c = 1.3$ psi	$\phi = 38^\circ$ $c = 3.6$ psi	$\phi = 23^\circ$ $c = 3.5$ psi
	7 d	$\phi = 28^\circ$ $c = 4.8$ psi	$\phi = 36^\circ$ $c = 8.4$ psi	$\phi = 34^\circ$ $c = 4.9$ psi
Resilient Modulus M_R in MPa@:	1 d	3.6–4.8 ksi	4.5–7.0 ksi	2.3–2.5 ksi
	2 d	6.9–8.7 ksi	6.2–6.4 ksi	3.3–4.4 ksi
	7 d	7.6–8.2 ksi	7.5–8.8 ksi	3.4–4.8 ksi

NOTE: 1 psi = 6.9 kPa. 1 ksi = 6.9 MPa.

Initial Backfilling

The test pipe was backfilled up to shoulder level in ODOT Type 2 Low-Strength Mortar on 13 July 2000. The pipe was raised 15–20 cm (6–8 in.) above the trench bottom on four loose soil mounds. The trench had an average width of 1.36 m (53.7 in.) and an average depth of 1.14 m (45 in.). A styrofoam block was temporarily inserted into the gap between the pipe and the trench wall on each side of the pipe to prevent any horizontal movement. The pipe was also secured down by erecting a plywood headwall at each end and by placing four 11 kg (25 lb) sand bags on the top. The CLSM was initially relatively dry, and a small hand vibrator was utilized to help spread it further. Once the CLSM reached the springline level, additional water (40 gal) was added to increase the flowability. No signs of pipe floatation problems were observed during the Lift 1 placement work. The dryness that the bottom portion of Lift 1 had might have led to less hydrostatic uplift force and increased bonding between the CLSM and the pipe. The weight of CLSM displaced by the pipe was about 6764 kg (14 900 lb). A simple calculation can show that interface adhesion as low as 14 kPa (2 psi) developing around 33 % of the pipe circumference will be more than sufficient to keep the pipe in its position. It was also observed that CLSM flowed evenly and filled all the void spaces between the trench wall and the corrugated pipe wall. On 14 July, additional CLSM was placed to bring the top surface of the CLSM to 15 cm (6 in.) above the pipe crown. On both of these dates, the CLSM was prepared at a nearby concrete plant and delivered to the site via a standard concrete mixer truck.

Basic tests were conducted on the CLSM placed in the field. Table 4 presents a summary of these test results. Fiberoptic strain gages located on the interior pipe wall surface at the west springline registered a maximum circumferential strain of 104 microstrains. Comparisons of the test results between the laboratory and field test mixes of Type 2 CLSM (Tables 2 and 4) reveal that these two mixes possessed very different hardening and strength properties. This may be explained by the fact that the mix provided by the local supplier was mostly drier. Additional cement might have found its way into the CLSM if the interior of the mixing drum was not washed thoroughly prior to the project.

TABLE 4—*Properties of CLSM placed for field test.*

	Type 2 CLSM Lift 1	Type 2 CLSM Lift 2
Unit Weight	19.8 kN/m^3 (126.3 pcf)	NA
Flowability	102 to 203 mm (4 to 8 in.)	203 mm (8 in.)
Penetration Resistance (PR in MPa)	0.09 (13.7 psi) @ 0.5 h	0.28 (41 psi) @ 1.7 h
	0.25 (36.8 psi) @ 1.2 h	1.11 (161 psi) @ 3.5 h
	1.94 (282 psi) @ 3.5 h	6.14 (890 psi) @ 5.6 h
	10.3 (1.50 ksi) @ 14.8 h	13.38 (1.94 ksi) @ 8.1 h
	12.6 (1.83 ksi) @ 16.8 h	30.00 (4.35 ksi) @ 19.6 h
Unconfined Compress. Strength (KPa)	118.6 (17.2 psi) @ 2 d	NA
	230.3 (33.4 psi) @ 4 d	

Post-Backfilling Observations

Readings from the sensors were taken at least once a day over the four-day curing period (13–17 July) to gain insight into the pipe-CLSM interactions. Table 5 presents a summary of the field data. No strain gage readings are included here, since most of them started malfunctioning during the CLSM placement. Some observations made by the authors are:

- Placement of CLSM induced small peaking deflections to the pipe.
- Pipe deflections stabilized within 2 h after the installation work.
- CLSM placement induced only small pressure against the pipe.

- Type 2 CLSM did not generate high heat during curing. The CLSM temperature peaked at 5.5 h.
- All pressures exerted against the pipe dissipated as the CLSM hardened and cooled down.

TABLE 5—*Field performance data collected before load test.*

(a) Pipe's inside diameter changes

Stage	Stage Description	Inside Diameter Change (%):	
		Vertical	Horizontal
1	Initial condition (no CLSM), sand bags on top	0.00	0.00
2	Lift 1 placed to shoulder level, sand bags on top	+ 0.57	- 0.73
3	17 h after Lift 1 placement, sand bags on top	+ 0.30	- 0.77
4	Lift 2 placed to 6 in. above pipe, no more sand bags	+ 0.37	- 0.73
5	2 h (0.08 d) after Lift 2 placement	+ 0.47	- 0.80
6	8 h (0.33 d) after Lift 2 placement	+ 0.47	- 0.80
7	20 h (0.83 d) after Lift 2 placement	+ 0.43	- 0.83
8	44 h (1.83 d) after Lift 2 placement	+ 0.40	- 0.83
9	52 h (2.17 d) after Lift 2 placement	+ 0.40	- 0.83
10	68 h (2.83 d) after Lift 2 placement	+ 0.40	- 0.83

(b) Pressure cell readings

Stage	Pressure Cell Readings (kPa) @:					
	Crown	Invert	E. Springline	E. Trench Wall	W. Springline	W. Trench Wall
1	0.0	NA	0.0	0.0	NA	0.0
2	0.0	NA	12.1	7.0	NA	1.3
3	0.8	3.6	NA	7.9	NA	2.0
4	3.2	4.8	6.7	5.4	NA	3.4
5	3.9	5.4	6.5	3.9	NA	3.6
6	6.0	5.8	13.3	3.2	NA	6.0
7	4.3	4.0	NA	6.8	NA	11.1
8	0.0	0.0	NA	0.0	NA	0.0
9	0.0	0.0	2.2	0.0	NA	0.0
10	0.0	0.0	0.0	0.0	NA	0.0

(c) Temperature readings

Stage	Temperature Reading (°C) @:					
	Crown	Invert	E. Springline	E. Trench Wall	W. Springline	W. Trench Wall
1	(28.4)	28.5	27.0	27.9	27.7	30.1
2	(36.5)	32.7	34.8	30.2	27.9	30.8
3	(29.7)	29.2	28.5	27.4	26.9	30.5
4	29.5	28.9	29.3	27.1	26.3	29.9
5	29.6	28.9	30.7	27.2	27.0	29.5
6	29.7	28.8	34.1	28.1	26.3	29.2
7	29.0	28.0	27.2	28.7	24.8	29.2
8	26.6	25.8	24.3	26.5	23.5	27.4
9	26.3	25.6	27.3	25.7	24.6	26.8
10	25.6	24.8	24.5	25.5	23.3	26.1

NOTE: Readings in parentheses = temperature of pipe surface and 1 kPa = 0.145 psi.

Performance Under External Loading

Surface load was applied by pressing two large hydraulic cylinders against a semi-rigid plate placed over the buried test pipe. The plate had dimensions of 2.4 m (8 ft) width by 3.7 m (12 ft) length. The hydraulic pressure in the cylinders was increased in increments, with each increment lasting for 15 min. to collect three sets of sensor readings. Table 6 summarizes the pipe performance data obtained during the load test. The symbols "HP" and "ASP" in the table are abbreviations for the hydraulic pressure and the average surface pressure. Deflections remained relatively small until the ninth load increment. Although the data is somewhat limited, the lateral pressure exerted to the trench wall ranged between 20 % and 30 % of the lateral pressure measured at the pipe springline.

TABLE 6—*Field performance data collected under incremental surface loading.*

(a) Pipe inside diameter changes

Load No.	Load Increment Description	Inside Diameter Change (%):	
		Vertical	Horizontal
1	HP = 1.79 MPa (260 psi); ASP = 38.6 kPa (5.6 psi)	- 0.17	+ 0.10
2	HP = 2.76 MPa (400 psi); ASP = 61.4 kPa (8.9 psi)	- 0.60	+ 0.30
3	HP = 4.14 MPa (600 psi); ASP = 92.4 kPa (13.4 psi)	- 0.86	+ 0.61
4	HP = 5.52 MPa (800 psi); ASP = 122.7 kPa (17.8 psi)	- 1.36	+ 0.97
5	HP = 6.90 MPa (1,000 psi); ASP = 153.8 kPa (22.3 psi)	- 1.83	+ 1.31
6	HP = 8.27 MPa (1,200 psi); ASP = 184.1 kPa (26.7 psi)	- 2.39	+ 1.68
7	HP = 9.65 MPa (1,400 psi); ASP = 215.1 kPa (31.2 psi)	- 3.02	+ 2.08
8	HP = 11.03 MPa (1,600 psi); ASP = 245.5 kPa (35.6 psi)	- 3.49	+ 2.35
9	HP = 12.41 MPa (1,800 psi); ASP = 276.5 kPa (40.1 psi)	- 4.32	+ 2.79
10	HP = 13.79 MPa (2,000 psi); ASP = 306.8 kPa (44.5 psi)	- 5.28	+ 3.33
11	HP = 15.17 MPa (2,200 psi); ASP = 337.9 kPa (49.0 psi)	- 6.31	+ 3.93
12	HP = 16.55 MPa (2,400 psi); ASP = 368.2 kPa (53.4 psi)	- 8.50	+ 5.18
13	HP = 17.93 MPa (2,600 psi); ASP = 399.9 kPa (58.0 psi)	- 10.7	+ 6.32

(b) Pressure cell readings

Load No.	Pressure Cell Reading (kPa) @:					
	Crown	Invert	E. Springline	E. Trench Wall	W. Springline	W. Trench Wall
1	17.9	13.1	10.3	1.4	NA	9.0
2	22.8	20.7	15.9	1.4	NA	14.5
3	37.2	20.7	25.5	6.2	NA	17.9
4	51.0	46.9	41.4	10.3	NA	21.4
5	61.4	56.5	60.7	15.9	NA	24.8
6	74.5	66.9	97.2	24.8	NA	26.9
7	93.1	81.4	146.9	35.9	NA	28.3
8	104.1	90.3	173.1	42.1	NA	29.0
9	122.0	108.3	220.0	53.1	NA	30.3
10	130.3	129.6	275.8	72.4	NA	35.9
11	138.6	155.8	333.0	84.1	NA	43.4
12	142.0	208.2	396.5	101.4	NA	61.4
13	138.6	251.0	410.3	120.0	NA	70.3

During the eighth load increment, mild longitudinal bending of the pipe was observed. During the ninth load increment, mild dimples appeared in the checkerboard pattern on the pipe wall in the springline region. These dimples were not a major concern, since they indicated localized buckling of the thin hydraulic liner only. During the twelfth load increment, a bulging was detected in the west haunch area. The curvatures in the crown and invert regions became increasingly flatter. Figure 1 shows pictures taken inside the pipe immediately after unloading the pipe.

The authors tested the same HDPE pipe product previously at the load frame site, using granular soil as the backfill material. Comparisons of the pipe performance data between the two tests show that structural responses of the flexible pipe installed in hardened CLSM were much less than those of the same pipe installed in a granular soil, as long as the stress levels in the CLSM remained below its ultimate strength. Structural performance of the HDPE pipe installed in the granular backfill can be found in the report by Sargand et al. [5].

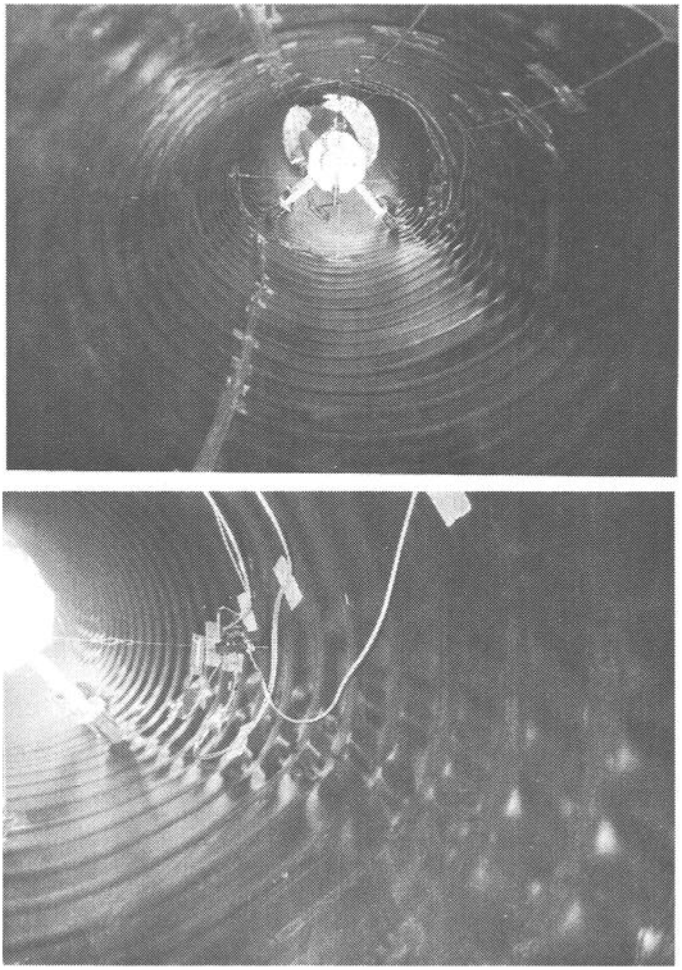

FIG. 1—*Pictures taken inside test pipe at end of load test.*

Post-Test Examinations

Excavatability of the CLSM was examined on 12 January 2001 (six months after the placement). Manual excavation by a hand shovel only scratched the surface. However, a large hoe (Caterpillar 322L) had no problem digging through the hardened material. This was predicted by the relatively low removability modulus value associated with this class of CLSM (see Table 2).

