Chapter 5

Controlled Low-Strength Material (CLSM) Containing We Energies Fly Ash

Introduction

During the past two decades fly ash has been increasingly used in the manufacture of controlled low-strength material (CLSM). CLSM is defined by ACI Committee 229 as a “self-compacted cementitious material used primarily as a backfill material in lieu of compacted fill with a compressive strength of 1200 psi or less.” However, where future excavation is anticipated, the ultimate compressive strength of CLSM should be less than 300 psi. This level of strength is very low, compared to concrete, but very strong when compared to soils. The composition of CLSM can vary depending on the materials used in the mixture. CLSM has the unique advantage of flowing and self-leveling. Hence, in applications like filling abandoned underground tanks or voids under pavements, CLSM may be the only viable method of completely filling the void. Additionally, there is no cost associated with vibrating or compacting the material in place.

CLSM may be known by such names as: unshrinkable fill, controlled density fill, flowable mortar, plastic soil-cement, soil-cement slurry and K-Krete (36). We Energies uses the registered trademark, Flo-Pac® for its CLSM. The range of strength required varies with the type of application. However, CLSM is normally designed to develop a minimum of at least 20 psi strength in 3 days and 30 psi at 28 days (ASTM C403 penetration resistance numbers of 500 to 1500).

A compressive strength of 100 psi is equivalent to the load bearing capacity of a well compacted soil with a capacity of 14,400 psf which is comparable to a densely compacted gravel or hard pan type soil. Where CLSM is used as a support layer for foundations, a compressive strength of 300 psi to 1200 psi is sometimes used. However, applications involving CLSM with strength in this range are very limited and often not necessary.

The CLSM mixture selected should be based on technical and economic considerations for a specific project. The desired strength level and flowability are two significant considerations for CLSM. Permeability, and shrinkage or expansion of the final product (hardened CLSM) are additional considerations.

We Energies CLSM Developments

The development of CLSM containing We Energies fly ash has been a long process involving manufacturing several trial mixes and studying their properties. Various parameters were considered; however, compressive strength and excavatability are primary considerations. In the early trials a wide variety of sample strengths were developed, some of which were higher than normally recommended for CLSM.

Several CLSM mix designs were developed and tested using We Energies fly ash at the Center for By-Products Utilization (CBU) at the University of Wisconsin-Milwaukee (UWM). The scope of these tests was to evaluate fly ash, the properties of the mixes and study potential field applications. The mixes were prepared using various percentages of Class C and Class F fly ash with various proportions of other ingredients. It is important to note that Class F fly ash can be used in much higher proportions (sometimes replacing aggregate) than cementitious Class C fly ash which is introduced primarily as a binder.

CLSM production is an excellent use for fly ash that does not meet all of the ASTM C618 requirements for use in concrete. The strength level required for CLSM is low when compared to concrete and can be easily obtained with off-spec fly ash. High carbon content can be a reason for concern in air-entrained concrete where air entraining admixtures are absorbed yielding inadequate or variable concrete air content. In CLSM, air content is often not a requirement and hence the presence of carbon particles do not affect its properties.

CLSM Produced with We Energies High-Lime (ASTM C618 Class C) Fly Ash

The mixtures shown in Table 5-1 were developed using ASTM C618 Class C fly ash produced at We Energies's Pleasant Prairie Power Plant from burning western United States sub-bituminous coal. The chemical and physical properties of the PPPP fly ash are listed in Chapter 3, Tables 3-1 and 3-2. The mixtures were produced at a commercial batch plant using standard procedures that were monitored to assure homogeneity of the products.

Table 5-1: Mixture Proportions and Field Test Data for CLSM (and Low-Strength Concrete) Produced With Class C Fly Ash

Mix No.	C-1	C-2	C-3	C-4	C-5	C-6	C-7
Specified Strength at 28-Day Age, psi	500	1000	1200	500	750	1000	500
Cement, lb./cu yd.	74	89	104	70	81	96	129
Fly Ash, lb./cu yd.	128	158	189	118	159	195	239
Water, lb./cu. yd.	332	293	283	345	337	338	351
SSD Sand, lb./cu. yd.	1763	1671	1609	1728	1611	1641	1543
SSD Pea Gravel, lb./cu. yd.	1773	1832	1863	1778	1761	1813	1721
Slump, inches.	1-3/4	3/4	1-1/4	7-1/2	6-1/4	6-1/2	9-1/4
Air Content, Percentage	3.2	2.7	2.6	2.1	2.3	2.2	1.0
Air Temperature, Fahrenheit	40	45	49	37	40	38	32
Concrete Temperature, Fahrenheit	64	62	58	55	60	60	58
Concrete Density, pcf	150.7	149.8	149.9	149.6	146.3	151.2	147.5
Concrete Weight, lb./cu. yd.	4070	4044	4048	4039	3969	4083	3983
W/(C+FA)	1.64	1.19	0.97	1.84	1.16	1.16	0.95

The first three mixtures were produced with low cement content and relatively low water content.

Mixtures C-1 to C-3 showed very low slump and did not flow as desired in a flowable slurry. Hence, new mixtures were developed, taking into consideration the drawbacks of previous mixes. (37)

The new mixes C-4 to C-7 showed good to very good flowability. A detailed discussion of the research can be obtained from reference 37.

Figure 5-1 is a graph showing compressive strength vs. age for these mixtures. Figure 5-2 shows 28-day compressive strength vs. total cementitious material, and Figure 5-3 shows 28-day compressive strength vs. water to cementitious ratio for these mixtures. Table 5-2 shows the CLSM compressive strength test results.

