Filling Abandoned Underground Facilities with CLSM Fly Ash Slurry

by Tarun R. Naik, Bruce W. Ramme, and Henry J. Kolbeck

The Wisconsin Electric Power Company (WE) is well along in developing a solution to the age-old problem of how to have one's cake and eat it, too: they're creating fly ash, but also using it. Working together with the University of Wisconsin-Milwaukee Center for By-Products Utilization, WE is identifying mix proportions for flowable fly ash slurry that can be used as backfill for excavation projects and as fill for abandoned underground facilities.

Through a joint research project, mix proportions have been developed for low-strength flowable fly ash slurries, controlled low strength materials (CLSM) as classified by ACI Committee 229, using fly ash produced at WE's Valley Power Plant in Milwaukee. (The chemical composition of the fly ash is shown in Table 1.) The plant uses bituminous coal from various eastern and midwestern sources.

CLSM is defined as a cementitious material that is in a flowable state at placement and has a specified compressive strength of 1200 psi (8.3 MPa) or less at 28 days. It is used primarily for nonstructural applications below grade where low strength is required; in some cases, it is intended to be no stronger than the surrounding soil after it has attained the final set. The type of CLSM selected should be based on technical and economical considerations for the specific application.

The mix proportions for the CLSM used in this project were selected to obtain a low strength material in the 50 to 100 psi (345 to 690 kPa) range. This level of strength is similar to that of many undisturbed or recompacted soils and makes it suitable as a backfill material for utility trenches containing ducts, pipes, and manholes; other excavations in streets and around foundations; and as fill for abandoned tunnels, sewers, and other underground cavities.

To achieve maximum utilization of the coal combustion by-product, the mixes were proportioned using a large quantity of the Class F fly ash, a small amount of cement, and water. In all cases, the material is proportioned to allow for easy future removal with ordinary excavating equipment while leaving the trench or excavation walls intact.

This phase of WE's research was limited to developing mix proportions consistent with specified strength and flowability requirements. Some of these CLSM slurry mixes have been used for trial construction projects, which are described later.

Background

In most of the literature reviewed, which covered the period from January 1970 to June 1988, it was noted that the subject of flowable fly ash slurry required further development and additional research.[1-6] The only work identified that directly relates to the present project was reported in 1979 by Fuston, Krell, and Zimmer,[7] who developed a flowable fly ash material that was used as a backfill either above or below water.

The material developed was composed principally of fly ash, cement (4 to 5 percent dry weight), and an appropriate amount of water to produce the flowability required for a particular application. The strength ranged between 50 and 100 psi (345 to 690 kPa) at 28 days and the dry density ranged from 70 to 85 lb/ft^3 (1120 to 1360 kg/m^3). The permeability was approximately 5×10^{-6} centimeters per second, which places it between typical soil backfill materials, (i.e., 10^{-1} to 10^{-3} for sand and 10^{-7} and lower for clay materials).

Fuston, Krell, and Zimmer reported that the material, which can be produced in pug mills, turbine-type mixers, and in central concrete mix plants, could be excavated if necessary with stable sidewalls. According to Swaffar and Price,[8] this material was used successfully for many applications, one of the more notable being to support a distressed tunnel internally prior to exterior grouting.[8]

Swaffar and Price also reported some limitations in using this new material, including handling, mixing, and placing problems, stating: "The new material cannot be handled as conventional fill material . . . the contractor must develop a feel for the flowable ash before working (easily) with it . . . the finished surface should not be considered a wearing surface . . . the surface will be slippery during rainfall, similar to a smooth clay."[8]

Flowable fly ash slurry is discharged from a ready-mix concrete truck into an abandoned steam utility manhole at Wisconsin Electric's Valley Power Plant in Milwaukee.

They concluded that further research and development would be needed to meet user needs.