Analysis

CANDE-89 was utilized to conduct a computer simulation of the field demonstration test. A half-mesh containing 18 two-node beam elements (for the pipe) and 96 four-node quadrilateral elements (for CLSM, in-situ soil, and loading plate) was used in the analysis. No interface elements were incorporated at the pipe/CLSM interface, assuming good bonding of CLSM to the pipe. The loading was applied to the loading plate in 68.95 kPa (10 psi) increments. Table 7 lists the values of input parameters specified for the analysis. Figures 2 and 3 present the analytical results.

According to these plots, the pipe deflections predicted by CANDE were about 0.5 to 1 % larger in magnitude than the actual field deflections. The shape of the deflection curves was similar between the CANDE predictions and field measurements. The crown pressure was predicted reasonably closely by CANDE. The fact that CANDE underestimated the springline pressure may suggest that there was a loose zone at the CLSM - trench wall interface. Further examination of the CANDE output indicated that the springline region was the most critical region in terms of bending and thrust actions in the pipe wall. CANDE also printed out safety factors against three potential failure modes (excessive deflections, wall crushing, and wall buckling). This diagnosis showed that the pipe had a far less chance of failing in wall buckling than in excessive deflection or wall crushing.

Economic analysis was also made to examine cost-effectiveness of the use of CLSM over the use of conventional granular soil backfill in the construction of a subsurface drainage pipe system. The cost analysis was broken down into four categories: backfill material cost, delivery cost, labor cost (during pipe installation), and cost associated with quality control (QC) tests. Material cost of CLSM generally tends to be 2.5–3 times higher than that of granular soil. However, the volume of material needed can be less for CLSM due to a narrower trench width. In case of the test pipe involved in the current study, the volume of CLSM was about 67 % of the volume of granular soil. Backfilling process with granular soil is more labor-intensive, since the granular soil must be compacted in 20 cm (8 in.) lifts to a designated minimum dry unit weight. Moist unit weight and moisture content of the granular backfill must be measured after compacting each lift. This fact implies that granular soil option requires more QC tests during construction. The economic competitiveness of the CLSM option is expected to increase as the diameter becomes larger. More details of the economic analysis can be found in the report by Sargand et al. [5].

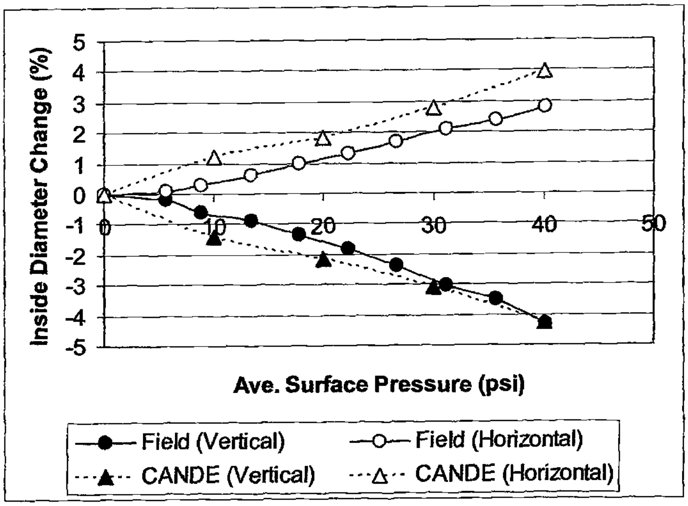

FIG. 2—*Deflections of test pipe predicted by CANDE-89. (1 psi = 6.895 kPa.)*

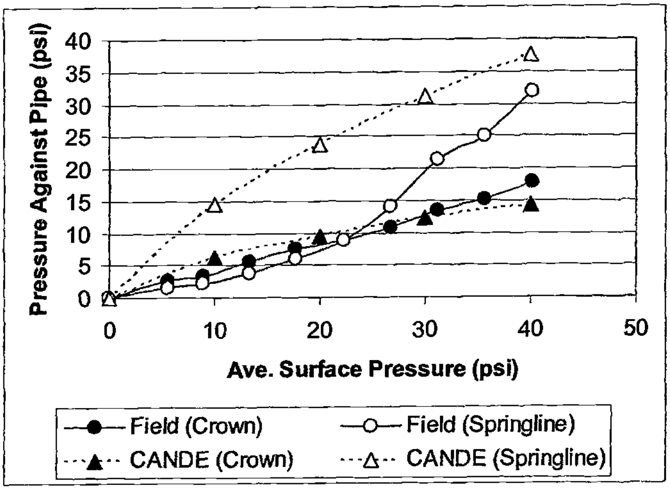

FIG. 3—*Pressure against test pipe predicted by CANDE-89. (1 psi = 6.895 kPa.)*

TABLE 7—*Detailed information for finite element analysis.*

(a) Input parameter values for test pipe

Nominal Diameter (D) in mm		762 (30.0 in.)
Pipe Wall	Thickness (t) in mm	41.1 (1.62 in.)
	Area (A) in mm^2/mm	41.1 (1.62 $in^2/in.$)
	Moment of Inertia (I) in mm^4/mm	5,768 (0.352 $in^4/in.$)
Elastic Modulus (E_P) in MPa		566 (82.1 ksi)
Poisson's Ratio (μ)		0.325
Yield Strength (σ_y) in MPa		10.7 (1.6 ksi)

(b) Input parameter values for other materials

		In-Situ Soil (CL)	Type 2 CLSM	Loading Plate
Material Type		CL-95	Type 2 CLSM	Steel
Elastic Modulus (kPa)		...	...	2E+8
Poisson's Ratio		...	...	0.3
Parameters	K	120	973	...
	n	0.45	0.47	...
Cohesion c (kPa)		62.1	57.9	...
Friction	ϕ_o (deg.)	15.0	33.5	...
Angle	$\Delta\phi$ (deg.)	4.0	9.4	...
Initial Bulk Modulus (normalized) Bi/Pa		21.2	74.8	...
Ultimate Volumetric Strain ε_u		0.13	0.02	...

Conclusions

Many conclusions can be drawn from the project. The potential for pipe floatation diminished when a few "common sense" measures were taken in the field. CLSM fill did not generate high hydration heat during the placement and curing stages. Backfilling with CLSM induced minimum deflections and strains to the flexible pipe. Pressure that developed initially around the pipe dissipated as the CLSM fill cooled down and hardened. It was somewhat difficult to produce consistent CLSM mixture between the laboratory and the commercial plant. Structural responses of the flexible pipe installed in hardened CLSM were much less than those of the same pipe installed in a granular soil, as long as the stress levels in the CLSM remained below its ultimate strength. Removability of CLSM by the standard construction equipment was found to be good six months after the placement. The finite element analysis had a reasonable success in simulating the field behavior of the flexible pipe installed shallowly in CLSM. The analysis showed that the springline region was the most critical region in terms of bending and thrust actions in the pipe wall. It also showed that the ring deflection would be the most limiting performance factor under the test condition. Overall, the study results showed that it was quite feasible to construct a structurally sound, cost-effective subsurface drainage system using flexible pipe and flowable fill.

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Freeze-Thaw Effects and Gas Permeability of Utility Line Backfill

ABSTRACT: Backfill materials used in utility trenches must maintain physical and mechanical integrity when subjected to the seasonal effects of freezing and thawing. Materials used over gas utility lines must also have adequate permeability to allow any leaking gas to flow upward and out. To help determine how soils and flowable fills might perform as backfill over utility lines, we conducted laboratory tests to measure the permeability of backfill materials before freezing, during freezing, and after thawing. The two materials investigated in this study were a silty sand, and a flowable fill made with Type F fly ash. Our work also examined the susceptibility of these materials to frost heave and thaw weakening. An apparatus and standard test method for performing permeability during freezing and after subsequent thawing did not exist. We developed a method by adapting the ASTM Standard Test Method for Frost Heave and Thaw Weakening Susceptibility of Soils (D 5918) and the ASTM Standard Test Method for Measurement of Pneumatic Permeability of Partially Saturated Porous Materials by Flowing Air (D 6539). Although more data are needed to confirm specific conclusions determined from this study, the test method developed here appears to be useful for evaluating the effects of freeze-thaw on backfill materials for utility trenches. Additional work is needed to demonstrate whether these laboratory results correspond to actual field conditions.

KEYWORDS: fly ash, gas permeability, freeze-thaw, utility lines, backfill, controlled low-strength material (CLSM), flowable fill

Background and Objectives

The objectives of this experimental program were to evaluate the freeze-thaw weakening and frost heave of backfills typically used as utility trench backfill, and to determine changes in their gas permeability during the freezing process.

The backfill material must maintain physical and mechanical integrity when subjected to the seasonal effects of freezing and thawing. For use over gas utility pipes, backfill must also have adequate permeability to minimize uncontrolled lateral flow of gas and to permit leaking gas to flow upward and out of the trench so that leaks can be located quickly.

The susceptibility of a soil to frost heave and freeze-thaw weakening can be evaluated in the laboratory using the ASTM Standard Test Method for Frost Heave and Thaw Weakening Susceptibility of Soils (D 5918). In this test, a soil specimen of 5.75-in. (14.6 cm) diameter and 6-in. (15.2 cm) height is subjected to two freeze-thaw cycles using specified temperatures and vertical heat flow. Temperature at points along the specimen height, as well as vertical deformation of the specimen, are monitored over time. At the end of the second thawing cycle,

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the bearing strength of the specimen is evaluated by ASTM Standard Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils (D 1883).

The effect of freeze-thaw cycles on the mechanical properties of flowable materials has not been well documented or studied. The ASTM Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing (C 666) has been used commonly to evaluate flowable fills; however, this method is an indirect measure of durability that is difficult to use in performance prediction. Some researchers have modified the ASTM C 666 method to attempt to better simulate actual field freezing conditions on flowable fill by forcing freezing and thawing to occur from the top only and at a much slower rate than the one specified in ASTM C 666. Results using this test method on flowable fill have shown that the dynamic modulus of elasticity (E) declined with additional cycles of freezing and thawing [1]. Such loss of durability was mainly attributed to the excessive pore water pressure developed in the saturated samples during freezing [1].

Unconfined compression tests on unsoaked specimens of flowable fill that had been subjected to various freeze-thaw cycles showed strength loss from freeze-thaw effects [2]. However, Stewart concluded that the testing conditions did not realistically represent those experienced by flowable fill in the field [2].

For this study, we adopted ASTM D 5918 because it was developed specifically for soils used in pavement systems. The method consists of placing a surcharge weight on top of the specimen to simulate the overlying pavement. Cooling/heating plates on both the top and bottom of the specimen produce freezing and then thawing from the top of the specimen down. Specimens are subjected to two freeze-thaw cycles. The amount of heave and the penetration of frost into the specimen are measured. CBR, a common strength-index of roadway materials, is also measured without freeze-thaw and after the test to provide an indication of the degree to which freeze-thaw weakened the material.

Scope of Work

The materials selected for evaluation included a silty sand and a flowable fill mix containing Type F fly ash. The silty sand is typical of indigenous soils that might be found in the New England area. The flowable fill was targeted to meet Massachusetts Highway Department (MHD) specifications.

In order to meet our objectives, we needed to subject the materials to freeze-thaw cycles while measuring gas permeability at specific times during the test. An apparatus and standard method for doing this did not exist. We developed a method by combining and adapting ASTM D 5918 and the ASTM Standard Test Method for Measurement of Pneumatic Permeability of Partially Saturated Porous Materials by Flowing Air (D 6539) into one method. ASTM D 5918 provides a comparative measure of frost heave and thaw weakening susceptibility of a material subjected to freeze-thaw cycles. Although it does not predict specifically how a material will perform in the field, this method provides a basis for comparison as well as a classification of a material that can be used in pavement design methods. ASTM D 6539 was specifically developed to measure the coefficient of gas permeability for unsaturated porous media such as materials used as backfill in utility trenches.

In this study, permeability tests were conducted on the trench backfill materials at ambient temperatures (e.g., 20°C) prior to freeze-thaw cycling, at sub-zero temperatures (e.g., –5°C) during the freeze cycle, and at ambient temperatures (e.g., 20°C) after freeze-thaw cycling.

Test Apparatus

ASTM D 5918 uses a 5.75 in. (14.6 cm) inner-diameter, 6 in. (15.2 cm) high specimen encased with a rubber membrane that is surrounded by six 1 in. (2.54 cm) high acrylic rings (See Fig. 1). Each acrylic ring contains a hole at its mid-height for insertion of a temperature probe. The top and bottom-most rings contain additional holes at the extreme top and bottom so probes can be placed at the ends of the specimen. A total of eight temperature probes are positioned vertically from top to bottom of the specimen. Liquid silicone rubber is used to form an impermeable seal between the probes and rubber membrane. A porous metal plate is placed on the bottom of the specimen and another on the top. For cases where the specimen is to be tested in a saturated condition, one port on the bottom porous plate is connected to a water source (a Mariotte bottle). A heat transfer plate is placed outside of each porous plate. Each heat transfer plate is connected to a controlled temperature bath that circulates an ethylene-glycol-water mixture at specified temperatures. A 5.5 kg surcharge intended to simulate a 6 in. (15.2 cm) thick pavement is placed on the top plate. A displacement transducer is located directly on top of the surcharge weight. The entire sample cell is contained within a temperature control chamber that maintains the ambient air temperature around the cell to within 2°C. The entire cell within the temperature control chamber is surrounded by vermiculite to insulate the system. Data generated from the temperature probes and displacement transducer are recorded by GeoComp data loggers.