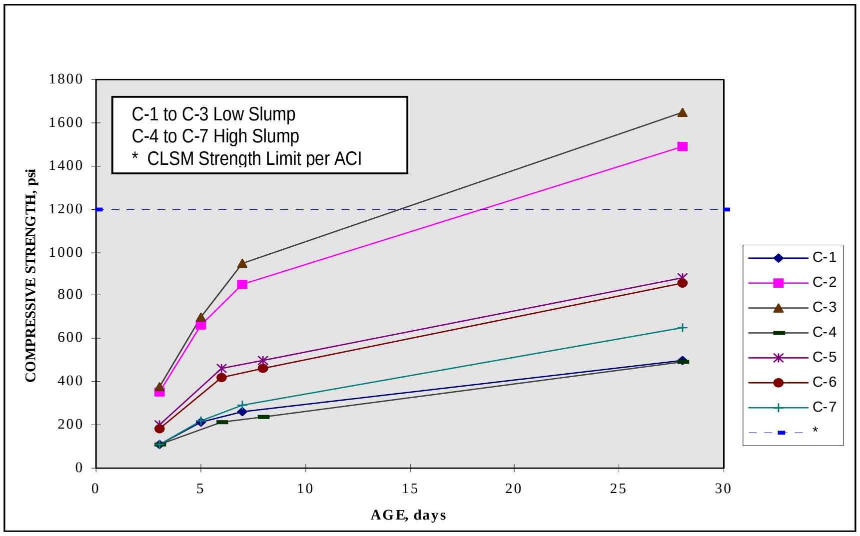

Figure 5-1: CLSM Compressive Strength vs. Age Comparison (Class C Fly Ash)

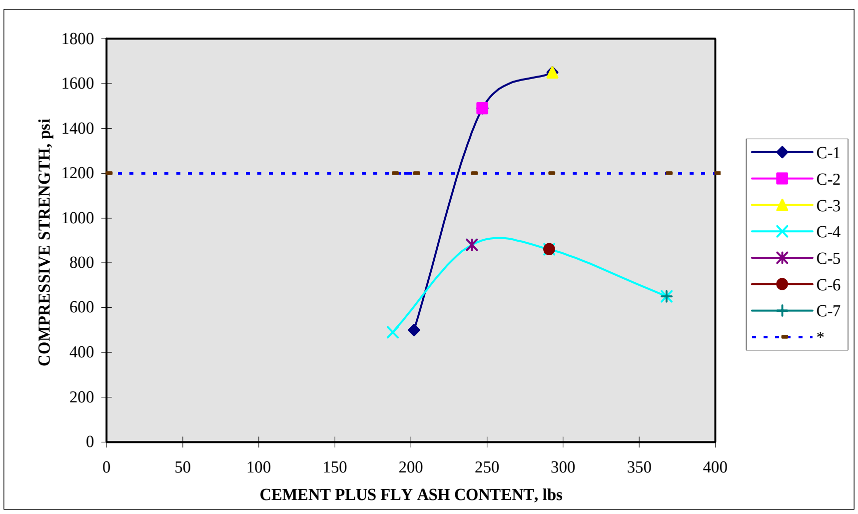

Figure 5-2: CLSM 28-Day Compressive Strength vs. Total Cementitious Material (Class C Fly Ash)

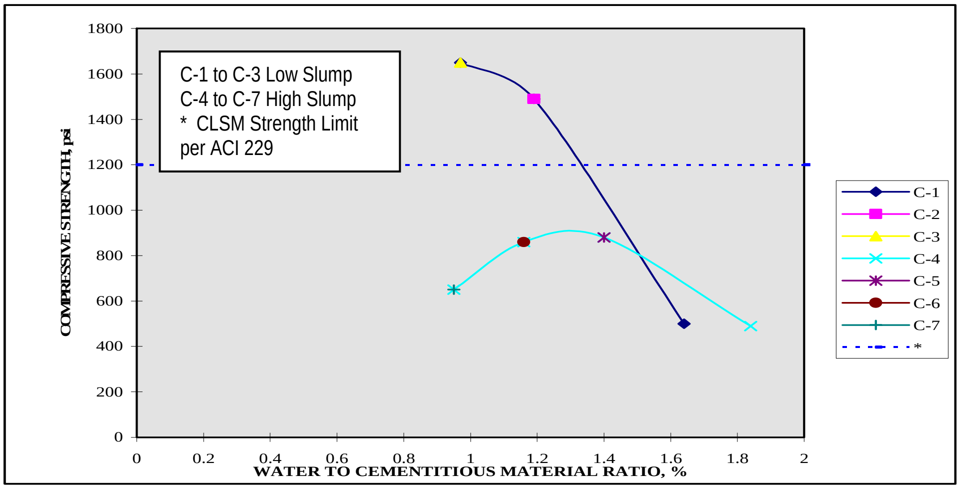

Figure 5-3: CLSM 28-Day Compressive Strength vs. Water to Cementitious Material Ratio

Table 5-2: High Fly Ash CLSM Test Data 500-1200 psi Specified Strength Range at 28-Day Age

MIX No.	C-1	C-2	C-3	C-4	C-5	C-6	C-7
Specified Strength, psi	500	1000	1200	500	750	1000	500
Class of Ash	C	C	C	C	C	C	C
Slump, in	1-3/4	3/4	1-1/4	7-1/2	6-1/4	6-1/2	9-1/4
TEST AGE, Days	COMPRESSIVE STRENGTH, psi						
3	110	350	375	110	200	180	110
5	210	660	700				220
6				210	460	420	
7	260	850	950				290
8				240	500	460	
28	500	1490*	1650*	490	880	860	650

* Exceeds CLSM strength cap of 1200 psi specified by ACI 229.

It can be concluded from these test results that:

1. As the water to cementitious materials ratio increases, the compressive strength decreases for the low slump mixtures.
2. The compressive strength did not change significantly for the higher slump mixtures as the water to cementitious materials ratio increased between 1.0 and 2.0.

3. All mixtures behaved well and can be used as a basis for selection of mixtures for CLSMs or low-strength high fly ash content concrete for non-structural applications.
4. The compressive strength results for all these trial mixtures are at a level where easy excavatability will not be possible.

CLSM Containing We Energies Valley Power Plant Off-Spec (ASTM C618 Class F) Fly Ash

The mixture proportions used in this project were designed to have a compressive strength of 500 psi to 1500 psi. This strength level is similar to the strength levels of many natural rock formations and can be used as foundation support, capable of distributing the load uniformly.

The CLSM mixtures were produced at a commercial batch plant in New Berlin, Wisconsin. The mixtures contained ⅜” (maximum size) pea gravel, in addition to fly ash, cement, sand and water. The final mixtures were designed with high slump (7” to 9”.).

From each concrete mixture, 6” diameter by 12” high cylinders were prepared for compressive strength and other tests. Cylinders were tested from each mixture at the ages of 3, 5, 7 and 28 days. Shrinkage was noted to be very low, ranging from 0 to 1/32” for the 12” high cylinders. A detailed discussion of this research can be obtained from reference 38.

Table 5-3 gives the chemical and physical test data for mixtures produced with off-spec ASTM C618 Class F fly ash from Valley Power Plant. Tables 5-4 and 5-5 show mixture proportions, field test data, and compressive strength data for the various mixtures.