Research program

Preliminary mix proportions

Several mixes were tested to establish a range of parameters that could be used for commercial application of flowable CLSM slurry using Class F fly ash from Valley Power Plant. Trial mix proportions were calculated for three mixes using about 47 lb (21.3 kg) of cement (Mix S-1), 94 lb (42.6 kg) of cement (Mix S-2), and 141 lb (63.9 kg) of cement (Mix S-3). A fourth mix (Mix S-4) was prepared using 141 lb (63.9 kg) of cement and a larger amount of water than in the Mix S-3 to achieve a very high flowability (almost like water). Mixes S-5 and S-6 were proportioned with lower slumps and higher cement contents. All mixes were chosen to simulate various applications and strength requirements.

CLSM production

The flowable CLSM slurry mixes were produced at a ready-mixed concrete plant in nominal 2-yd^3 (1.2-m^3) batches. The mix materials were loaded into the ready-mix truck in the usual manner using automated plant equipment. However, it was found that a more homogeneous mixture could be obtained if cement were loaded into the ready-mix truck first, then water, and then, after thoroughly mixing these materials, the fly ash. Additional mixing for a minimum of 15 minutes produced a good, completely mixed, homogeneous slurry. This falls well within the usually available delivery time of ready mixed materials. Type I cement was used for the test mixes because it is most frequently used in the Milwaukee area.

Final mix proportions

Mixes S-1, S-5, and S-6 were produced in 2-yd^3 (1.2-m^3) batches; Mixes S-2, S-3, and S-4 were produced in 1½-yd^3 (0.9-m^3) batches. The total weight of each component material was recorded for each mix. The final mix proportions per cubic yard were calculated using the actual material weights and checked against the unit weights of the mixes, which were obtained according to standard ASTM procedures. Final mix proportions along with field test data are given in Table 2.

Preparing the specimens

Each batch of slurry was visually evaluated and tested for acceptability before proceeding with the actual testing work. The fresh slurry was tested for flow, according to the procedure suggested by ACI Committee 229, as well as for temperature, ambient air temperature, and density.

The flow test is performed by placing an open-ended 3 in. diameter by 6 in. high (75 x 150 mm) steel cylinder form on a flat surface and filling it with the slurry. The form is then slowly lifted, letting the slurry spread laterally on the flat surface. After the slurry stops flowing (in 10 to 15 seconds), the diameter of the slurry mass is measured in two directions and the average diameter is recorded.

From each slurry mix, eight 6 in. diameter by 12 in. high (150 x 300 mm) cylinders were prepared for compressive strength testing at 7, 14, 28, and 56 days (two at each age). The cylinders were stored at room temperature, 65 ±5 F (18 ±2.8 C), and covered with plastic bags to minimize evaporation for a minimum of seven days before transport to the testing laboratory.

Mixes S-1 and S-2 were soupy (thick peak soup consistency) to liquid and flowed easily [8¾ in. (222 mm)]. Mix S-3 was more fluid than Mixes S-1 and S-2, and Mix S-4 was more fluid than Mix S-3, showing excellent flowability. Within approximately one hour, about $\frac{1}{16}$ in. (1.6 mm) of bleed water had collected on the top of most cylinders. Mixes S-5 and S-6 had lower flowability than others, but had good workability (similar to other mixes).

Flowable fly ash slurry is funneled into a 9½ ft diameter abandoned tunnel crossing the Menomonee River in downtown Milwaukee. The self-leveling material flowed over 235 ft.

The top surfaces of the cylinders were inspected periodically for condition of set, settlement, bleed water, and shrinkage cracks. Based on observations of the top surfaces of the cylinders at 3 days, Mixes S-1 and S-4 had not achieved final set and showed some settlement as well as retention of bleedwater. Mix S-2 showed no settlement and no bleedwater. Mix S-3 showed minor settlement and no bleedwater. There was no evidence of shrinkage cracks.

At 5 days, Mixes S-2 and S-3 had hardened further while Mixes S-1 and S-4 still were relatively soft, with a 2 in. (50 mm) long nail penetrating 2 and 1 in. (25 and 50 mm), respectively, under only moderate pressure [5 to 10 lb (142 to 284 kg)]. Mixes S-5 and S-6 showed no settlement or bleedwater and hardened faster than all others.

At 7 days, Mix S-1 had not changed appreciably and Mix S-4 had hardened further as indicated by lesser nail penetration. At 10 days, Mixes S-2 and S-3 had hardened sufficiently for transfer to the lab for testing. Final set had been achieved but they still were soft enough to allow a slight thumb print and approximately ⅛ in. (3.2 mm) nail penetration.