ASTM D 6539 describes a permeameter cell consisting of a set-up similar to the freeze/thaw apparatus. The specimen is encased in a rubber membrane with porous plates connected to the top and bottom of the sample. (See Fig. 2.) Ports on the bottom plate lead to a desiccant tube, which vents to the atmosphere. The desiccant removes moisture from the gas before it enters the flow meter. Each plate has two directly opposing ports: one for gas flow, and the other for monitoring pressure. The cell required by ASTM D 5918 for freeze-thaw prevents application of a confining pressure. Consequently, applying positive gas pressure to create flow and measure permeability is not possible in the ASTM D 5918 test chamber. The positive internal gas pressure would separate the membrane from the specimen and produce short circuit flow of gas outside the specimen. However, the ASTM D 6539 test could be performed by using a vacuum to create a differential pressure in the specimen at less than atmospheric pressure. This presses the membrane tight against the specimen and prevents short circuit flow. The vacuum, equal to ($H\gamma_W$-P_a), is created in a large sealed reservoir with an adjustable Mariotte tube. The Mariotte bottle is connected to the top porous plate. The bottom is open to atmospheric pressure. The pressure difference of $H\gamma_W$ causes gas to flow upward through the sample and into the reservoir. Gas flow into the reservoir is automatically compensated by water flow out of the reservoir. The pressure difference stays constant. The displaced water from the reservoir is measured to determine gas flow rates. Different vacuums and thus gas flow rates are applied by adjusting the height of the tip of the Mariotte tube. Figure 3 shows the actual test cell. Figure 4 shows the complete gas permeability—freeze/thaw test apparatus.

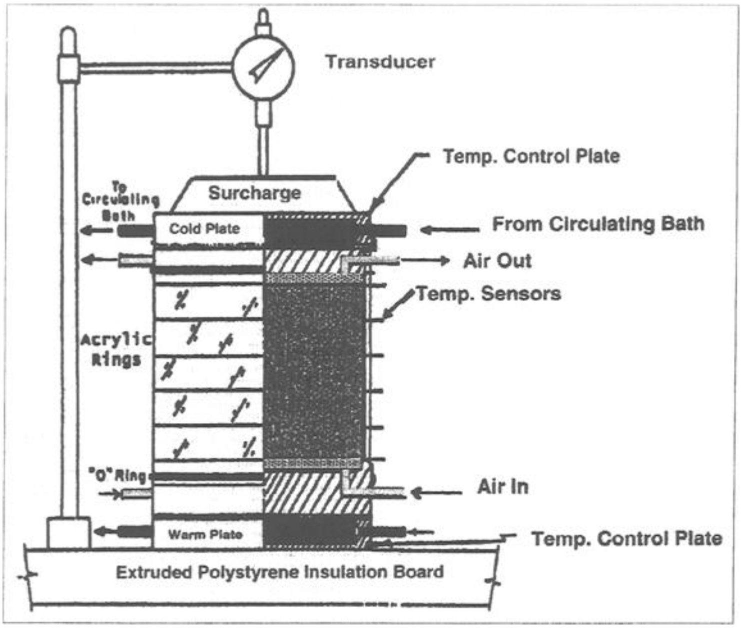

FIG. 1—*Freeze-thaw test cell (adapted from ASTM D 5918).*

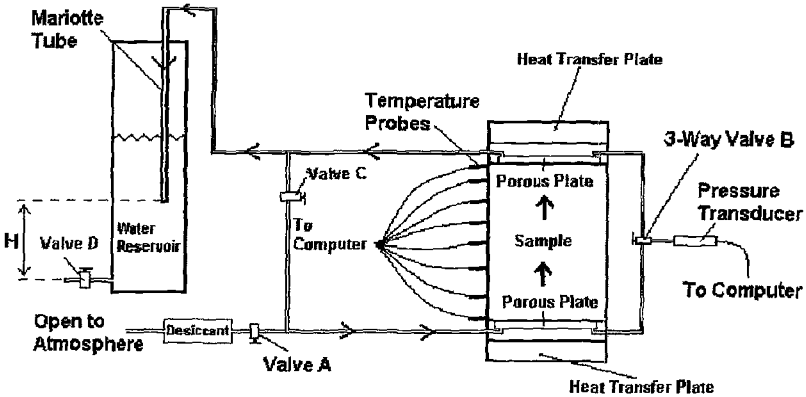

FIG. 2—*Schematic of freeze-thaw/gas permeability test apparatus.*

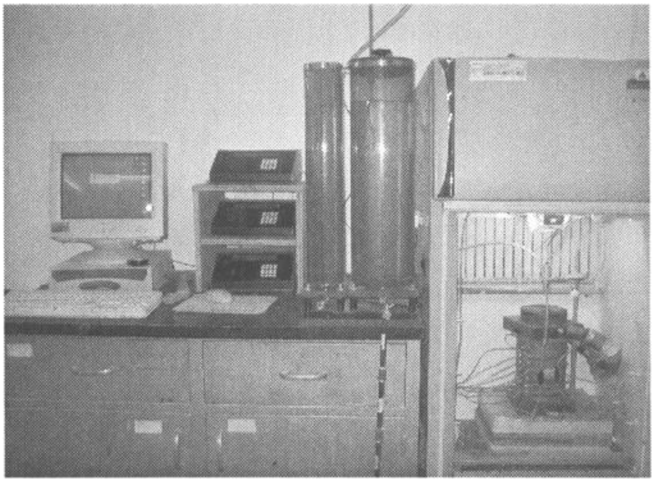

FIG. 3—*Actual freeze-thaw/gas permeability test cell.*

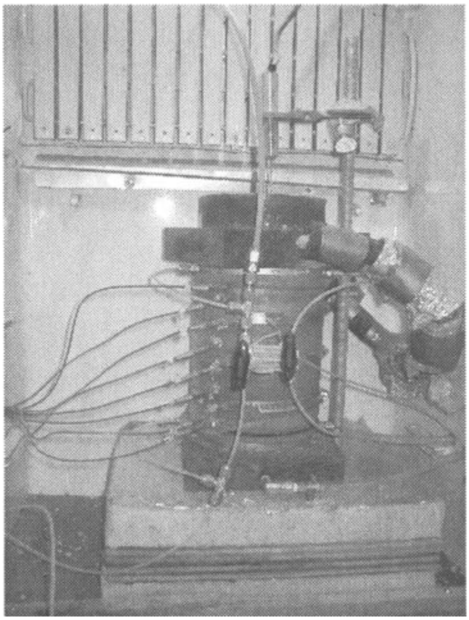

FIG. 4—*Entire freeze-thaw/gas permeability test apparatus.*

Materials

The silty sand was selected because it is typical of indigenous soils that might be found in the New England area and therefore used as a trench backfill. Results from tests on this soil will be compared with results on the flowable fill mix to obtain a relative comparison of material performance. As shown in Table 1, the silty sand has properties that classify it as an AASHTO A-4 type soil.

The flowable fill mix was made with Type F fly ash and designed to meet Massachusetts Highway Department specifications for a mix classified as "Type 2E". Table 2 summarizes the mix design and mix properties. Flowable fill samples were cured in a high humidity environment.

TABLE 1—*Silty sand properties.*

Sieve Size/Parameter	Silty Sand (% Passing)	AASHTO A-4 Classification Criteria (% Passing)
3/8 in (9.5 mm)	...	...
No. 4	100	...
No. 8	89	...
No. 10	...	...
No. 16	81	...
No. 20	...	...
No. 30	73	...
No. 40	...	...
No. 50	67	...
No. 60	...	...
No. 100	58	...
No. 200	47	36 minimum
Plasticity Index, %	Non-Plastic	10 maximum
Optimum Moisture, %	15.1	...
Max. Density, PCF (N/m^3)	114.2 (17.9)	...

TABLE 2—*Fly ash flowable fill properties.*

Material/Property	Fly Ash Flowable Fill Mix lb/yd^3 (kN/m^3)	MHD Type 1E & 2E Specification (M4.08.0)
Cement	56 (0.33)	...
Sand	2871 (16.71)	...
Water	510 (2.97)	...
Fly Ash	276 (1.61)	...
Entraining Agent, oz/yd^3	0	...
Air, %	0.6	...
Flow, in. (cm)	10.5 (26.7)	9–14 (22.9–35.6)
Unit Weight of Fresh Mix, pcf (kN/m^3)	145 (22.8)	...
Compressive Strength, psi (Pa):		
7 d	30 (207)	...
28 d	52 (359)	30–80 (207–552)
56 d	...	...
90 d	67 (462)	30–100 (207–689)
135 d	...	...

... = not measured or specified.

Test Specimen Preparation

A 6 in. (15.2 cm) inner-diameter steel mold was used for compaction of the silty sand. Prior to placing the soil in the mold, the six acrylic rings were placed inside the steel mold, with a rubber membrane placed on the inside of the rings. The soil was compacted inside the rubber membrane to the required density at the optimum moisture content. The resulting outer diameter of the compacted specimen was 5.75 in. (14.6 cm), with a height of 6 in. (15.2 cm). The steel mold was fabricated to split in half to allow it to be removed. The compacted specimen inside the acrylic rings and membrane was placed into the freeze-thaw/gas-permeability set-up.

The flowable fill mixture was poured into a 5.75 in. (14.6 cm) inner diameter mold, 6 in. (15.2 cm) high. This mold was constructed of a single, 5.75 in. (14.6 cm) inner-diameter, 6 in. (15.2 cm) high acrylic tube which had been split vertically on one side to allow for easy sample removal after curing. No rubber membrane was placed on the inside of the acrylic tube. The acrylic tube was placed on the inside of a standard plastic concrete mold that had also been split down one side and taped to hold the mold together during curing. After pouring fresh flowable fill mix into the mold, the material was allowed to cure for about 1 week in a high humidity chamber. Then the mold was removed and the sample was cured with all sides exposed to a high humidity environment. After the requisite amount of curing time (e.g., 28 d) the sample was tested for gas permeability and freeze-thaw.

Test Procedure

System Check

Prior to all permeability tests, a system check was run to ensure a gastight (closed) system (See Fig. 2). Valve C was opened, valve A was closed, and valve D was opened to allow water to flow from the reservoir. The water flowing out of the reservoir induced a vacuum to the system. Valve D was then closed, and the pressure of the system was monitored at valve B. (Valve B is a 3-way valve allowing measurement of pressures at both the top and bottom of the specimen with one transducer.) If the pressure (vacuum) of the system stays constant over time, the system is considered gastight (closed).

Gas Permeability

For each specimen, data were collected at six different vacuum pressures. The different pressures were produced by varying the height of the Mariotte tube, hence changing the head of water that gravity was acting upon. For each test, the pressure transducer offset was adjusted by current atmospheric pressure such that true pressure differences across the specimen could be determined. Permeability data were taken by closing valve C, opening valve A, and opening valve D to allow water to flow from the reservoir and induce a vacuum in the system. The vacuum in turn creates a pressure difference across the specimen that induces flow of gas through the specimen from bottom to top. Placing valve B in the up position allowed the monitoring of the pressure at the top of the sample. Once the pressure reached equilibrium, pressures were recorded at the top and bottom of the specimen. Concurrent with pressure readings, the volumetric flow rate was recorded by collecting the water displaced from the reservoir over a measured period of time. The weight of water was then converted to the corresponding volume of gas that had flowed through the specimen.

The pressure and flow data are used to calculate the volumetric flow rate (at average pressure and temperature) as follows:

$$Q_{AV} = (Q * P_B)/(P_I + P_B - (\Delta P/2)) \qquad (1)$$

where,

Q_{AV} = volumetric flow rate at average pressure and temperature, m^3/s
Q = exit flow rate of gas, m^3/s
P_B = barometric pressure, Pascals
P_I = specimen inlet gage pressure, Pascals
ΔP = specimen pressure drop, Pascals

To satisfy Darcy's Law, the gas flow rate must be linearly related to the pressure difference across the specimen. ASTM D 6539 requires that measured data fall within ± 25 % of the slope of a best-fit line passing through the origin. Due to the large differences in flow and ΔP, the data are plotted on a log-log plot (Fig. 5).

The average gas permeability was then calculated in units of Darcy or square meters, as follows:

$$K_p = (Q_{AV} * \mu * L * 1.013 \times 10^{12})/(\Delta P * A) \qquad (2)$$

where,

K_p = average gas permeability, Darcy or m^2
Q_{AV} = volumetric flow of gas through the specimen, m^3/s
ΔP = pressure difference across specimen, Pascals
L = specimen length, m
A = specimen cross-sectional area, m^2
μ = viscosity of gas at test temperature, Pascal-seconds

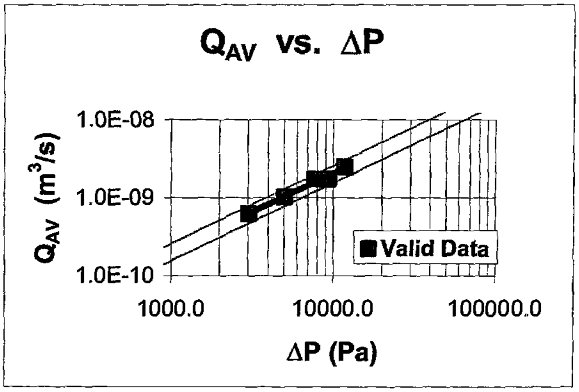

FIG. 5—*Log-log plot of volumetric flow rate vs. differential pressure.*

Testing Samples

Unsaturated Condition—Prior to initiating freeze-thaw, specimens were tested for gas permeability. After permeability testing, the freeze-thaw test was begun. The freeze-thaw test

(ASTM D 5918) consists of cooling and warming the top and bottom heat transfer plates to the temperatures given in Table 3, while measuring frost penetration and heave of specimen. ASTM D 5918 requires the specimen to be subjected to two freeze-thaw cycles. After approximately one-half hour into each freeze cycle, nucleation at the top of the specimen is initiated by tapping the surcharge weight. This prevents the water in the sample from super-cooling. The idea is to freeze the specimen from the top down, to realistically simulate field conditions.