Figure 5-4 is a graph showing compressive strength vs. age for these mixtures. Figure 5-5 shows compressive strength vs. total cementitious material for the same mixtures, and Figure 5-6 shows compressive strength vs. water to cementitious material ratio for the above mixtures.

Table 5-3: Chemical and Fineness Test Data for Class F Fly Ash from Valley Power Plant

Chemical Composition	No. of Samples	Range, %	Average, %	ASTM C-618
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, $SiO_2+Al_2O_3+Fe_2O_3$	4	89.96-90.82	90.36	50 Min
Sulfur Trioxide, SO_3	4	0.20-0.33	0.26	5.0 Max
Calcium Oxide, CaO	4	1.18-1.44	1.27	-
Magnesium Oxide, MgO	4	0.70-0.74	0.71	5.0 Max
Carbon	4	3.59-6.94	5.08	6.0 Max
Available Alkalis as Na_2O	4	1.61-1.70	1.65	
Sulfur	4		0.22	
Physical Tests				
Fineness: % Retained on #325 Sieve	1	25		34.0 max

Table 5-4: Mixture Proportions and Field Test Data for Class F Fly Ash CLSM

Mix No.	F-1	F-2	F-3	F-4	F-5	F-6
Specified Strength at 28-Day Age, psi	1000	1500	2000	1500	1500	1500
Cement, lb./cu. yd.	102	151	229	138	211	263
Fly Ash, lb./cu. yd.	499	519	500	452	459	446
Water, lb./cu. yd.	439	375	422	323	294	320
SSD Sand, lb./cu. yd.	1206	1198	1111	1090	1053	1060
SSD Pea Gravel, lb./cu. yd.	1614	1697	1680	1783	1774	1688
Slump, inches	9	7-3/4	8-1/4	9	7-1/4	8-1/4
Air Content, Percentage	1.0	1.8	1.9	0.5	1.4	1.7
Air Temp., Fahrenheit	38	36	35	32	33	33
Concrete Temperature, Fahrenheit	65	64	64	58	60	62
Concrete Density, pcf	143.0	145.9	146.0	140.2	140.4	139.5
Concrete Weight, lb./cu. yd.	3861	3940	3942	3786	3791	3777
W/C	4.3	2.5	1.8	2.34	1.39	1.22
W/(C+FA)*	0.73	0.56	0.58	0.55	0.44	0.45

* May not be meaningful because all of the Type F fly ash probably should not be accepted as cementitious

Table 5-5: Class F Fly Ash CLSM Test Data

Mix No.	F-1	F-2	F-3	F-4	F-5	F-6
Specified Strength, psi	500	1000	1500*	500	1000	1500*
Class of Ash	F	F	F	F	F	F
Slump, inches	9	7¾	8¼	9	7¼	8¼
Test Age, days	Compressive Strength, psi					
3	110	270	500	123	263	420
5				200	383	630
6	210	470	820			
7				237	443	693
8	220	510	880			
28	490	930	1640*	677	900	1210*

* Exceeds CLSM strength cap specified by ACI 229 of 1200 psi

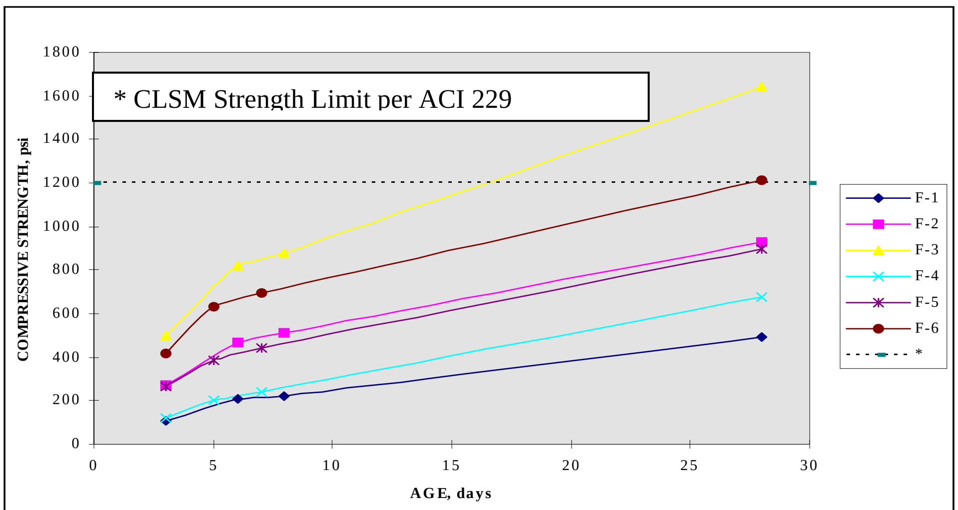

Figure 5-4: CLSM Compressive Strength vs. Age Comparison (Class F Fly Ash)