Mixes S-5 and S-6 achieved earlier final set and showed no bleedwater or settlement. They were tested at 7 days. None of the mixes (S-1 to S-6) showed any shrinkage cracks and settlement had not increased perceptibly since the 3-day measurement. The remaining cylinders were stored in a moist room until further compression tests were performed.

Observations during the second week showed that Mix S-1 had become somewhat less plastic, still permitting full penetration of the 2 in. (50 mm) long nail. Several small 0.01 x 1 in. (0.25 x 25 mm) shrinkage cracks were visible and there was no bleed water left. Settlement had not increased. Mix S-4 also had hardened further and permitted only a ⅜ in. (9.5 mm) deep nail penetration. Bleed water remained on five of eight cylinders and settlement had not increased.

During the third and fourth weeks, Mix S-1 remained plastic with one more crack on the top surface; bleed water had disappeared. Mix S-4 had hardened sufficiently for transfer to the testing laboratory at 28 days.

At 42 days, Mix S-1 cylinders still had not completely hardened. The 2 in. (50 mm) long nail could still penetrate fully into the cylinder. No further settlement had occurred and there were no additional shrinkage cracks, but circumferential shrinkage of ±0.01 in. (0.25 mm) was visible. The condition of the cylinders had not changed appreciably at the age of 55 days when they were discarded.

Test results and discussion

Compressive strength tests were performed on capped cylinders for Mixes S-2 and S-3 at 10, 15, 28, and 56 days. Mixes S-5 and S-6 were tested at 7, 14, and 28 days. The compressive strength tests for Mix S-4 were started at 28 days, after the cylinders had hardened sufficiently, and thereafter they were tested at 56 and 112 days. Compressive strength test results are shown in the Table 3 and Fig. 1.

Mixes S-5 and S-6 reached final set in less than 2 days. Mixes S-2 and S-3 reached final set in less than 3 days and had a compressive strength of 5 psi (34 kPa) at 28 days. Mix S-1, with a cement content of less than 47 lb (21.3 kg), did not reach its final set and had no strength at 28 days. Mix S-4, with more than 1050 lb/yd^3 (623 kg/m^3) total water, had excellent flowability (thick soup) but required up to 28 days to reach the final set and had a compressive strength of 50 psi (345 kPa).

The mix proportions indicate that a cement content of about 150 lb/yd^3 (90 kg/m^3) is necessary to produce compressive strengths greater than 50 psi (345 kPa) at 28 days. The flowability of mixes can

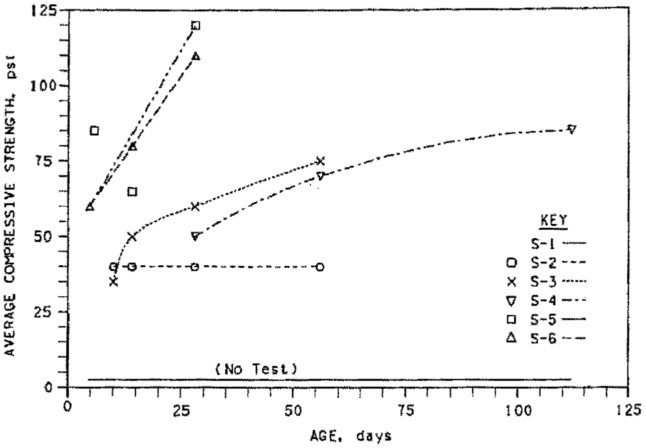

Fig. 1—Compressive strength versus age comparison for flowable fly ash slurry made with Class F fly ash and cement without aggregates.