TABLE 3—*Boundary temperature conditions (from ASTM D 5918).*

Day	Elapsed Time (h)	Top Plate Temperature (°C)	Bottom Plate Temperature (°C)	Comments
1	0	3	3	24 h Conditioning
2	24	-3	3	First 8 h freeze
	32	-12	0	Freeze to bottom
3	48	12	3	First thaw
	64	3	3	
4	72	-3	3	Second 8 h freeze
	80	-12	0	Freeze to bottom
5	96	12	3	Second thaw
	112	3	3	
	120	Room	Room	End Test

Gas permeability was measured both in the frozen state at the end of the second freeze cycle and in the fully thawed state after the specimen had undergone the two freeze-thaw cycles. The displacement transducer, surcharge weight, temperature probes, etc. were removed from the cell. The specimen was then tested for CBR to provide an index of strength. A surrogate sample that had not been subjected to freeze-thaw cycling was also tested for CBR. Specimens were not soaked prior to conducting CBR. After running CBR on the freeze-thaw specimen, moisture contents were determined for 1 in. (2.54 cm) thick slices of the specimen from top to bottom. An example of typical results is plotted in Fig. 6. Assuming the moisture distribution through the specimen prior to freeze-thaw testing is constant (e.g., 15.1 % for sample in Fig. 6), this presentation provides an indication of moisture movement occurring as a result of freezing and thawing.

ASTM D 5918 suggests the amount of heave should be plotted versus time and examined in conjunction with a plot of frost penetration (Fig. 7). It is helpful to view the plots in conjunction with the boundary temperature settings of the cooling/heating plates (Table 3). The top plot shows that during the 24 h conditioning period at 3°C, there is no heave of the sample, and the bottom plot shows that there is no frost penetration. However, once the top plate goes to -3°C, the sample heaves (top plot), and the frost penetrates the sample down to about 60 mm from the top (bottom plot). Once the top plate is set at -12°C, the frost penetration goes almost immediately through the entire 160 mm (6 in.) of the specimen (bottom plot), and the specimen heaves at a high rate up to a maximum height (top plot). When the top plate is then set at 12°C and the bottom plate it set at 3°C, the heave of the sample is almost immediately relaxed (top plot), and at about 48 h, the sample begins to thaw at both the top and bottom of the specimen (bottom plot). The specimen remains frozen at the middle of the specimen (~100 mm from the surface) until about 55 h into the test (bottom plot). After about 20 h of thawing, the second freeze cycle is initiated. According to ASTM D 5918, the heave rate from the second cycle, as well as CBR results after two freeze-thaw cycles, are compared with the values in Table 4 to classify the materials' susceptibility to frost heave and thaw weakening.

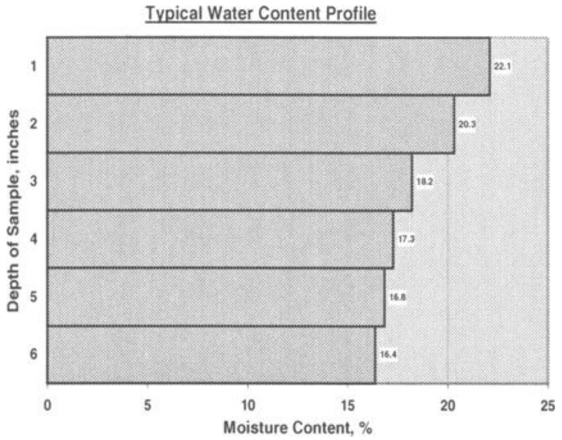

FIG. 6—*Typical water content profile of specimen after freeze-thaw cycling.*

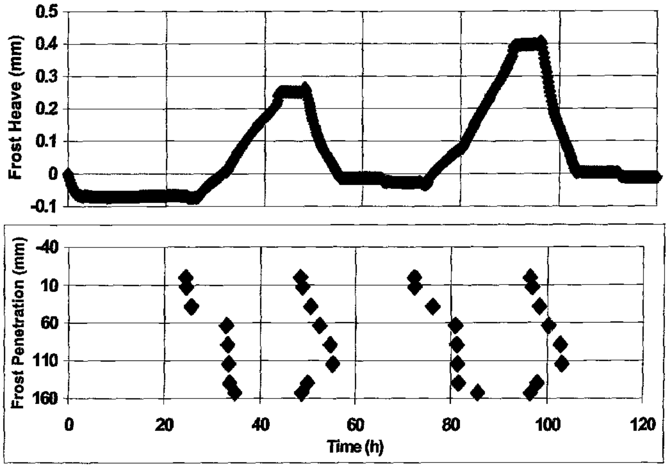

FIG. 7—*Frost heave vs. frost penetration over freeze-thaw cycles.*

TABLE 4—*ASTM D 5918 classification table for freeze-thaw results.*

Susceptibility Classification	Heave Rate mm/d	Thaw CBR %
Negligible	<1	>20
Very Low	1–2	20–15
Low	2–4	15–10
Medium	4–8	10–5
High	8–16	5–2
Very High	>16	<2

Saturated Condition—ASTM D 5918 suggests testing specimens in a saturated condition if the material is likely to be used in a high water-table area. Saturation of the specimen is accomplished by connecting the water outflow tube from the Mariotte bottle to one of the ports on the bottom porous plate (with the other port plugged). The water head is then raised at a rate of 25-mm per h (by setting the Mariotte tube) until standing water is visible on the upper surface of the sample or until 8 h have passed. The water supply head is then lowered to the level of the upper surface of the specimen and held for 16 h. Then the water supply is lowered to 10 mm above the bottom of the sample, and the upper porous plate is secured into place. The specimen is then subjected to the same freeze-thaw cycling described previously, with the Mariotte water supply remaining in place and open to provide a continuous supply of water to the specimen.

When gas permeability tests were attempted on the specimens before and after freeze-thaw cycles, water flowed out of the specimens. This indicates essentially zero gas permeability.

In order to measure gas permeability of the sample when the saturated specimen is in the frozen state, the top and bottom porous plates must be carefully removed and dried. To avoid disrupting temperature probes and thus losing subsequent thaw data, the gas permeability was measured during an additional (third) freeze cycle.

Results and Discussion

Silty Sand

Results of the silty sand are shown in Table 5.

Heave Rate—Testing the silty sand under saturated conditions resulted in a doubling of the heave rate from unsaturated conditions.

Thaw Weakening—The unsaturated silty sand maintained its CBR-strength after freeze-thaw cycling. According to ASTM D 5918 (see Table 4), the thaw-weakening classification of this material was 'very low'. For the sample tested under saturated conditions, there was a significant change in CBR resulting from freeze-thaw cycling. The CBR before freezing was 18 % and after freezing and thawing was 1 %. The thaw-weakening classification of this material in the saturated condition was subsequently "very high".

Permeability—The permeability of the silty sand tested under unsaturated conditions increased one (1) order of magnitude from pre-freeze-thaw values when subjected to freezing temperatures. Once thawed, the permeability decreased to about ½ order of magnitude below the value prior to the freeze-thaw test. Silty sand tested under saturated conditions did not have measurable permeabilities.

Fly Ash Flowable Fill

Results of the fly ash flowable fill are shown in Table 6.

Heave Rate—The heave rate for the fly ash flowable fill was negligible for both saturated and unsaturated conditions.

Thaw Weakening—According to ASTM D 5918 (see Table 4), the fly ash flowable fill tested under unsaturated conditions is classified as having 'negligible' thaw-weakening susceptibility. Saturation lowered the CBR-strength by over a factor of two (from 40 % to 17 %), resulting in a thaw-weakening susceptibility classification of "very low".

Permeability—Permeabilities of the fly ash mix tested in the unsaturated condition decreased about one (1) order of magnitude when subjected to sub-zero temperatures, but returned to original values once thawed. The fly ash mix tested at above freezing temperatures under saturated conditions did not have measurable permeabilities. However upon freezing, the permeability increased into the 10^{-15} m^2 range.

TABLE 5—*Freeze-thaw and gas permeability results for silty sand.*

Property	Silty Sand Unsaturated	Silty Sand Saturated
Frost Heave Susceptibility		
2nd Heave Rate (mm/d)	4.40	9.50
Frost Heave Susceptibility	Medium	High
Thaw-Weakening Susceptibility		
CBR Before Freeze/Thaw (%)	11	18
CBR After Freeze/Thaw (%)	16	1
Thaw-Weakening Susceptibility	Very Low	Very High
Gas Permeability Results		
Pre-Freeze/Thaw (m^2)	1.5×10^{-14}	**
During Freeze/Thaw (m^2)	1.6×10^{-13}	***
Post-Freeze/Thaw (m^2)	6.4×10^{-15}	**

**Sample became fully saturated through the entire height of sample. When gas permeability test was attempted, significant internal transport of pore water was induced such that water was drawn into the permeameter tubing.

***Flow was less than system capability.

TABLE 6—*Freeze-thaw and gas permeability results for fly ash flowable fill.*

Property	Fly Ash Flowable Fill Unsaturated	Fly Ash Flowable Fill Saturated
Frost Heave Susceptibility		
2nd Heave Rate (mm/d)	0.36	0.47
Frost Heave Susceptibility	Negligible	Negligible
Thaw-Weakening Susceptibility		
CBR Before Freeze/Thaw (%)	42	23
CBR After Freeze/Thaw (%)	40	17^
Thaw-Weakening Susceptibility	Negligible	Very Low
Gas Permeability Results		
Pre-Freeze/Thaw (m^2)	6.4×10^{-16}	**
During Freeze/Thaw (m^2)	3.1×10^{-17}	9.2×10^{-16}^^
Post-Freeze/Thaw (m^2)	7.7×10^{-16}	**

**Sample became fully saturated through the entire height of sample. When gas permeability test was attempted, significant internal transport of pore water was induced such that water was drawn into the permeameter tubing.

^This is the CBR after three freeze-thaw cycles.

^^Frozen gas permeability measure during a third freeze cycle.

Conclusions and Recommendations

Although more data are needed to confirm specific conclusions from this study, the test method developed here appears to be useful for evaluating the performance of materials for backfilling utility trenches.

For silty sands like AASHTO A-4 types and flowable fill mixtures containing fly ash, the degree of saturation appears to affect the amount of frost heave, thaw-weakening, and gas permeability. Subjecting these materials to a high water table or a significant level of moisture may result in increased heave rates, increased thaw weakening, and the flow of gas may be significantly limited during both freeze and thaw conditions. Other backfill materials (e.g., high fly ash content flowable fill, air entrained flowable fill, sandy soil, etc.) are currently being evaluated.

Additional work is needed to demonstrate how the laboratory results correspond to actual field conditions.

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[2] Stewart, H. E., Bond, T. K., Carino, S. J., and Hover, K. C., *Freeze-Thaw Effects and Field Performance of Flowable Fill,* Civil Engineering Report No. 99-2, Cornell University, Ithaca, NY, 1999.

APPENDIX

Designation: D 4832 – 02

Standard Test Method for Preparation and Testing of Controlled Low Strength Material (CLSM) Test Cylinders[1]

This standard is issued under the fixed designation D 4832; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope*

1.1 This test method covers procedures for the preparation, curing, transporting and testing of cylindrical test specimens of controlled low strength material (CLSM) for the determination of compressive strength.

1.2 This test method also may be used to prepare and test specimens of other mixtures of soil and cementitious materials, such as self-cementing fly ashes.

1.3 CLSM is also known as flowable fill, controlled density fill, soil-cement slurry, soil-cement grout, unshrinkable fill, K-Krete, and other similar names.

1.4 The values stated in SI units are to be regarded as the standard. The inch-pound equivalents are shown for information only.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.* See Section 7.

2. Referenced Documents

2.1 *ASTM Standards:*

C 31 Practoce for Making and Curing Concrete Test Specimens in the Field[2]

C 39 Test Method for Compressive Strength of Cylindrical Concrete Specimens[2]

C 192 Practice for Making and Curing Concrete Test Specimens in the Laboratory[2]

C 470 Specification for Molds for Forming Concrete Test Cylinders Vertically[2]

C 617 Practice for Capping Cylindrical Concrete Specimens[2]

C 1231 Practice for Use of Unbonded Caps in Determination of Compressive Strength of Hardened Concrete Cylinders

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[3]

D 3740 Practice for Agencies Engaged in the Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction[3]

D 5971 Practice for Sampling Freshly Mixed Controlled Low Strength Material (CLSM)[4]

D 6023 Test Method for Unit Weight, Yield, and Air Content (Gravimetric) of Controlled Low Strength Material (CLSM)[4]

D 6024 Test Method for the Ball Drop on Controlled Low Strength Material (CLSM) to Determine Suitability for Load Application[4]

D 6103 Test Method for Flow Consistency of Controlled Low Strength Material (CLSM)[4]

3. Terminology

3.1 *Definitions*

3.1.1 For common definitions of terms in this standard, refer to Terminology D 653.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *Controlled Low Strength Material (CLSM), n*— A mixture of soil, cementitious materials, water, and sometimes admixtures, that hardens into a material with a higher strength than the soil but less than 8400 kPa (1200 psi). Used as a replacement for compacted backfill, CLSM can be placed as a slurry, a mortar, or a compacted material and typically has strengths of 350 to 700 kPa (50 to 100 psi) for most applications.

4. Summary of Test Method

4.1 Cylinders of CLSM are tested to determine the compressive strength of the material. The cylinders are prepared by pouring a representative sample into molds, curing the cylinders, removing the cylinders from the molds,and capping the cylinders for compression testing. The cylinders are then tested to obtain compressive strengths. Duplicate cylinders are required.

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[1] This test method is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.15 on Stabilization with Admixtures.

Current edition approved July 10, 2002. Published September 2002. Originally published as D 4832 – 88. Last previous edition D 4832 – 95$^{\epsilon 1}$

[2] *Annual Book of ASTM Standards*, Vol 04.02.

[3] *Annual Book of ASTM Standards*, Vol 04.08.

[4] *Annual Book of ASTM Standards*, Vol 04.09.

*A Summary of Changes section appears at the end of this standard.

5. Significance and Use

5.1 This test method is used to prepare and test cylindrical specimens of CLSM to determine the compressive strength of the hardened material.