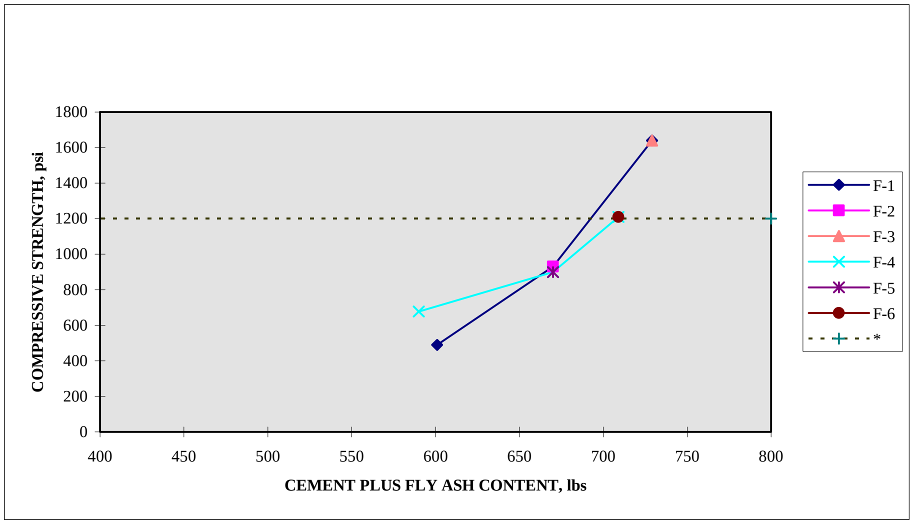

Figure 5-5: CLSM 28-Day Compressive Strength vs. Total Cementitious Material

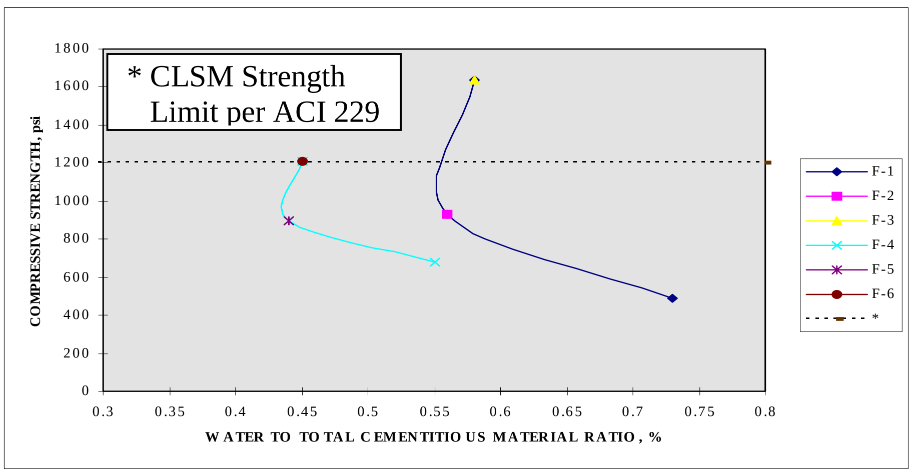

Figure 5-6: CLSM 28-Day Compressive Strength vs. Water to Cementitious Material Ratio

The following conclusions were made from this research (38).

1. The compressive strength decreased as water to cementitious material ratio increased.
2. All mixtures showed good flowability and workability.
3. Shrinkage was minimal.
4. The mixture designs developed performed well and can be used as a basis for selecting mixture proportions for CLSMs or low-strength concrete with high slump for non-structural applications, using the same materials.
5. All of these mixtures <u>will not</u> be easily excavatable.

CLSM Made with We Energies Port Washington Power Plant Off-Spec (ASTM C618 Class F) Fly Ash

This study was conducted by We Energies with a local ready mix firm to determine various properties of CLSM material containing off-spec ASTM C618 Class F fly ash from Port Washington Power Plant (PWPP). CLSM fly ash slurry was initially used for limited applications in filling abandoned underground facilities and voids such as tunnels, manholes, vaults, underground storage tanks, sewers and pipelines. Another obvious application is the backfilling of trenches for underground utility lines. For this application it is important that the backfill material be compatible with the underground utility line material. Also, the material should be easily excavatable and also provide for special needs such as high thermal conductivity for underground high-voltage transmission lines.

ASTM C618 chemistry tests were not performed on PWPP fly ash at the time of this research because this fly ash was not used for the production of concrete. However, fly ash from Valley Power Plant that used the same coal was tested. The chemical composition is shown in Table 5-3 for reference purposes. The physical properties of PWPP fly ash are shown in Table 5-6.

Table 5-6: Physical Properties of Port Washington Power Plant Class F Fly Ash

Test	Class F Fly Ash	ASTM C618	
		Min	Max
Fineness	28.8	-	34
% Retained on #325 Sieve	30.2	-	
Pozzolanic Activity Index			
With Cement (28 days), %	99.4	75	-
With Lime (7 days), psi	*	800	-
Water Requirement, % of Control	109	-	105
Autoclave Expansion, %	0.05	-	0.8
Specific Gravity	2.33 2.34	- -	- -
Variation from Mean			
Specific Gravity, %	0.214	-	5
Fineness, %	2.290	-	5

* Not enough material was available to do this test

CLSM laboratory trial mixtures using PWPP fly ash were also developed at the Center for By-Products Utilization (CBU) at the University of Wisconsin-Milwaukee (UWM) laboratory in November of 1991. The mixture proportions and corresponding compressive strength test results are shown in Table 5-7 (laboratory tests) and Table 5-8 (ready-mix plant production tests). Figure 5-7 is a graph showing compressive strength vs. age for these mixtures.

Table 5-7: Laboratory CLSM Mixture Proportions for PWPP Class F Fly Ash and Compressive Strength Data

Ingredient	Actual Weight	Cubic Yard Basis
Cement (Type 1)	2.2 lbs	69 lbs
Fly Ash	44.2 lbs	1389 lbs
Water	34.0 lbs	1069 lbs
Water/Cement Ratio	15.45	15.45 lbs
Water/Cementitious Material ratio	0.73	
Compressive Strength Data		
Test Age	Max. Load, lb	Compressive Strength, psi
7 day	640	23
28 day	1150	41
56 day	1090	38

Table 5-8: Ready Mix CLSM Mixture Proportions for PWPP Class F Fly Ash and Compressive Strength Data

Mix No.	1	2	3	4
Cement (Type 1), lbs	94	94	94	94
Fly Ash*, lbs	1731	1329	1153	699
Water, lbs	853	644	617	372
Sand (SSD), lbs	-	1000	-	1200
¾" Aggregate (SSD), lbs	-	-	1000	1700
Slump, in	9	9	10	8 3/4
Average Compressive Strength, psi				
1 Day	0	6	5	43
3 Day	7	22	17	96
4 Day	4	10	11	117
7 Day	16	36	30	162
28 Day	39	62	50	276

* Dry Weight

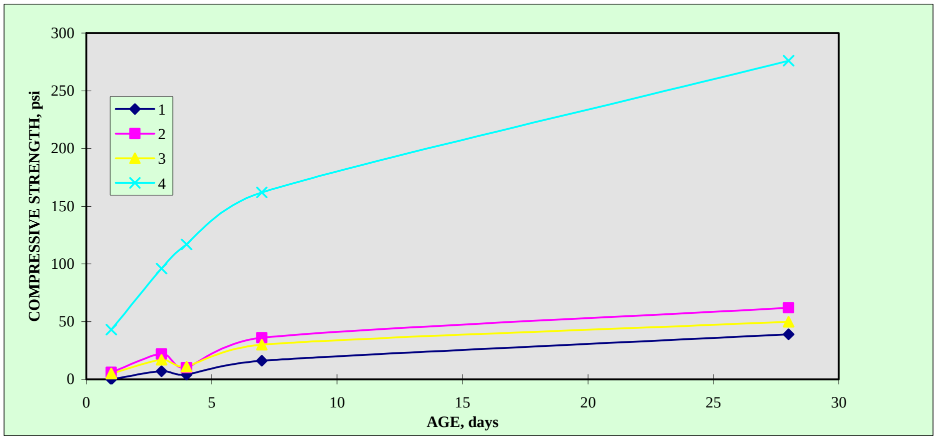

Figure 5-7: Compressive Strength vs. Age Comparison (Class F Fly Ash with One Bag Cement)

The compressive strength test results for mixtures 1 – 3 at a 28-day age ranged from 39 – 62 psi and are comparable to many undisturbed or recompacted soils, which makes it suitable as a backfill material. Mixture 4, with a 28-day compressive strength of 276 psi, may be suitable in applications below foundations where future excavatability concerns are not important. It is important to note that all four mixtures contained only one bag of Portland cement and that mixture 4 contained both coarse and fine aggregates.