Table 1 — Typical analysis of Class F fly ash from Valley Power Plant

Chemical composition	Number of samples	Range, percent	Average, percent	ASTM C-618, maximum
Silicon Oxide, SiO_2	4	50.06-50.20	50.14	—
Aluminum oxide, Al_2O_3	4	25.24-25.36	25.27	—
Iron oxide, Fe_2O_3	4	14.66-15.39	14.93	—
Total, $S_iO_2 + Al_2O_3 + Fe_2O_3$	4	89.96-90.82	90.36	70.5
Sulfur trioxide, SO_3	4	0.20-0.33	0.26	5.0
Calcium oxide, CaO	4	1.18-1.44	1.27	—
Magnesium oxide, MgO	4	0.70-0.74	0.71	5.0
Carbon	4	3.59-6.94	5.08	6.0
Available Alkalis as Na_2O	4	1.61-1.70	1.65	
Sulfur			0.22	—
Physical tests				
Fineness, percent retained on #325 wet sieve	1	25	25	34.0 Max.

be increased by adding 5 to 10 percent more water, if necessary.

Using the CLSM slurry mixes

Wisconsin Elelctric had used the high fly ash content CLSM slurry for three projects as of the fall of 1989. Another high fly ash content CLSM slurry project using WE-supplied fly ash was performed by a contractor as part of a sewer construction project. In addition, fly ash-aggregate slurries have been used on several projects, which will be discussed elsewhere.

Abandoned steam service tunnels

The first WE project involved filling two obsolete steam service tunnels in downtown Milwaukee in December of 1983. One tunnel was 6 ft. in diameter by 290 ft. long (1.8 x 88 m) and the other was a 5 ft. high by 4 ft. wide (1.5 x 1.2 m) ellipsoid section. Both tunnels were of brick construction and had 15 and 7 ft (4.6 and 2.1 m) of cover, respectively. Over 420 yd^3 (249 m^3) of CLSM slurry material was produced from 2152 lb (976 kg) of dry Class F fly ash, 859 lb (390 kg) of water, and 88 lb (40 kg) of Type I Portland cement.

The tunnels were bulkheaded with concrete blocks that were braced to resist the temporary lateral pressure of the material. Small openings were left at the top of the bulkheads for filling and venting air. All steam and drain lines in the areas to be filled were abandoned in place.

The fly ash was loaded directly into the ready-mix trucks from the wet unloaders under the ash silos that are used for loading open ash trucks. The unloading was timed and the average rate of flow was about 2 yd (1.8 m) per minute. The ash contained an average of 15 percent moisture. There were some problems with spillage at the truck hopper, indicating that truck positioning was critical.

After loading for 5 minutes, the ready-mix truck was moved out of the unloader area and the cement was added at the truck hopper with a concrete bucket. The remaining water was added from the truck's metered water tank. The drum was rotated a minimum of 60 revolutions during transit.

Adding about 100 gal. (0.38 m^3) of water to the drum prior to loading the ash seemed to alleviate some of the dusting problems. Also, the drum was rotated to help "feed" the ash inside. All but about 50 gal. (0.19 m^3) of water were added at the plant. The remaining water was added as required at the jobsite. About another 30 mixing revolutions were given depending on the amount of water added.

The material was pumped into the tunnels by a "squeeze-type" truck-mounted concrete pump, rated at 30 yd (27 m) per hour, using 2 in. (50 mm) diameter rubber hoses. The maximum length of pump line used was approximately 200 ft (61 m) and no pumping problems were experienced with any length of hose. The maximum distance of fly ash slurry flow was approximately 130 ft (40 m).

Cylinders were cast of the material as delivered. Unconfined compression tests that were run on the cylinders after 7 and 28 days showed strengths between 50 to 100 psi (345 to 690 kPa) and greater than 100 psi (690 kPa), respectively.

Sidewalk cavity

The second project involved backfilling a hollow sidewalk cavity containing locker room facilities in downtown Milwaukee during the summer of 1984. The filling covered a length of about 80 ft (24.4 m)