5.2 CLSM is typically used as a backfill material around structures, particularly in confined or limited spaces. Compressive strength testing is performed to assist in the design of the mix and to serve as a control technique during construction. Mix design is typically based on 28-day strengths and construction control tests performed 7 days after placement. The compressive strength(s) and other test age(s) will vary according to the requirements for the end product. Additional information on the use and history of CLSM is contained in Appendix X1.

5.3 This test is one of a series of quality control tests that can be performed on CLSM during construction to monitor compliance with specification requirements. The other tests that can be used during constructioncontrol of CLSM are Test Methods D 5971, D 6023, D 6024, and D 6103.

5.4 There are many other combinations of soil, cement, flyash (cementitious or not), admixtures or other materials that could be tested using this method. The mixtures would vary depending on the intended use, availability of materials, and placement requirements.

NOTE 1—The quality of the result produced by this standard is dependent on the competence of the personnel performing it, and the suitability of the equipment and facilities used. Agencies that meet the criteria of Practice D 3740 are generally considered capable of competent and objective testing/sampling/inspection/and the like. Users of this standard are cautioned that compliance with Practice D 3740 does not in itself assure reliable results Reliable results depend on many factors; Practice D 3740 provides a means of evaluating some of those factors.

6. Apparatus

6.1 *Single-Use Cylindrical Molds*—Plastic single-use 15 cm (6-in.) diameter by 30 cm (12-in.) high molds with tight fitting lids, conforming to Specification C 470. Other sizes and types of molds may be used as long as the length to diameter ratio is 2 to 1. The 15-cm by 30-cm (6 in. by 12 in.) molds are preferred because of the low strength of the material and the larger surface area of the ends of the cylinders.

6.2 *Sampling and Mixing Receptacle*— The receptacle shall be a suitable heavy-gage container, wheelbarrow, etc. of sufficient capacity to allow easy sampling and mixing and to allow preparation of at least two cylinders and for other tests such as described in Test Methods D 5971, D 6023, PS D6024, and D 6103.

6.3 *Storage Container*—A tightly constructed, insulated, firmly braced wooden box with a cover or other suitable container for storage of the CLSM cylinders at the construction site. The container shall be equipped, as necessary, to maintain the temperature immediately adjacent to the cylinders in the range of 16 to 27°C (60 to 80°F). The container shall be marked for identification and shall be a bright color to avoid disturbance.

6.4 *Transportation Container*—A sturdy wooden box or other suitable container constructed to minimize shock, vibration, or damage to the CLSM cylinders when transported to the laboratory.

6.5 *Testing Machine*—The testing machine shall meet the requirements as described in Test Method C 39.

NOTE 2—Since the compressive strength of CLSM cylinders will typically be 100 kPa (about 15 to 1200 lbf/in.^{2}), the testing machine must have a loading range such that valid values of compressive strength can be obtained.

6.6 *Curing Environment*—A curing environment (water bath, damp sand, fog room) that meets the requirements of Method C 192. The cylinders may be cured in the same curing environment used for concrete cylinders at the laboratory performing the testing.

6.7 *Small Tools*—Tools and items that may be required such as shovels, pails, trowels, and scoops.

7. Hazards

7.1 *Technical Precaution*—The procedure for the preparation of CLSM test cylinders has many similarities to preparing concrete test cylinders (Practice C 31 and Practice C 192). However, the cylinders are much more fragile than concrete cylinders, and special care should be taken in their preparation, storage, and handling.

7.2 *Safety Hazards*:

7.2.1 Strictly observe the safety precautions stated in Practice C 617.

7.2.2 If the cylinders are capped with molten sulfur mortar, wear proper personnel protective equipment, including gloves with cuffs at least 15 cm (6-in.) long.

8. Sampling and Test Specimens

8.1 Take samples of the CLSM for each test specimen in accordance with D 5971. Record the identity of the CLSM represented and the time of casting.

8.2 The sample from the batch should be a minimum of 0.03 m^3 (1 ft^3) for each two cylinders to be prepared. Prepare a minimum of two compressive strength cylinders for each test age to represent each sampled batch. Additional material may be required if other testing is to be performed, such as in Test Methods D 5971, D 6023, D 6024,, and D 6103.

NOTE 3—In the initial stage of CLSM usage, preparation of three cylinders is recommended to obtain reliable compressive strength data for each test age. Subsequently, two cylinders may be used to maintain testing records and to ascertain an overall quality of the mix. However, since the cylinders are fragile and may be damaged during transportation, mold removal, and capping, preparation of an extra cylinder may be necessary to provide the minimum number of test specimens (see Note 8 and Note 9). In addition, it may be useful to determine the density of the test cylinders to help evaluate the uniformity of the compressive strength values.

9. Specimen Molding and Curing

9.1 *Place of Molding*—Mold specimens promptly on a level, rigid, horizontal surface free from vibration and other disturbances. The specimens should be prepared at a place as near as practicable to the location where they are to be stored during the first four days.

9.2 *Placing the CLSM*:

9.2.1 Thoroughly mix the CLSM in the sampling and mixing receptacle.

9.2.2 With a bucket or pail, scoop through the center portion of the receptacle and pour the CLSM into the cylinder mold. Repeat until the mold is full. Place a lid on the mold.

NOTE 4—Use of an airtight lid has been known to cause low strength materials to crack, possibly due to a creation of a vacuum inside the mold. If an airtight lid is contemplated, its use should be evaluated before doing routine testing.

NOTE 5—Some mixtures will bleed rapidly, that is, free water will appear in the mixing receptacle and the mold. Obtaining the material to fill the cylinder must be done quickly after mixing. A few minutes after filling the mold, thoroughly mix the CLSM in the sampling and mixing receptacle and place a scoopful in the top of the mold, displacing the water. If possible, a slight mound of material should be left on the top of the mold. This refilling may be required again after about 15 min. Leave the mound on the top of the mold and cover.

9.3 *Curing*:

9.3.1 Store the cylinders at the construction site in the storage container until the fourth day after preparation.

9.3.2 The cylinders shall be stored under conditions that maintain the temperature immediately adjacent to the cylinders in the range of 16 to 27°C (60 to 80°F). The cylinders must always be protected from freezing. After the first day, provide a high humidity environment by surrounding the cylinders with wet burlap or other highly adsorbent material.

9.3.3 On the fourth day, carefully transport the cylinders to the site of the curing environment in the transportation container and place in a curing environment (see 6.6).

9.3.4 The cylinders are typically left at the contruction site for four days and then transported to a curing environment. If extremely low strength CLSM (below 350 kPa) would be damaged by moving on the fourth day, then the cylinders are to be placed in a water storage tank with a temperature between 16° and 27°C (60° and 80°F) at the construction site until they are able to be moved without damage.

10. Capping the Cylinders

10.1 On the day of testing, carefully remove the molds from the cylinders and allow the cylinders to air-dry for 4 to 8 h before capping. If the upper surface of the cylinder is not a horizontal plane, use a wire brush to flatten the surface. Brush off all loose particles. Provide a cap for the cylinders using one the following methods:

10.1.1 Cap the cylinders using sulfur mortar in accordance with Practice C 617.

NOTE 6—Sulfur mortars are not recommended for capping CLSM cylindrs because the strenght of the cap is generally significantly greater than the CLSM sylinder strength which may lead to erroneous results.

10.1.2 Cap the cylinder using gypsum plaster in accordance with Practice C 617.

10.1.3 Use elastomeric pads in accordance with Practice C 1231. The results of the qualification tests in Practice C 1231 for acceptance of the caps must not indicate a reduction of strength of more than 20 %, rather than 2 % as stated in Practice C 1231. The larger difference is acceptable because of the less critical uses of CLSM and 20 % is estimated to be the inherent variation in compressive strength results because of the lower strength values, for example 350 kPa (50 psi).

NOTE 7—Although compressive strengths below 10 MPa (1500psi) are not within the scope of Practice C 1231, acceptable results have been found in many laboratories. Qualification testing should be performed prior to using unbonded capping systems for acceptance testing of CLSM mixtures.

10.2 Use the same capping method throughout each project to avoid any variation in the test results from using different capping systems.

NOTE 8—CLSM cylinders are more fragile than concrete cylinders and must be handled carefully during the mold removal and during capping.

NOTE 9—If sulfur mortar is used as the capping compound, oil is placed on the capping plate to ensure release of the capping material from the capping plate. More oil may be required on the capping plate when capping CLSM cylinders than is normally used when capping concrete cylinders. Capped CLSM cylinders will normally contain more air voids between the cap and the cylinder than capped concrete cylinders, and this should be considered if the caps are tapped to check for voids.

11. Compressive Strength Testing

11.1 *Placing the Specimen*—Place the lower bearing block, with its hardened face up, on the table or platen of the testing machine directly under the spherically seated (upper) bearing block. Wipe clean the bearing faces of the upper and lower bearing blocks and of the test specimen, and place the test specimen on the lower bearing block. Carefully align the axis of the specimen with the center of thrust of the spherically seated block. As the spherically seated block is brought to bear on the top of the specimen, rotate its movable portion gently by hand so that uniform seating is obtained.

11.2 *Rate of Loading*—Apply the load continuously and without shock. Apply the load at a constant rate such that the cylinder will fail in not less than 2 min. Make no adjustment in the controls of the testing machine while a specimen is yielding rapidly immediately before failure.

11.3 Apply the load until the specimen fails, and record the maximum load carried by the specimen during the test. For about one out of every ten cylinders, continue the loading until the cylinder breaks enough to examine the appearance of the interior of the specimen. Note any apparent segregation, lenses, pockets, and the like in the specimen.

12. Calculation

12.1 Calculate and record the compressive strength of the specimen as follows:

$$C = \frac{L}{\pi(D^2)/4} \quad (1)$$

where:

C = compressive strength, kPa (lbf/in.^{2}),

D = nominal diameter of cylinder (normally 15 cm or 6 in.), and

L = maximum load, kN (lbf).

13. Report

13.1 The report shall include the following:

13.1.1 Identification, for example, mix, cylinder number, location, etc.

13.1.2 Diameter and length, cm (in.).

13.1.3 Cross-sectional area, cm^2 (in. ^{2}).

13.1.4 Maximum load, kN (lbf).

13.1.5 Compressive strength, kPa (lbf/in.^{2}).

13.1.6 Age of specimen.

13.1.7 Appropriate remarks as to type of failure, defects noted, or nonuniformity of material.

14. Precision and Bias

14.1 *Precision*—Test data on precision is not presented due to the nature of the CLSM materials tested by this test method. It is either not feasible or too costly at this time tohave ten or more laboratories participate in a round-robin testing program.

14.1.1 Subcommittee D18.15 is seeking any data from the users of this test method that might be used to make a limited statement on precision.

14.2 *Bias*—There is no accepted reference value for this test method, therefore, bias cannot be determined.

15. Keywords

15.1 backfill; CLSM; compressive strength; construction control; mix design; quality control; soil stabilization

APPENDIX

(Nonmandatory Information)

X1. HISTORY

X1.1 This standard was developed to provide an accepted, consensus method of preparing and testing CLSM cylinders. Because the cylinders are more fragile than normal concrete cylinders, the standard provides a workable method of preparation and testing based on much trial and error.

X1.2 CLSM is a combination of soil, Portland cement, sometimes admixtures, and enough water so that the mixture has the consistency of a thick liquid. In this form, the CLSM flows readily into openings, filling voids, and provides a hardened material that has a strength greater than the untreated soil used in the mix. Some cementitious fly ashes have been successfully used in place of the cement.

X1.3 Although the primary use to date of CLSM or other similar materials has been as embedment for pipelines, it also has been used as trench backfill and structure backfill.[5,6]

X1.4 Typically, CLSM contains about 5 to 10 % cement. One of the definite advantages is that CLSM may be produced using local soils. As opposed to a lean concrete slurry, the soil for the CLSM can contain up to about 20 to 25 % nonplastic or slightly plastic fines. Although clean concrete sands have been used, the presence of fines can help keep the sand-sized particles in suspension. This allows the mixture to flow easier and helps prevent segregation. Soils that are basically sand sizes work best with the maximum particle compatible with the space to be filled. Central batch plants with the slurry delivered in ready-mix trucks and trench-side, trail-along portable batch plants have been used, with the latter normally used when the soil comes from the trench excavation.

X1.5 *Testing Techniques:*

X1.5.1 The 15 by 30-cm plastic cylinders (see 6.1) are suggested as a matter of economics; that size is not necessary based on the particle sizes normally used in CSLM. A minimum test age of 7 days is recommended for construction control testing because the cylinders may not be intact enough for transporting and testing in 3 days. In addition, the testing that has been done for 3-day strength has resulted in extremely erratic values.

X1.5.2 The mounding of the material in the cylinders was found to be necessary for mixtures that did not contain many fines; the water bled so quickly that a space was left on top of the cylinders and the hardened cylinders were not of a uniform height.

X1.5.3 At the moisture content required for the mixture to have the necessary flow properties, consolidation of the CSLM in the cylinder mold by vibration is not necessary.

X1.6 *Typical Use:*

X1.6.1 The use of CLSM as pipe embedment illustrates the relationship between the testing requirements and a typical application. For pipe installations, CLSM is used to fill the gap between the pipe and the excavated trench. The CLSM transfers the load from the pipe to the in situ material, so the native soil must be able to provide the necessary support for the pipe. The circular trench bottom shape is advantageous because it reduces excavation quantities and thus reduces handling of the soil materials. The CLSM eliminates the problem of trying to shape a cradle in the trench bottom to fit the pipe. A cradle is labor intensive and may not result in full contact between the pipe and the soil. The CLSM does ensure uniform support for the pipe. Placement of the CLSM is much faster than compacting the soil in layers alongside the pipe, and potential damage to the pipe from the compacting equipment is eliminated. It is also quicker than flooding and jetting or the saturation and vibration methods of compacting granular bedding materials. This faster installation is a distinct advantage where the construction is in populated areas or through streets.