Electric Resistivity, Thermal Conductivity and Plastics Compatibility Properties of CLSM Produced with We Energies Fly Ash

Figure 5-8: CLSM flows into place and completely filled this underground equipment vault.

Electric resistivity, thermal conductivity and plastics compatibility evaluations were performed on solidified CLSM fly ash slurry produced from a mixture of 1,275 lbs. of Valley Power Plant fly ash, 150 lbs. of Type 1 Portland cement and 1,050 lbs. of water per cubic yard (39).

Compressive strength tests were also performed per ASTM C39 for comparison of these special properties. Electrical resistivity tests were performed in accordance with California Test 643-1978. Moisture content in the selected samples varied from 20% to 100%. Thermal conductivity tests were conducted using the thermal needle test method (Mitchell and Kao, 1978). Electrical resistivity test values are used to predict corrosiveness of soils. The electrical resistivity values obtained from the tests indicate that CLSM fly ash slurry is not considered corrosive. Table 5-9 shows commonly used soil corrosivity vs. resistivity values.

Table 5-9: Electrical Resistivity vs. Soil Corrosivity

Resistivity (ohm-cm)	Corrosivity
Below 500	Very Corrosive
1,000 - 2, 000	Moderately Corrosive
2,000 - 10,000	Mildly Corrosive
Above 10,000	Progressively Less Corrosive

Thermal conductivity results exhibited a near linear relationship with moisture content. Thermal conductivity increases with an increase in moisture content and dry density. In applications like backfill for underground power cables where high thermal conductivity is desired, high-density, low porosity mixtures are preferable. Thermal conductivity values of high-volume flowable fly ash slurry are typically lower than sand, silt and clays but higher than peat.

Figure 5-9: Excavating hardened CLSM with a backhoe at We Energies' Valley Power Plant in downtown Milwaukee, Wisconsin.

A study conducted by Dr. Henry E. Haxo, Jr. of Matrecon, Inc., Alameda, California, concluded that high-density polyethylene-coated steel gas pipe, medium-density polyethylene gas pipe and low-density polyethylene jacketed cable would not be adversely affected by CLSM fly ash slurry (39).

Tables 5-10 and 5-11 show the electrical resistivity test results and thermal conductivity test results respectively.

Table 5-10: Resistivity Test Results CLSM Fly Ash Slurry (ohm-cm)

Moisture Content %	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
20	213606	-	-	-	-	-
30	133504	-	-	-	-	-
40	13478	-	-	-	-	-
50	73427	-	-	150859	173555	106803
60	60077	140847	94788	134171	146854	101463
70	56739	126161	120821	108138	140179	100128
80	60077	108138	118151	97458	132169	92118
90	60077	95455	120154	86778	120154	86778
100	60077	94120	120154	87445	120154	86778
Dry Wt. (pcf)	50.74	54.81	50.74	52.28	55.73	68.29

Table 5-11: Thermal Conductivity Test Results CLSM Fly Ash Slurry (BTU/hr-ft-°F)

Moisture Content, %	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
0.0	0.08	0.08	0.08	0.1	0.09	0.09
2.6	-	0.09	-	-	-	-
3.0	0.08	-	-	-	-	-
16.0	-	-	0.19	-	-	-
16.1	-	-	-	-	-	0.18
17.7	-	-	-	0.22	-	-
25.0	-	-	-	-	0.2	-
62.9	-	0.53	-	-	-	-
65.0	0.42	-	-	-	-	-
66.9	-	-	0.46	-	-	-
75.3	-	-	-	-	0.47	-
76.0	-	-	-	0.49	-	-
77.4	-	-	-	-	-	0.46
Dry Density, pcf	55.6	55.9	55.1	50.6	50.2	50.4

It can be concluded from this research that:

1. Good quality CLSM fly ash slurry for utility trench backfill can be produced with off-spec Class F fly ash produced at PWPP and VAPP.
2. CLSM fly ash slurry using PWPP or VAPP fly ash has less corrosion potential than typical soil used for trench backfill.
3. High-density, very low porosity CLSM should be used where high thermal conductivity is desired, such as backfill around underground power cables.
4. CLSM fly ash slurry has no adverse effect on polyethylene plastics used for underground gas lines and power cables.

Conductive CLSM Containing We Energies High Carbon Fly Ash (US Patent 6,461,424 B1) (35)

Materials

Materials used in this project consisted of one source of fly ash, cement, clean concrete sand, crushed quartzite limestone aggregates, and taconite pellets. Materials were characterized for chemical and physical properties in accordance with the appropriate ASTM standards. Table 5-12 shows the mixture proportions.

Type I cement (Lafarge Cement Co.) was used throughout this investigation. One source of fly ash was used for this project (We Energies, Port Washington Power Plant, Units 2 and 3).

The CLSM mixtures were proportioned to maintain a practical value of flow that would not have excessive segregation and bleeding. The flow was reduced for mixtures containing sand and gravel to maintain the cohesiveness and the workability of the mixture.

Fresh CLSM properties such as air content (ASTM D 6023), flow (ASTM D 6103), unit weight (ASTM D 6023), and setting and hardening (ASTM D 6024) were measured and recorded. All test specimens were cast in accordance with ASTM D 4832. These specimens were typically cured for one day in their molds at about 70 ± 5ºF. The specimens were then demolded and placed in a standard moist-curing room maintained at 100% relative humidity and 73 ± 3ºF temperature until the time of test (ASTM D 4832).