Table 2 — Mix proportions and field test data for flowable fly ash slurry*

Mix number	S-1	S-2	S-3	S-4	S-5	S-6
Specified design strength, at 28 days psi	50	50	50	50	100	100
Cement, lb/yd^3	36	98	158	144	222	273
VPP fly ash, lb/yd^3	1425	1366	1262	1155	1496	1417
Water, lb/yd^3	1084	1068	1052	1146	970	963
Flow/spread,*† in. diameter	8¾	8¾	10½	16¾	5½	5¾
Air content, percent	0.7	0.8	1.1	0.6	0.9	1.1
Air temperature, F	49	55	49	49	32	32
Slurry temperature, F	95	96	91	89	64	86
Slurry density, lb/ft^3	94.2	93.7	91.5	90.6	99.61	98.27
Slurry weight, lb/yd^3	2545	2532	2472	2445	2688	2653
Date cylinders cast	11/25/88	11/25/88	11/25/88	11/25/88	2/13/89	2/13/89

*Supplied by New Berlin Redi-Mix, Inc.
†Measured by ACI Committee 229 procedure.

of sidewalk that was about 14 ft (4.3 m) wide and 7 ft (2.1 m) deep out of a total depth of over 10 ft (3 m). The remaining 3 ft (0.9 m) of height was filled with sand to provide a cushion for the sidewalk slab. Concrete block bulkheads were constructed in all openings leading into the structure's basement.

The mix proportions to produce 300 yd^3 (230 m^3) of CLSM slurry material were 1950 lb (885 kg) of dry Class F fly ash, 1000 lb (454 kg) of water, and 128 lb (58 kg) of Type I Portland cement.

The slurry was discharged from the truck directly into the cavity. Since the mix is very fluid, it flowed the length of the sidewalk [about 75 ft (23 m)], with a residual surface elevation differential of about 6 in. (152 mm). It was possible to walk on the material the next day without leaving any imprints.

Several shrinkage cracks were noticed the next day, probably because at the end of the day the ready-mix drums were rinsed with water that was then discharged into the sidewalk cavity. However, no cracks or voids developed where the slurry was in contact with the surrounding walls. Even when extra water was added, there was very little ponding. The water was quickly absorbed, merely raising the moisture content of the upper layer of slurry temporarily. Seven-day strengths ranged from 50 to 130 psi (345 to 896 kPa) and 28 day strengths ranged from 170 to 320 psi (1172 to 2206 kPa).

It was necessary to install a water supply lateral line several months after installing the slurry. The excavation was performed with a tractor-mounted backhoe. The hardened slurry was rippable and the excavation had straight walls on each side, showing that this type of material can be excavated without problems provided the compressive strength, as a measure of hardness, is less than 300 psi (2069 kPa) at 28 days.

Table 3 — Compressive strength test results for flowable fly ash slurry

Mix number	S-1		S-2		S-3		S-4		S-5		S-6	
Specified strength, psi	50		50		50		50		100		100	
Class of fly ash	F		F		F		F		F		F	
Spread diameter, in.	8¾		8¾		10½		16¾		5½		5¾	
Test age, days	Compressive strength, psi											
	Actual	Average	Actual	Average	Actual	Average	Actual	Average	Actual	Average	Actual	Average
7	—	—	—	—	—	—	—	—	80 90	85	60 60	60
10	—	—	40 40	40	40 30	35	—	—	—	—	—	—
14	—	—	50 30	40	50 50	50	—	—	60 60	60	90 70	80
28	—	—	40 40	40	60 60	60	60 40	50	100 140	120	110 110	110
56	—	—	50 30	40	80 70	75	70 70	70	—	—	—	—
112	—	—	—	—	—	—	90 79	85	—	—	—	—

Because of its low strength, excavating the hardened CLSM is easily accomplished with ordinary excavation equipment.

Steam utility facilities

The third project involved filling a number of abandoned steam utility facilities in the Menomonee River Valley of Milwaukee:

- 375 ft (114 m) of single 30 in. (76 cm) diameter main in a concrete trench box and 340 ft (104 m) of double 30 in. (76 cm) diameter main and trench box
- 235 ft (72 m) of a 9½ ft (2.9 m) diameter steel tunnel under the Menomonee River Canal
- Two 18 ft diameter by 65 ft (5.5 x 20 m) deep concrete shafts for access to the Menomonee River Canal tunnel
- Associated valve bunkers and manholes

Mix proportions to produce 2324 yd^3 (1778 m^3) of CLSM slurry for the project were 1520 lb (690 kg) of dry Class F fly ash, 874 lb (396 kg) of water, and 56 lb (25 kg) of Type I Portland cement. The material was produced in the same manner described previously and was discharged from the truck directly into the cavities. The material flowed freely and the filling of the tunnel beneath the river was monitored from the opposite shaft.