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[5] Lowitz, C A, and DeGroot, G., "Soil-Cement Pipe Bedding, Canadian River Aqueduct," *Journal of the Construction Division*, ASCE, Vol 94, No C01, 1968.

[6] "Cement-Treated Pipeline Bedding," Portland Cement Association Publication No. PA0011.01

SUMMARY OF CHANGES

In accordance with D18 policy, this section identifies the location of changes to this standard since the last edition (95e1) thay may impact the use of this standard.

(1) Titles and reference in Section 2.1 revised to reflect current editions of the standards.

(2) Deleted C172 from Section 2.1 since the standard is no longer referenced.

(3) Revised Terminology Section in accordance with D18's Standards Preparation Manual.

(4) Revised 3.2.1 to identify CLSM as a noun and the word "replaced" was changed to "placed."

(5) Revised sections 5.3, 6.2, 8.1 and 8.2 to reflect current titles of the standards.

(6) Added note 1 referencing Practice D3740 in accordance wtih D18 policy. Renumbered subsequent notes.

(7) Revised section 6.3 to contain mandatory language.

(8) Added note 6 regarding caution for using sulfur mortar capping systems reflecting industry findings.

(9) Added note 7 referencing limits fo the scope of C 1231 and reflecting industry findings.

(10) Corrected typos in 12.1 — Equation 1.

(11) Revised section 14.1 in accordance with D18's Standards Preparation Manual.

(12) Revised entire document removing extra spaces between words and other miscellaneous "spell check" items.

(13) Updated the Summary of Changes section.

Designation: D 5971 – 01

Standard Practice for
Sampling Freshly Mixed Controlled Low-Strength Material[1]

This standard is issued under the fixed designation D 5971; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope*

1.1 This practice explains the procedure for obtaining a representative sample to test of freshly mixed controlled lowstrength material (CLSM) as delivered to the project site (Note 1). This practice includes sampling from revolving-drum truck mixers and from agitating equipment used to transport central-mixed CLSM.

1.2 The values stated in SI units are to be regarded as the standard. The inch-pound equivalents are shown for information only.

Note 1—Composite samples are required by this practice unless specifically excepted by procedures governing the tests to be performed, such as tests to determine uniformity of consistency and mixer efficiency. Procedures used to select the specific test batches are not described in this practice. It is recommended that random sampling be used to determine overall specification compliance.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

1.4 *This practice offers a set of instructions for performing one or more specific operations. This document cannot replace education or experience and should be used in conjunction with professional judgement. Not all aspects of this practice may be applicable in all circumstances. This ASTM standard is not intended to represent or replace the standard of care by which the adequacy of a given professional service must be judged, nor should this document be applied without consideration of a projects many unique aspects. The word "standard" in the title of this document means only that the document has been approved through the ASTM consensus process.*

2. Referenced Documents

2.1 *ASTM Standards:*

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[2]

D 3740 Practice for Minimum Requirements for Agencies Engaged in the Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction[2]

D 4832 Test Method for Preparation and Testing of Controlled Low Strength Material (CLSM) Test Cylinders[2]

D 6023 Test Method for Unit Weight, Yield and Air Content (Gravimetric) of Controlled Low Strength Material (CLSM)[3]

D 6103 Test Method for Flow Consistency of Controlled Low Strength Material (CLSM)[3]

3. Terminology

3.1 *Definitions:* For common definitions of terms in this standard, refer to Terminology D 653.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *composite sample, n*—a sample that is constructed by combining equal portions of grab samples taken at two or more regularly spaced intervals during discharge of the middle portion of the batch of CLSM.

3.2.2 *controlled low-strength material (CLSM), n*—a mixture of Portland cement, fly ash, aggregates, water, and possibly chemical admixtures that, as the cement hydrates, forms a soil replacement material. The CLSM is a self compacting, flowable, cementitious material that is primarily used as a backfill or structural fill instead of compacted fill or unsuitable native soil. Depending on the amount of water used in the CLSM mixture, it can be placed as a non-flowable compacted material or as a mortar.

3.2.3 *flow consistency, n*—measured by the average diameter of the spread achieved by removal of the flow cylinder.

4. Significance and Use

4.1 This practice shall be used to provide a representative sample of the material for the purpose of testing various properties. The procedures used in sampling shall include the use of every precaution that will assist in obtaining samples that are truly representative of the nature and condition of the CLSM.

Note 2—The quality of the result produced by this standard is dependent on the competence of the personnel performing it and the suitability of the equipment and facilities used. Agencies that meet the criteria of Practice D 3740 are generally considered capable of competent

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[1] This practice is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.15 on Stabilization with Admixtures.

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[2] *Annual Book of ASTM Standards*, Vol 04.08.

[3] *Annual Book of ASTM Standards*, Vol 04.09.

***A Summary of Changes section appears at the end of this standard.**

and objective testing/sampling/inspection/ and the like. Users of this standard are cautioned that compliance with Practice D 3740 does not in itself assure reliable results. Reliable results depend on many factors. Practice D 3740 provides a means of evaluating some of these factors.

5. Sampling

5.1 *Size of Sample*—The sample of CLSM for compressive strength testing shall be a minimum of 14 L (0.5 ft^3). For other tests, the composite size shall be large enough to perform the test and to ensure a representative sample of the batch was taken.

6. Procedure

6.1 *Sampling from Revolving-Drum Truck Mixers or Agitators*—Sample the CLSM at two or more regularly spaced intervals during discharge of the middle portion of the batch. These grab samples shall be obtained within the time limit specified in 6.2 and composited into one sample for test purposes. In any case do not obtain samples until after all water has been added to the mixer; also do not obtain samples from the very first or last portions of the batch discharge. Sample by repeatedly passing a receptacle through the entire discharge stream or by completely diverting the discharge into a sample container. Regulate the rate of discharge of the batch by the rate of revolution of the drum and not by the size of the gate opening.

NOTE 3—Sampling normally should be performed on the CLSM as delivered from the truck to the job site excavation.

6.2 The elapsed time between obtaining the first and final portions of the composite sample shall be as short as possible and in no instance shall it exceed 2 min.

6.3 Transport the composite samples to the place where fresh CLSM tests are to be performed or where test specimens are to be molded. The composite sample shall be combined and remixed with a shovel or scoop the minimum amount necessary to ensure uniformity and compliance with the minimum time limits specified in 6.4.

6.4 Start tests for flow consistency (Test Method D 6103), unit weight, and air content (Test Method D 6023) within 5 min after obtaining the final portion of the composite sample. Complete these tests as expeditiously as possible. Start molding specimens for strength tests (Test Method D 4832) within 10 min after obtaining the final portion of the composite sample. Keep the elapsed time between obtaining and using the sample as short as possible and protect the sample from the sun, wind, and other sources of rapid evaporation, and from contamination.

7. Keywords

7.1 air content; CLSM; composites; flow consistency; quality control; sampling; unit weight

SUMMARY OF CHANGES

This section identifies the principle changes to this guide that have been incorporated since the last issue.

(1) SI units made the standard.

(2) Added section 1.4 the "Professional Judgement" caveat.

(3) Revised sections 2.1 and 6.4 to reflect current titles of standards.

(4) Revised section 3 on Terminology in accordance with D18's Standards Preparation Manual.

(5) Added Note 2 referencing Practice D3740 in accordance with D18 policy. Renumbered subsequent notes.

(6) Added "Summary of Changes" section.

Designation: D 6023 – 02

Standard Test Method for
Unit Weight, Yield, Cement Content, and Air Content (Gravimetric) of Controlled Low Strength Material (CLSM)[1]

This standard is issued under the fixed designation D 6023; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope*

1.1 This test method explains determination of the mass per cubic foot (cubic meter) of freshly mixed Controlled Low Strength Material (CLSM) and gives formulas for calculating the yield, cement content, and the air content of the CLSM. This test method is based on Test Method C 138 for Concrete.

NOTE 1—Unit Weight is the traditional terminology used to describe the property determined by this test method. The proper term is density. It has also been termed unit mass or bulk density. To be compatible with terminology used in the concrete industry, unit weight is referenced in this test method.

1.2 All observed and calculated values shall conform to the guidelines for significant digits and rounding established in Practice D 6026.

1.2.1 The method used to specify how data are collected, calculated, or recorded in this standard is not directly related to the accuracy to which the data can be applied in design or other uses, or both. How one applies the results obtained using this standard is beyond its scope.

1.3 The values stated in SI units are to be regarded as standard. The inch-pound equivalents are shown for information only.

1.4 CLSM is also known as flowable fill, controlled density fill, soil-cement slurry, soil-cement grout, unshrinkable fill, "K-Krete," and other similar names.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

C 29/C29M Test Method for Unit Weight and Voids in Aggregate[2]

C 125 Terminology Relating to Concrete and Concrete Aggregates[2]

C 128 Test Method for Specific Gravity and Absorption of Fine Aggregates[2]

C 138 Test Method for Unit Weight, Yield and Air Content (Gravimetric) of Concrete[2]

C 150 Specification for Portland Cement[2]

C 231 Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method[2]

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[3]

D 3740 Practice for Minimum Requirements for Agencies Engaged in the Testing and/or Inspection of Soil and Rock as used in Engineering Design and Construction[3]

D 4832 Test Method for Preparation and Testing of Controlled Low Strength Material (CLSM) Test Cylinders[3]

D 5971 Practice for Sampling Freshly Mixed Controlled Low Strength Material[4]

D 6024 Test Method for the Ball Drop on Controlled Low Strength Material (CLSM) to Determine Suitability for Load Application[4]

D 6026 Practice for Using Significant Digits in Geotechnical Data[4]

D 6103 Test Method for Flow Consistency of Controlled Low Strength Material (CLSM)[4]

3. Terminology

3.1 *Definitions*—For definitions of terms in this standard, refer to Terminology C 125 and D 653.

3.1.1 *Controlled Low Strength Material (CLSM), n*— a mixture of soil or aggregates, cementitious material, fly ash, water, and sometimes chemical admixtures, that hardens into a material with a higher strength than the soil, but less than 8400 kPa (1200 psi).

3.1.1.1 *Discussion*—Used as a replacement for compacted backfill, CLSM can be placed as a slurry, a mortar, or a compacted material and typically has strengths of 350 to 700 kPa (50 to 100 psi) for most applications.

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[1] This test method is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.15 on Stabilization with Admixtures.

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[2] *Annual Book of ASTM Standards*, Vol 04.02.

[3] *Annual Book of ASTM Standards*, Vol 04.08.

[4] *Annual Book of ASTM Standards*, Vol 04.09.

***A Summary of Changes section appears at the end of this standard.**

3.1.2 *mass, n*—the quantity of matter in a body. (See *weight.*)

3.1.2.1 *Discussion*—Units of mass are the kilogram (kg), the pound (lb) or units derived from these. Masses are compared by weighing the bodies, which amounts to comparing the forces of gravitation acting on them.

3.1.3 *weight, n*—the force exerted on a body by gravity. (see *mass.*)

3.1.3.1 *Discussion*—Weight is equal to the mass of the body multiplied by the acceleration due to gravity. Weight may be expressed in absolute units (newtons, poundals) or in gravitational units (kgf, lbf). Since weight is equal to mass times the acceleration due to gravity, the weight of a body will vary with the location where the weight is determined, while the mass of the body remains constant. On the surface of the earth, the force of gravity imparts to a body that is free to fall an acceleration of approximately 9.81 m/s^2 (32.2 ft/s^2).

3.1.4 *yield*—the volume of CLSM produced from a mixture of known quantities of the component materials.

4. Summary of Test Method

4.1 The density of the CLSM is determined by filling a measure with CLSM, determining the mass, and calculating the volume of the measure. The density is then calculated by dividing the mass by the volume. The yield, cement content, and the air content of the CLSM is calculated based on the masses and volumes of the batch components.

5. Significance and Use

5.1 This test method provides the user with a procedure to calculate the density of freshly mixed CLSM for determination of compliance with specifications, for determining mass/volume relationships or conversions such as those found in purchase agreements, and also for quality control purposes.

5.2 This test method is intended to assist the user for quality control purposes and when specified to determine compliance for air content, yield, and cement content of freshly mixed CLSM.

5.3 This test method is not meant to predict the air content of hardened CLSM, which may be either higher or lower than that determined by this test method.

5.4 This test is one of a series of quality control tests that can be performed on CLSM during construction to monitor compliance with specification requirements. The other tests that can be used during construction control are Test Methods D 4832, D 6024, and D 6103

Note 2—The qulaity of the results produced by this standard is dependent on the competence of the personnel performing it and the suitability of the equipment and facilities used. Agencies that meet the criteria of Practice D 3740 are generally considered capable of competent and objective testing/sampling/inspection/ and the like. Users of this standard are cautioned that compliance with Practice D 3740 does not in itself assure reliable results. Reliable results depend on many factors; Practice D 3740 provides a means of evaluation some of those factors.

6. Apparatus

6.1 *Balance*—A balance or scale accurate to within 0.3 % of the test load at any point within the range of use. The range of use shall be considered to extend from the mass of the measure empty to the mass of the measure plus the CLSM.

6.2 *Filling Apparatus*—Scoop, bucket or pail of sufficient capacity to facilitate filling the measure in a rapid, efficient manner.

6.3 *Sampling and Mixing Receptacle*— The receptacle shall be a suitable container, wheelbarrow, and the like of sufficient capacity to allow easy sampling and remixing of the CLSM.

6.4 *Measure*—A cylindrical container made of steel or other suitable metal (Note 3). It shall be watertight and sufficiently rigid to retain its form and calibrated volume under rough usage. Measures that are machined to accurate dimensions on the inside and provided with handles are preferred. All measures, except for measuring bowls of air meters shall conform to the requirements of Test Method C 29/C 29M. The minimum capacity of the measure shall conform to the requirements of Table 1. When measuring bowls of air meters are used, they shall conform to the requirements of Test Method C 231. The top rim of the air meter bowls shall be smooth and plane within 0.01 in. (0.25 mm) (Note 4).