Table 5-12: CLSM Mixtures with We Energies High Carbon Fly Ash

Mixture No.	100	100S	100SG
Laboratory Mixture Designation	100-5	100S-5	100SG-5
Fly Ash, FA (lb/yd^3)	1365	665	660
Cement, C (lb/yd^3)	100	65	45
SSD Fine Aggregate, S (lb/yd^3)	0	1335	865
SSD Coarse Aggregate, G (lb/yd^3)	0	0	1430
Fly Ash Content, % [FA/(FA+C+S+G)]	93	32	22
Water, W (lb/yd^3)	1045	525	480
Air Temperature (ºF)	78	79	78
Fresh CLSM Temperature (ºF)	77	77	84
Flow (in.)	11-1/4	10-1/4	6-3/4
Air Content (%)	1.7	1.2	0.9
Unit Weight (lb/ft^3)	92.8	95.7	129.2

Mechanical Properties of CLSM with We Energies High Carbon Fly Ash

The CLSM strength increased with increasing age. In general, the rate of strength increase was the highest for the mixtures containing aggregates (sand and/or stone) content. Compressive strength for Mixture 100 (fly ash and cement) was 50 psi at the 28-day age. Compressive strength of Mixture 100S and 100SG were higher, 140 psi and 130 psi, respectively, even with reduced cement content, as shown in Table 5-13.

Table 5-13: Compressive Strength of CLSM Mixtures with We Energies High Carbon Fly Ash

Mixture No.	Fly Ash Content, % [FA/(C+S+G)]	Compressive Strength (psi)							
		3-day		7-day		14-day		28-day	
		Act.	Avg.	Act.	Avg.	Act.	Avg.	Act.	Avg.
100	93	15	15	35	35	60	60	60	50
		15		35		60		40	
		15		30		65		45	
100S	32	30	30	105	100	130	120	135	140
		30		100		115		135	
		30		95		115		140	
100SG	22	15	17	140	110	105	110	135	130
		15		95		110		115	
		20		100		110		145	

The compressive strength of Mixture 100S and 100SG at the age of 28-days indicates that a backhoe may be required to excavate these mixtures in the future. However, standard excavation practices typically do utilize a backhoe for excavations for efficiency. Therefore, the 28-day strength levels of the 100S and 100SG mixtures should not be expected to pose a problem for future excavations with mechanical equipment.

Electrical Properties of CLSM with We Energies High Carbon Fly Ash

The electrical properties of the CLSM mixtures are shown in Table 5-14. The electrical resistivity of the air dried CLSM prepared is in the range of $3\text{-}6\times10^3$ ohm-cm. The resistivity value of the saturated specimens were lower than that obtained for air dried specimens. The permeability of most CLSM specimens prepared with high carbon fly ash exceeds that of air, indicating a greater capability to carry an electrical current. The use of fly ash having greater levels of carbon would further decrease the resistivity of the resulting CLSM. In addition, the increased concentration of high carbon fly ash in the composition will result in increased conductivity. The most significant decrease in resistivity occurs when increasing the high carbon fly ash content in the controlled low-strength materials from 22%–32%. This is evident in the high carbon fly ash controlled low-strength material mixtures for both the saturated and air dry specimens.

Table 5-14: Electrical Properties of CLSM Mixtures

Mixture No.			100	100S	100SG
Fly Ash Content wt., % [FA/(FA+C)]			93	91	93.6
Fly Ash Content wt., % [FA/(FA+C+S+G)]			93	32	22
Resistivity (ohm-cm)	Air Dried	3	40.1	65.8	151.4
		7	225.6	309.4	863.6
		14	837.9	911.5	1430.4
		28	3890.1	3417.9	5824.9
	Saturated	3	40.1	65.8	151.4
		7	40.1	85.6	161.6
		14	40.1	103.5	168.8
		28	48.5	101.7	183.7
Relative Permeability	Air Dried	3	1.001	1.004	1.006
		7	1.001	1.004	1.006
		14	1.004	1.004	1.006
		28	1.012	1.004	1.006
	Saturated	3	1.001	1.004	0.999
		7	0.999	1.004	1.008
		14	1.001	1.004	1.005
		28	1.012	1.004	1.006

Conductive CLSM Containing We Energies High Carbon Fly Ash and Carbon Fibers (US Patent 6,821,336)

Electrically conductive CLSM is advantageous where lower electrical resistance is sought, such as for use in structures where it is necessary to protect electrical equipment from lighting strikes. Electrically conductive CLSM has the following features:

(1) Provides low inductance, low resistance and subsequently low impedance values for all frequencies up to 1 MHz,

(2) Conducts energy efficiently across and through its surface without damage while providing true equalized ground potential rise values,

(3) Conducts energy efficiently into the earth quickly and seamlessly by providing the lowest impedance-coupling path,

(4) Compatible with copper, aluminum and galvanized steel products, and

(5) Fully excavatable, without heavy equipment

Conductive CLSM is made by using electrically conductive materials in close contact with each other throughout the CLSM. Electrically conductive additives include carbon fibers, steel fibers, steel shavings, carbon black, coke breeze, and other similar types of materials.

Since high carbon content fly ash is readily available as a coal combustion product, and carbon is known to be highly conductive, its use as an additive to CLSM to lower electrical resistance has been investigated. The goal of this testing work was to determine the feasibility of incorporating carbon fibers in the CLSM to lower electrical resistance of these construction materials. The lower electrical resistance of these construction materials will reduce the required length, or entirely replace, the grounding electrodes currently in use for protection of electrical equipment from lightning strikes.

Materials

Materials utilized in this project consisted of one source of fly ash, cement, and carbon fibers. One source of fly ash was used for this project (We Energies, Presque Isle Power Plant). This selection was made to represent a typical high-carbon fly ash available from We Energies. Type I cement (Lafarge Cement Co.) was used throughout this investigation. Carbon fibers were used in one CLSM mixture (Mixture CLSM-B) to attempt to enhance the electrical resistance characteristics.

All CLSM ingredients were manually weighed and loaded in a rotating-drum concrete mixer. The CLSM was mixed using the rotating-drum mixer. Fresh CLSM properties such as air content (ASTM D 6023), flow (ASTM D 6103), and unit weight (ASTM D 6023) were measured and recorded. Air and CLSM temperature was also measured and recorded. CLSM test specimens were prepared from each mixture for compressive strength (ASTM D 4832) and density. Compressive strengths of the CLSM mixtures were evaluated at the designated ages of 3, 7, 14, and 28 days. All test specimens were cast in accordance with ASTM D 4832. Three CLSM test specimens were tested at each test age. These specimens were typically cured for one day in their molds in the University of Wisconsin at Milwaukee – Center for By-Products Utilization laboratory at about 70°± 5°F. After setting, the test specimens were then demolded and placed in a standard moist-curing room maintained at 100% relative humidity and 73°± 3°F temperature until the time of test.