Strengths at 28 days averaged 40 psi (276 kPa), 56 day strengths averaged 44 psi (303 kPa), and 91 day strengths averaged 49 psi (338 kPa). By increasing the cement content to 100 lb (43.4 kg), the unconfined compression strength of the slurry reached 100 psi (690 kPa).

Sewer

Another project using high fly ash content CLSM slurry was performed by Mainline Sewer & Water Inc. for the Milwaukee Metropolitan Sewer District. The project involved filling the abandoned Indian Creek Parkway Sewer. Mix proportions to produce 831 yd^3 (636 m^3) of material were 1377 lb (625 kg) of dry Class F fly ash, 550 lb 250 lb) of water, and 56 lb (25 kg) of Type I Portland cement. The material reportedly flowed up to 300 ft (91 m) and had a 7-day strength of 115 psi (793 kPa) and a 28-day strength of 137 psi (945 kPa).

These four projects have demonstrated that high fly ash content CLSM slurry can be used successfully to fill abandoned tunnels and sewers and to backfill hollow sidewalks. It should also be suitable in other applications where ordinarily sand and gravel backfills or slurries are used, such as backfilling for sewer and other utility excavations where settlement has to be prevented.

Please note that the mix proportions shown represent the actual recipes used and do not necessarily yield exactly one cubic yard of material.

Excavation of the material using ordinary excavation equipment was also shown to be possible without undue effort.

Conclusions

Test results shown in Table 3 indicate that a flowable fly ash slurry mix with low cement content, all Class F fly ash, and no aggregates can be produced that has excellent flowability and a compressive strength in the range of 50 to 100 psi (345 to 690 kPa). The cement content should be 100 ± 50 lb/yd^3 (59 ± 30 kg/m^3). The water content should be kept in the range of 1000 lb (454 kg), depending on the specific cement and fly ash used. While other methods have been used elsewhere, the sequence of mixing the cement and water in the ready-mix truck before adding the fly ash worked well in these tests.

The primary purpose of these tests was to establish that a low cement, all Class F fly ash slurry has suitable properties and some compressive strength. Higher strengths can be achieved by adding more cement, and/or aggregate such as sand or bottom ash, and/or less mixing water. However, higher strength slurries may have less flowability and would be more difficult to remove using regular excavation methods.

High fly ash content CLSM slurry was successfully used to fill abandoned underground utility structures and should also be suitable in other applications where ordinarily sand and gravel backfills or slurries are used, especially for backfill where settlement has to be prevented. Excavating the material was also possible without undue effort using ordinary excavation equipment.

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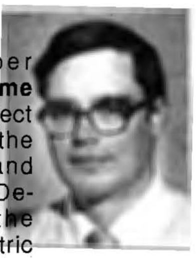
Selected for reader interest by the editors.

ACI Fellow **Tarun R. Naik** is director of the Center for By-Products Utilization and an associate professor of civil engineering at the University of Wisconsin, Milwaukee. He received his BE degree from the Gujarat University, India, and MS and PhD degrees from the University of Wisconsin, Madison. He is a member of ACI Committees 201, Durability of Concrete; 232, Fly Ash and Natural Pozzolans in Concrete; 123, Research; Concrete Materials Research Council; E 801, Student Concrete Projects; and 214, Evaluation of Results of Tests Used to Determine the Strength of Concrete, and others.

ACI member **Henry J. Kolbeck** is assistant director of the Center for By-Products Utilization at the University of Wisconsin, Milwaukee, and is engaged in research on the use of such by-products as coal ashes in concrete construction materials and products. He is a member of ACI Committees 229, Controlled Low Strength Materials; and 232, Fly Ash and Natural Pozzolans in Concrete.



ACI member **Bruce W. Ramme** is a senior project engineer with the Engineering and Construction Department of the Wisconsin Electric Power Company, Milwaukee. He received his BS and MS degrees in structural engineering from the University of Wisconsin, Milwaukee.