Note 3—The metal should not be readily subject to attack by cement paste. However, reactive materials such as aluminum alloys may be used in instances where, as a consequence of an initial reaction, a surface film is rapidly formed which protects the metal against further corrosion.

Note 4—The top rim is satisfactorily plane if a 0.01-in. (0.25-mm) feeler gage cannot be inserted between the rim and a piece of ¼ in. (6 mm) or thicker plate glass laid over the top of the measure.

6.5 *Strike-Off Plate*—A flat rectangular metal plate at least ¼ in. (6 mm) thick or a glass or acrylic plate at least ½ in. (12 mm) thick with a length and width at least 2 in. (50 mm) greater than the diameter of the measure with which it is to be used. The edges of the plate shall be straight and smooth within a tolerance of 1/16 in. (1.5 mm).

6.6 *Calibration Equipment*—A piece of plate glass, preferably at least ¼ in. (6 mm) thick and at least 1 in. (25 mm) larger than the diameter of the measure to be calibrated. A thin film of vacuum, water pump or chassis grease smeared on the flange of the bowl will make a watertight joint between the glass plate and the top of the bowl.

7. Sample

7.1 Obtain the sample for freshly mixed CLSM in accordance with Practice D 5971.

7.2 The size of the sample shall be approximately 125 to 200 % of the quantity required to fill the measure.

8. Calibration of Measure

8.1 Calibrate the measure and determine the calibration factor (1/volume), following the procedure outlined in Test Method C 29/C 29M.

TABLE 1 Minimum Capacity of Measure

Nominal Maximum Size of Coarse Aggregate[A]		Capacity of Measure, min[B]	
in.	mm	ft^3	L
1	25.0	0.2	6
1½	37.5	0.4	11
2	50	0.5	14

[A] Aggregate of a given nominal maximum size may contain up to 10 % of particles retained on the sieve referred to.

[B] To provide for wear, measures may be up to 5 % smaller than indicated in this table.

NOTE 5—For the calculation of unit weight, the volume of the measure in acceptable metric units should be expressed in cubic metres, or the factor as 1/m ^{3}. However, for convenience the size of the measure may be expressed in liters.

8.2 Measures shall be recalibrated at least once a year or whenever there is reason to question the accuracy of the calibration.

9. Procedure

9.1 Place the measure on a level, rigid, horizontal surface free from vibration and other disturbances.

9.2 *Placing the CLSM*:

9.2.1 Start this procedure within 5 min after obtaining the sample of CLSM and complete as expeditiously as possible.

9.2.2 Thoroughly mix the sample of CLSM in the sampling and mixing receptacle to ensure uniformity.

9.2.3 With the filling apparatus, scoop through the center portion of the sample and pour the CLSM into the measure. Repeat until the measure is full.

9.3 On completion of filling, the measure shall not contain a substantial excess or deficiency of CLSM. An excess of CLSM protruding approximately ⅛ in. (3 mm) above the top of the mold is optimum. To correct a deficiency, add a small quantity of CLSM.

9.4 *Strike-Off*—After filling, strike-off the top surface of the CLSM and finish it smoothly with the flat strike-off plate using great care to leave the measure just level full. The strike-off is best accomplished by pressing the strike-off plate on the top surface of the measure to cover about two thirds of the surface and withdrawing the plate with a sawing motion to finish only the area originally covered. Then place the plate on the top of the measure to cover the original two thirds of the surface and advance it with a vertical pressure and a sawing motion to cover the whole surface of the measure. Several final strokes with the inclined edge of the plate will produce a smooth finished surface.

9.5 *Cleaning and Mass Measurement*— After strike-off, clean all excess CLSM from the exterior of the measure and determine the gross mass of the CLSM in the measure to an accuracy consistent with the requirements of 6.1.

10. Calculation

10.1 *Density*—Calculate the mass of the CLSM in megagrams or grams (pounds) by subtracting the mass of the measure from the gross mass. Calculate the density, W, by multiplying the mass of the CLSM by the calibration factor for the measure determined in 8.1.

10.2 *Yield*—Calculate the yield as follows:

$$Y_f(\text{ft}^3) = W_1/W \tag{1}$$

or,

$$Y(\text{yd}^3) = W_1/(27W) \tag{2}$$

$$Y(\text{m}^3) = W_1/W \tag{3}$$

or,

where:

Y_f = volume of CLSM produced per batch, ft^3,

Y = volume CLSM produced per batch, m^3(ft ^{3}),

W = density of CLSM, kg/m ^{3}(lb/ft^3), and

W_1 = total mass of all materials batched, kg (lb) (Note 6).

NOTE 6—The total mass of all materials batched is the sum of the masses of the cement, the fly ash, the filler aggregate in the condition used, the mixing water added to the batch, and any other solid or liquid materials used.

10.3 *Relative Yield*—Relative yield is the ratio of the actual volume of CLSM obtained to the volume as designed for the batch calculated as follows:

$$R_y = Y/Y_d \tag{4}$$

where:

R_y = relative yield,

Y = volume CLSM produced per batch, m^3(yd^3), and

Y_d = volume of CLSM which the batch was designed to produce, m^3(yd^3).

NOTE 7—A value for R_y greater than 1.00 indicates an excess of CLSM being produced whereas a value less than this indicates the batch to be "short" of its designed volume.

10.4 *Cement Content* (Note 8)—Calculate the actual cement content as follows:

$$N = N_t/Y \tag{5}$$

where:

N = actual cement content kg/m^3(lb/yd^3),

N_t = mass of cement in the batch, kg (lb), and

Y = volume CLSM produced per batch, m^3(yd^3).

NOTE 8—In determining cement content on CLSM's that contain Class C fly ash, the actual mass of Class C fly ash shall be added to the mass of cement.

10.5 *Air Content*—Calculate the air content as follows:

$$A = [(T - W)/T] \times 100 \tag{6}$$

or,

$$A = [(Y_f - V)/Y_f] \times 100 \text{ (inch-pound units)} \tag{7}$$

or,

$$A = [(Y - V)/Y] \times 100 \text{ (SI units)} \tag{8}$$

where:

A = air content (percentage of voids) in the CLSM,

T = theoretical density of the CLSM computed on an air free basis, kg/m^3(lb/ft^3) (Note 7),

W = density of CLSM, kg/m^3(lb/ft^3),

Y_f = volume of CLSM produced per batch, ft^3,

V = total absolute volume of the component ingredients in the batch, ft^3 or m^3, and

Y = volume CLSM produced per batch, m^3(yd^3).

NOTE 9—The theoretical density is, customarily, a laboratory determination, the value for which is assumed to remain constant for all batches made using identical component ingredients and proportions. It is calculated from the following equation.

$$T = W_1/V \tag{9}$$

The absolute volume of each ingredient in cubic feet is equal to the quotient of the mass of that ingredient divided by the product of its specific gravity times 62.4. The absolute volume of each ingredient in cubic meters is equal to the mass of the ingredient in kilograms divided by

1000 times its specific gravity. For the aggregate components, the bulk specific gravity and mass should be determined by Test Method C 128. A value of 3.15 may be used for cements manufactured to meet the requirements of Specification C 150.

11. Report

11.1 Report the results for the density to the nearest 1 lb/ft^3 (10 kg/m^3). The density may be reported as unit weight to be compatible with the terminology used in the concrete industry.

11.2 Report the following information:

11.2.1 Yield, to the second decimal.

11.2.2 Relative yield, to the second decimal.

11.2.3 Cement content, to the second decimal.

11.2.4 Air content, to the nearest 0.5 %.

12. Precision and Bias

12.1 *Precision*—Test data on precision is not presented due to the nature of the CLSM materials tested by this test method. It is either not feasible or too costly at this time to have ten or more laboratories participate in a round-robin testing program.

12.1.1 The Subcommittee D18.15 is seeking any data from the users of this test method that might be used to make a limited statement on precision.

12.2 *Bias*—The procedure in this test method for measuring unit weight has no bias because the value for unit weight can be defined only in terms of a test method.

13. Keywords

13.1 air content; backfill; cement content; CLSM; construction control; density; flowable fill; mix design; quality control; relative yield; soil stabilization; unit weight; yield

SUMMARY OF CHANGES

In accordance with Committee D18 policy, this section identifies the location of changes to this standard since the last edition (1996) that may impact the use of this standard.

(1) Sections 1.2 and 1.2.1 were added in accordance with Committee D18 policy and the subsequent sections renumbered.
(2) Practice D 6026 was added to Referenced Documents section.
(3) Test Method D 6103 replaced PS 28 and Practice D 5971 replaced PS 30.
(4) Section 3 was revised to comply with Committee D18 policy.
(5) Section 5.4 was revised with the current standard designations.
(6) Note 2 was revised to comply with the current wording according to Committee D18 policy.
(7) Section 7.1 was revised with the current standard designation.
(8) The precision statement was revised to comply with Committee D18 policy as found in the Standards Preparation Manual.

Designation: D 6024 – 02

Standard Test Method for
Ball Drop on Controlled Low Strength Material (CLSM) to Determine Suitability for Load Application[1]

This standard is issued under the fixed designation D 6024, the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope*

1.1 This specification explains the determination of the ability of Controlled Low Strength Material (CLSM) to withstand loading by repeatedly dropping a metal weight onto the in-place material.

1.2 All observed and calculated values shall conform to the guidelines for significant digits and rounding established in Practice D 6026.

1.2.1 The method used to specify how data are collected, calculated, or recorded in this test method is not directly related to the accuracy to which the data can be applied in design or other uses, or both. How one applies the results obtained using this standard is beyond its scope.

1.3 The values stated in SI units are to be regarded as the standard. The inch-pound equivalents are shown for information only.

1.4 CLSM is also known as flowable fill, controlled density fill, soil-cement slurry, soil-cement grout, unshrinkable fill," K-Krete," and other similar names.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

C 125 Terminology Relating to Concrete and Concrete Aggregates[2]

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[3]

D 3740 Practice for Minimum Requirements for Agencies Engaged in the Testing and/or Inspection of Soil and Rock as used in the Engineering Design and Construction[3]

D 4832 Test Method for Preparation and Testing of Controlled Low Strength Material (CLSM) Test Cylinders[3]

D 6023 Test Method for Unit Weight, Yield, and Air Content (Gravimetric) of Controlled Low Strength Material (CLSM)[4]

D 6026 Practice for Using Significant Digits in Geotechnical Data[4]

D 6103 Test Method for Flow Consistency of Controlled Low Strength Material (CLSM) [3]

3. Terminology

3.1 *Definitions*—For definitions of terms in this test method, refer to Terminology C 125 and D 653.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *Controlled Low Strength Material (CLSM), n*— a mixture of soil or aggregates, cementitious material, fly ash, water and sometimes chemical admixtures, that hardens into a material with a higher strength than the soil, but less than 8400 kPa (1200 psi).

3.2.1.1 *Discussion*—Used as a replacement for compacted backfill, CLSM can be placed as a slurry, a mortar, or a compacted material and typically has strengths of 350 to 700 kPa (50 to 100 psi) for most applications.

4. Summary of Test Method

4.1 A standard cylindrical weight is dropped five times from a specific height onto the surface of in-place CLSM. The diameter of the resulting indentation is measured and compared to established criteria. The indentation is inspected for any free water brought to the surface from the impact.

5. Significance and Use

5.1 This test method is used primarily as a field test to determine the readiness of the CLSM to accept loads prior to adding a temporary or permanent wearing surface.

5.2 This test method is not meant to predict the load bearing strength of a CLSM mixture.

5.3 This test is one of a series of quality control tests that can be performed on CLSM during construction to monitor compliance with specification requirements. The other tests

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[1] This test method is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.15 on Stabilization with Admixtures

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[2] *Annual Book of ASTM Standards*, Vol 04.02.

[3] *Annual Book of ASTM Standards*, Vol 04.08

[4] *Annual Book of ASTM Standards*, Vol 04.09.

*A Summary of Changes section appears at the end of this standard.

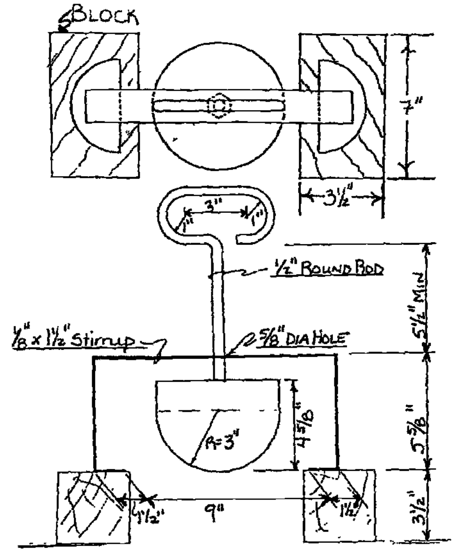
that can be used during construction control are Test Methods D 4832, D 6023, and D 6103.

NOTE 1—The quality of the result produced by this standard is dependent on the competence of the personnel performing it, and the suitability of the equipment and facilities used. Agencies that meet the criteria of Practice D 3740 are generally considered capable of competent and objective testing/sampling/inspection/and the like. Users of this standard are cautioned that compliance with Practice D 3740 does not in itself assure reliable results Reliable results depend on many factors; Practice D 3470 provides a means of evaluating some of those factors.

6. Apparatus

6.1 *Ball-drop Apparatus*—a cylinder with a hemispherically shaped bottom and handle with a mass of 14 + 0.05 kg (30 + 0.1 lb), and a stirrup or frame to guide the handle (Fig. 1).

6.1.1 *Weight*—The cylindrical weight (ball) shall be approximately 15 cm (6 in.) in diameter and 12 cm (4⅝ in.) in height, with the top surface at right angles to the axis and the bottom in the form of a hemisphere of 75 mm (3 in.) radius. The cylindrical weight may be machined from metal stock or cast or spun provided the dimensions and weight with the handle meet requirements, and the finish is smooth.