Mixture Proportions

Two different types of CLSM mixtures were tested. CLSM mixture proportions and fresh CLSM test results are shown in Table 5-15. The CLSM mixtures were proportioned to maintain a "practical" value of flow that would not lead to excessive segregation and bleeding.

Table 5-15: CLSM Mixtures

Mixture No.	**CLSM-A**	**CLSM-B**
Laboratory Mixture Designation	W-1	WF
Mixture Description	High-Carbon Fly Ash CLSM	High-Carbon Fly Ash CLSM with Carbon Fibers
Fly Ash, FA (lb/yd^3)	1250	490
Cement, C (lb/yd^3)	97	95
Carbon Fibers (lb/yd^3)	--	23
Fly Ash Content, % [FA/(FA+C)]100	93	82
Water, W (lb/yd^3)	1010	1370
[W/(C+FA)]	0.75	2.3
Air Temperature (ºF)	79	72
Fresh CLSM Temperature (ºF)	76	60
Flow (in.)	11	8
Air Content (%)	1.7	0.6
Unit Weight (lb/ft^3)	87.2	73.6
Hardened CLSM Density (lb/ft^3)	85	90

Mechanical Properties

The compressive strength data for the CLSM mixtures are presented in Table 5-16. Compressive strength of the high-volume fly ash CLSM mixture (Mixture CLSM-A, fly ash and cement) increased slightly between the ages of 3 and 28 days. Compressive strength for Mixture CLSM-A was 70 psi at the 3-day age, and increased to 85 psi at the 28-day age. When carbon fibers were introduced into the CLSM mixture, compressive strength was significantly reduced, to approximately 10 psi. The 28-day strength levels achieved for the CLSM-A and CLSM-B mixtures should not be expected to pose a problem in case of future excavation.

Due to the addition of carbon fibers, the flowability of the CLSM was significantly reduced for Mixture CLSM-B. In order to obtain flow characteristics for a typical CLSM, water for Mixture CLSM-B needed to be increased by approximately 30% over the amount used for Mixture CLSM-A (CLSM without fibers). Reduced flowability is to be expected since the fibers would tend to interlock and restrict the flow of the mixture.

Table 5-16: Compressive Strength of CLSM Mixtures

Mixture No.	Fly Ash Content, % [FA/(C+FA)]	Compressive Strength (psi)							
		3-day		7-day		14-day		28-day	
		Act.	Avg.	Act.	Avg.	Act.	Avg.	Act.	Avg.
CLSM-A	93	75	70	85	75	80	75	85	85
		70		70		70		80	
		65		70		75		90	
CLSM-B	82	--	--	10	10	10	10	10	10
		--		5		10		10	
		--		10		10		10	

Electrical Properties of CLSM Mixtures

The electrical resistivity values of the CLSM mixtures shown in Table 5-17 and Figure 5-10 are for air-dried specimens and Table 5-18 and Figure 5-11 for saturated specimens. Electrical resistivity of high-carbon fly ash mixture, CLSM-A, increased from 162.8 ohm-cm at the age of three days to over 55000 ohm-cm at the age of 28 days. Saturated specimens increased from 162.2 ohm-cm to only 535.7 ohm-cm at the age of 28 days. A significant improvement in the electrical resistance of CLSM occurred when carbon fibers were incorporated in Mixture CLSM-B. Both air-dried and saturated specimens exhibited very low rsistivity of approximately 13.2 ohm-cm or less when tested at ages between three and 28 days. These results illustrate that using carbon fibers in CLSM has a greater positive effect on lowering the resistivity above that normally achieved through the use of high-carbon fly ash alone. Electrical permeability decreased slightly when carbon fibers were used (Mixture CLSM-B).

Table 5-17: Electrical Resistivity of CLSM Mixtures – Air-Dried Specimens

Mixture No.	Fly Ash Content, % [FA/(C+S+G)]	Resistance (Ohm-cm)							
		3-day		7-day		14-day		28-day	
		Act.	Avg.	Act.	Avg.	Act.	Avg.	Act.	Avg.
CLSM-A	93	167.0	165.0	456.6	597.5	3357.4	4967.6	44706.0	55458.6
		159.8		544.0		4500.5		43568.9	
		168.2		791.8		7050.0		78100.8	
CLSM-B	82	6.6	6.4	7.8	7.8	9.0	8.8	13.2	13.4
		6.0		7.8		8.4		13.2	
		6.6		7.8		9.0		13.8	

Table 5-18: Electrical Resistivity of CLSM Mixtures - Saturated Specimens

Mixture No.	Fly Ash Content, % [FA/(C+S+G)]	Resistance (Ohm-cm)							
		3-day		7-day		14-day		28-day	
		Act.	Avg.	Act.	Avg.	Act.	Avg.	Act.	Avg.
CLSM-A	93	159.8	164.0	239.4	263.9	350.1	383.4	482.4	535.0
		168.2		293.3		420.7		583.5	
		164.0		259.1		379.4		541.0	
CLSM-B	82	10.2	10.8	7.2	7.6	9.0	8.8	9.6	9.2
		9.0		7.8		8.4		9.6	
		13.2		7.8		9.0		8.4	