		Metric Equivalents	
in.	mm	in.	mm
⅛	3.2	4⅝	117
½	13	5½	140
⅝	16	5⅝	143
1	25	9	228
1½	38	12	305
3	76		

FIG. 1 Ball-drop Apparatus

6.1.2 *Handle*—The handle shall be a metal rod, 13 mm (½ in.) in diameter. The handle may be T-shaped or a closed rectangle at the top to permit grasping by the hand.

6.1.3 *Stirrup*—The stirrup shall be at least 38 mm (1½ in.) in width. The stirrup frame is attached securely to blocks elevating it 9 cm (3½ in.).

6.1.4 *Blocks*—pieces of wood, or ultra high molecular weight plastic (UHMW) that are 9 cm (3½ in.) high are used to elevate the stirrups to the proper height. The stirrups must be centered on the blocks to avoid tipping, and attached securely to the stirrups so shifting does not occur. The blocks shall be parallel to each other and perpendicular to the main stirrup frame. The blocks must not interfere with the ball-drop apparatus. Each block shall have the minimum dimension of 9-cm (3½ in.) wide by 18-cm (7-in.) long with a minimum bearing area of 155 cm ^{2} (24 in^2).

6.2 *Measuring Device*—capable of measuring the diameter of the indentation. It must be capable of measuring a minimum of 3 mm (⅛ in.).

7. Procedure

7.1 The surface of the CLSM will need to be as level as possible either by self-leveling or by slight brooming action with hand tools. Set the elevated base of the apparatus on the leveled CLSM surface, with the handle in a vertical position and free to slide through the frame. Put slight pressure on the frame with your free hand to stabilize the device. Lift the handle as far as possible allowing the top surface of the ball to contact the underside of the stirrup frame. Release the weight allowing it to free fall to the surface of the CLSM. Repeat this for a total of five times at each location tested. Before testing a new location of the in-place CLSM remove any material that has adhered to the ball from previous testing.

7.2 Measure the diameter of the indentation left by the ball with a measuring device (Note 2). If the diameter of indentation is 76 mm (≤3 in.) then the CLSM is suitable for the load application. If the diameter of indentation is 76 mm (>3 in.) then the CLSM is unsuitable or not ready for load application.

NOTE 2—It has been shown under limited use that an indentation of ≤75 mm (3 in.) is suitable for normal load application.

7.3 Inspect the indentation for visible surface water or sheen brought to the surface by the dropping action of the ball. The surface should look similar to that before the test with the exception of an indentation. The presence of surface water indicates that the CLSM is unsuitable or not ready for load application.

8. Report

8.1 Report the following:

8.1.1 Project Identification,

8.1.2 Location of test,

8.1.3 Identification of individual performing the test method, and

8.1.4 Date test is performed.

8.2 Report the following information:

8.2.1 Visible surface water or sheen brought to the surface by the dropping action, 8.2.2 Irregularities on the surface of the in place CLSM such as indentations left by the blocks or severe cracking, and

8.2.3 Diameter of indentation to nearest 3 mm (⅛ in.).

9. Precision and Bias

9.1 *Precision*—Test data on precision is not presented due to the nature of this test method. It is either not feasible or too costly at this time to have ten or more agencies participate in an in situ testing program at a given site.

9.1.1 The Subcommittee D18.15 is seeking any data from users of the test method that might be used to make a limited statement on precision.

9.2 *Bias*—There is no accepted reference value for this test method, therefore, bias cannot be determined.

10. Keywords

10.1 backfill; ball drop apparatus; bearing; CLSM; construction control; early load; flowable fill; mix design; quality control; soil stabilization; surface water; wearing surface

SUMMARY OF CHANGES

In accordance with Committee D18 policy, this section identifies the location of changes to this test method since the last edition (1996) that may impact the use of this standard.

(1) Sections 1.2 and 1.2.1 were added in accordance with D18 policy and the subsequent sections renumbered.

(2) C 360 was removed and Practice D 6026 was added to the list of Referenced Documents.

(3) The designation "PS 28" was updated to Test Method D 6103 in Sections 2 and 5.3

(4) Section 3 was revised to comply with D18 policy.

(5) Note 1 was revised to comply with the current wording according to D18 policy.

(6) Section 9, was revised to comply with suggested wording found in the D18 Standards Preparation Manual.

Designation: D 6103 – 97

Standard Test Method for Flow Consistency of Controlled Low Strength Material (CLSM)[1]

This standard is issued under the fixed designation D 6103; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope*

1.1 This test method covers the procedure for determination of the flow consistency of fresh Controlled Low Strength Material (CLSM). This test method applies to flowable CLSM with a maximum particle size of 19.0 mm (¾ in.) or less, or to the portion of CLSM that passes a 19.0 mm (¾ in.) sieve.

1.2 The values stated in SI units are to be regarded as standard. The inch-pound equivalents are given for information only.

1.3 CLSM is also known as flowable fill, controlled density fill, soil-cement slurry, soil-cement grout, unshrinkable fill, K-Krete, and other similar names.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

C 143 Test Method for Slump of Hydraulic Cement Concrete[2]

C 172 Practice for Sampling Freshly Mixed Concrete[2]

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[3]

D 3740 Practice for Minimum Requirements of Agencies Engaged in the Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction[3]

D 4832 Test Method for Preparation and Testing of Controlled Low Strength Material (CLSM) Test Cylinders[3]

D 5971 Practice for Sampling Freshly Mixed Controlled Strength Material[4]

D6023 Test Method for Unit Weight, Yield, and Air Content (Gravimetric) of Controlled Low Strength Material[4]

D 6024 Test Method for Ball Drop on Controlled Low Strength Material to Determine Suitability for Load Application[4]

3. Terminology

3.1 *Definitions*—Except as follows in 3.2, all definitions are in accordance with Terminology D 653

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *controlled low strength material (CLSM), n*—a mixture of soil or aggregates, cementitious material, fly ash, water and sometimes chemical admixtures, that hardens into a material with a higher strength than the soil, but less than 84 00 kPa (1200 psi). Used as a replacement for compacted backfill, CLSM can be placed as a slurry, a mortar, or a compacted material and typically has strengths of 350 to 700 kPa (50 to 100 psi) for most applications.

3.2.2 *flow consistency, n*—a measurement of the spread of a predetermined volume of CLSM achieved by removal of the flow cylinder within a specified time.

4. Summary of Test Method

4.1 An open-ended cylinder is placed on a flat, level surface and filled with fresh CLSM. The cylinder is raised quickly so the CLSM will flow into a patty. The average diameter of the patty is determined and compared to established criteria.

5. Significance and Use

5.1 This test method is intended to provide the user with a procedure to determine the fluidity of CLSM mixtures for use as backfill or structural fill.

5.2 This test method is considered applicable to fresh CLSM containing only sand as the aggregate or having coarse aggregate small than 19.0 mm (¾ in.). If the coarse aggregate is larger than 19.0 mm (¾ in.), the test method is applicable when it is made on the fraction of CLSM passing a 19.0 mm (¾ in.) sieve, with the larger aggregate being removed in accordance with the section on Additional Procedures for Large Maximum size Aggregate Concrete in Practice C 172.

NOTE 1—Removing the coarse aggregate will alter the characteristics of the mix and therefore will give information only about the remaining

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[1] This test method is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.15 on Stabilization with Admixtures

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[2] *Annual Book of ASTM Standards*, Vol 04.02.

[3] *Annual Book of ASTM Standards*, Vol 04.08.

[4] *Annual Book of ASTM Standards*, Vol 04.09.

***A Summary of Changes section appears at the end of this standard.**

material. It is suggested that for mixes containing coarse aggregate 19.0 mm (¾ in.) or larger, a measurement of the slump is more appropriate.

5.3 For nonflowable CLSM, or for mixtures that do not come out of the flow cylinder easily, measure the slump as outlined in Test Method C 143.

5.4 This test method is one of a series of quality control tests that can be performed on CLSM during construction to monitor compliance with specification requirements. The other tests that can be used during construction control are Test Methods D 4832, D 6023, and D 6024.

NOTE 2—Not withstanding the statements on precision and bias contained in this test method, the precision of this test method is dependent on the competence of the personnel performing it and the suitability of the equipment and facilities used. Agencies that meet the criteria of Practice D 3740 generally are considered capable of competent and objective testing. Users of this test method are cautioned that compliance with Practice D 3740 does not in itself assure reliable testing. Reliable testing depends on several factors. Practice D 3740 provides a means of evaluating some of those factors.

6. Apparatus

6.1 *Flow Cylinder*—The flow cylinder shall be a 150 mm (6 in.) length of 76 mm (3 in.) inside diameter, straight tubing of steel, plastic or other non-absorbent material, non-reactive with CLSM containing Portland cement. Individual diameters and lengths shall be within ± 3 mm (⅛ in.) of the prescribed dimensions. The flow cylinder shall be constructed such that the planes of the ends are parallel to one another and perpendicular to the longitudinal axis of the cylinder. The flow cylinder shall have a smooth interior, open at both ends and a rigid shape that is able to hold its dimensions and under conditions of severe use.

6.2 *Sampling and Mixing Receptacle*—The receptacle shall be a suitable container, wheelbarrow, etc., of sufficient capacity to allow easy sampling and remixing of the CLSM.

6.3 *Filling Apparatus*—Scoop, bucket, or pail of sufficient capacity to facilitate filling of the flow cylinder in a rapid, efficient manner.

6.4 *Nonporous Surface*—A 0.6 m (2-ft) square, or larger, made of a nonporous material that is also noncorroding, such as acrylic, cast aluminum, or stainless steel. The surface must be smooth, free of defects, and rigid.

6.5 *Miscellaneous Equipment*:

6.5.1 *Timing Device*—Watch, clock, or stopwatch capable of timing 1 s intervals.

6.5.2 *Straight edge*—A stiff metal straightedge of any convenient length but not less than 254 mm (10 in.). The total length of the straightedge shall be machined straight to a tolerance of +0.1 mm (+0.005 in). The metal shall be made of suitable material that is noncorroding.

6.5.3 Measuring device, capable of measuring spread diameter. Must be able to measure a minimum of 6 mm (¼ in.).

7. Test Sample

7.1 Obtain the sample of freshly mixed CLSM in accordance with D 5971.

8. Procedure

8.1 Place the nonporous surface on a flat, level area that is free of vibration or other disturbances.

8.2 Dampen the flow cylinder with water and place it on end, on a smooth nonporous level surface. Hold firmly in place during filling.

8.3 Thoroughly remix the CLSM, the minimum amount necessary to ensure uniformity, in the sampling and mixing receptacle.

NOTE 3—The test for flow consistency, unit weight, and air content (D 6023) must be started within 5 min after obtaining the final portion of the composite sample, Complete these tests as expeditiously as possible.

8.4 With the filling apparatus, scoop through the center portion of the receptacle and pour the CLSM into the flow cylinder. Fill the flow cylinder until it is just level full or slightly overfilled.

8.5 Strike off the surface with a suitable straight edge, until the surface is flush with the top of the flow cylinder, while holding the flow cylinder in place. Remove any spillage away from the cylinder after strike off.

8.6 Within 5 s of filling and striking off, raise the flow cylinder quickly and carefully in a vertical direction. Raise the flow cylinder at least 15 cm (6 in.) by a steady upward lift with no lateral or torsional motion in a time period between 2 and 4 s. Complete the entire test from the start of filling through removal of the flow cylinder without interruption within an elapsed time of 1½ min.

8.7 Immediately measure the largest resulting spread diameter of the CLSM. Take two measurements of the spread diameter perpendicular to each other. The measurements are to be made along diameters which are perpendicular to one another.

NOTE 4—As the CLSM spreads, segregation may occur, with the water spreading beyond the spread of the cohesive mixture. The spread of the cohesive mixture should be measured.

NOTE 5—For ease in measuring perpendicular diameters, the surface that the flow cylinder will be placed on can be marked with perpendicular lines and the cylinder centered where the lines cross.

NOTE 6—The average diameter of the CLSM patty typically is established by the specifying organization and may vary depending on how the CLSM is being used. For flowable CLSM used to readily fill spaces (without requiring vibration), the average diameter of the patty typically is 20 to 30 cm (8 to 12 in.).

9. Report

9.1 *Include the following information in the report*:

9.1.1 Sample identification.

9.1.2 Identification of individual performing the test method.

9.1.3 Date the test is performed.

9.1.4 Record the two measurements to the nearest 1 cm(½ in.). Compute the average of the two measurements rounded off to the nearest 5 mm (¼ in.), and report as the average flow consistency of the CLSM.

10. Precision and Bias

10.1 *Precision*—Data are being evaluated to determine the precision of this test method. Additionally, Subcommittee D 18.15 is seeking pertinent data from users of the test method.[5]

10.2 *Bias*—No statement on bias can be prepared because there are no standard reference materials.

11. Keywords

11.1 backfill; CLSM; construction control; flowable fill; flow consistency; flow cylinder; mix design; quality control; soil stabilization

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[5] Anyone having data pertinent to the precision of this test method or wishing to participate in a round robin test, contact the D18.15 Subcommittee Chairman at ASTM Headquarters.

APPENDIX

(Nonmandatory Information)

X1. Rationale

X1.1 This test method was developed to provide an accepted, consensus method of measuring the flow characteristics of CLSM. Although CLSM may be mixed and delivered like concrete, the mixture typically is much more fluid than concrete so that it readily will fill voids and spaces. This test method provides a procedure to quantify the flow characteristics.

SUMMARY OF CHANGES

This test method previously was provisional standard (PS) 28 and has been revised and approved as a full consensus standard.

(1) This standard previously had the designation PS 28–95, a provisional standard.
(2) The differences between this version of the standard and the previous one are as follows:
(3) Addition of Sections 1.3, 5.4, 6.4, 6.5, 8.1, 8.2, 8.3, 8.4, Note 2, Note 4, Note 5, Note 6, Appendix X1.1 and this section.
(4) Revised wording in Sections 3.2.1, 3.2.2, 4.1, 6.1, 8.2, 8.4, 8.5, 8.6, 9.1, 10.1, 11 and Note 4
(5) SI units made the standard