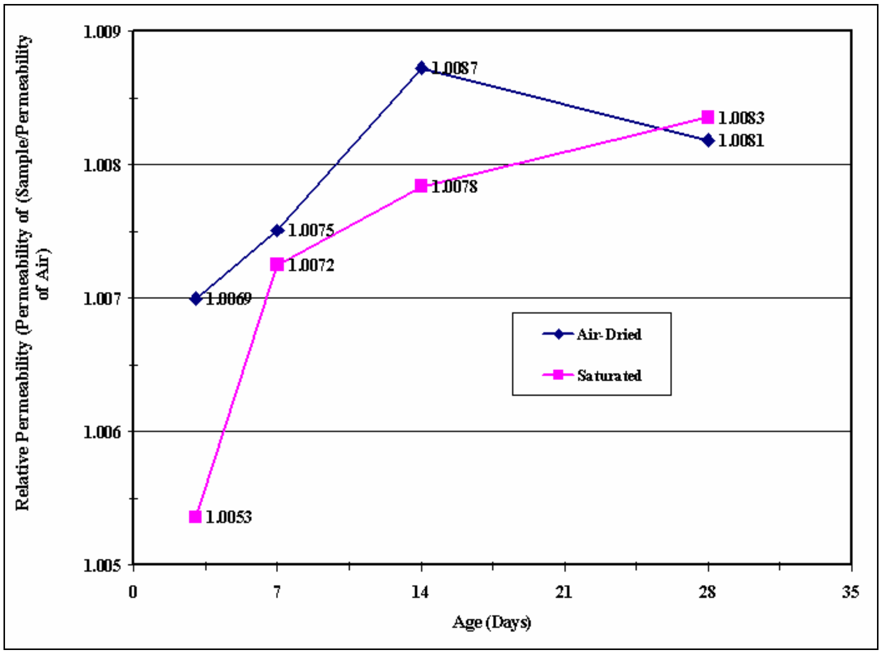

Figure 5-10: Electrical permeability of High Carbon Fly Ash CLSM Mixture CLSM-A

Dried vs. Saturated Specimens

Measurements taken for saturated CLSM specimens produced significantly smaller resistivity values compared to the air-dried specimens when tested without carbon fibers (Mixture CLSM-A). For the dried specimens, the aging process affected the resistivity significantly; the older the specimens, the higher the resistivity. The aging process affected the dried specimens more than the saturated ones. This indicates adding moisture to the material in place improves its conductivity. For the mixture containing carbon fibers, Mixture CLSM-B, air-dried specimens also had a higher electrical resistivity, but the difference between saturated and air-dried specimens were much less. Typically the difference between air-dried and saturated specimens was one ohm-cm or less. This may be attributed to the conductivity of the carbon fibers used in the mixtures.

Commonly-Used CLSM Mixtures

We Energies has been testing and utilizing controlled low-strength materials containing fly ash for construction for over 15 years. Though several mixture proportions have been tried, a few mixtures are commonly used that are re-excavatable by ordinary methods. These mixtures usually are required to be self-leveling and essentially free from shrinkage after hardening. The mixtures that are most commonly used are designed to reach a state of hardening such that they can support the weight of a person in less than 24 hours.

We Energies has developed and currently markets three different CLSM mixtures under the commercial name Flo-Pac. Flo-Pac is placed to lines and grades shown on the construction plans. Table 5-19 shows the mix designs for Flo-Pac 1, Flo-Pac 2 and Flo-Pac 5.

Table 5-19: Commonly Used High Carbon* Class F Fly Ash Mixtures and Proportions

Mixtures (lbs./Cu. ft.)	Flo-Pac 1	Flo-Pac 2	Flo-Pac 5**
Portland Cement	100	70	200
PWPP or VAPP Class F Fly Ash	1450	925	700
SSD Stone	0	0	1500
SSD Sand	0	1175	750
Water	950	832	533
Total Weight	2500	3002	3683

* Carbon content exceeds ASTM C618 requirements

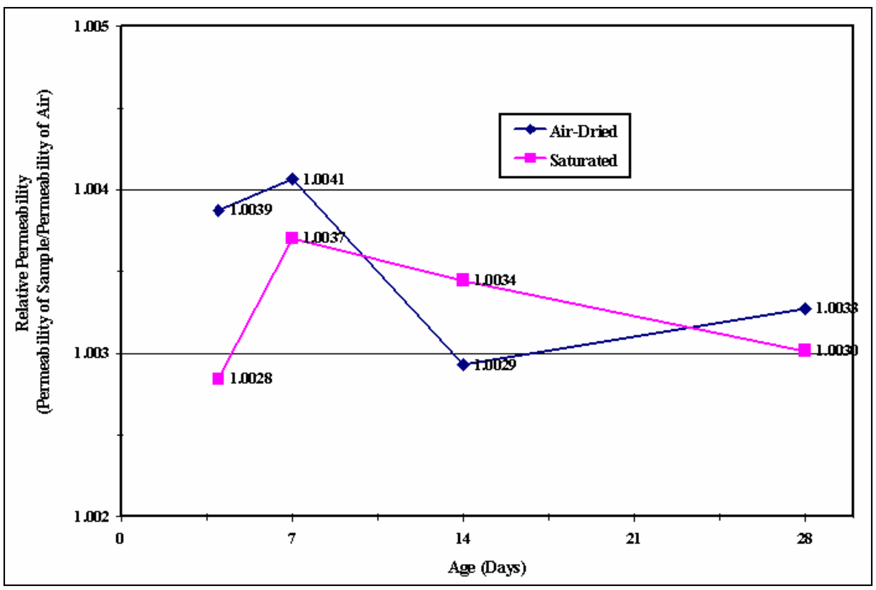

Figure 5-11: Electrical Permeability of High Carbon Fly Ash CLSM Mixture Containing Carbon Fiber CLSM

** Not excavatable

Pilot Projects Using We Energies CLSM

We Energies has utilized CLSM fly ash slurry on the following projects, where low strength and flowability were essential.

Abandoned Steam Service Tunnels

This was the first documented We Energies pilot project utilizing CLSM fly ash slurry. The project involved filling two obsolete brick lined steam service tunnels in downtown Milwaukee in December 1983. One tunnel was 6 ft. in diameter by 290 ft. long and the other had a 5 ft. by 4 ft. wide ellipsoid cross section.

Figure 5-12: ASTM D6103, Standard Test for CLSM Flow Consistency

Over 420 cubic yards of CLSM slurry material were produced from a typical mixture of 2,152 pounds of dry Class F fly ash, 859 pounds of water, and 88 pounds of Type I Portland cement. The fly ash was loaded directly into the ready-mix truck. The cement and water were also added directly and the drum was rotated at least 60 times during transit.

The CLSM flowable fly ash slurry was pumped into the tunnel. The maximum distance of CLSM flow was approximately 130 ft. Cylinders measuring 6” $\times$ 12” was prepared, and unconfined compression tests were run on the cylinders after 7 and 28 days, showing strengths between 50 and 100 psi, and greater than 100 psi, respectively. The project was completed over 15 years ago and no problems have been detected.

Figure 5-13: CLSM flowing through a funnel to fill an underground tunnel in downtown Milwaukee, Wisconsin.

Figure 5-14: We Energies' Flo-Pac CLSM being placed in a direct buried steam pipe trench in downtown Milwaukee, Wisconsin.

Sidewalk Cavity

This project was undertaken in 1984 and involved filling a hollow sidewalk cavity containing former locker room facilities in downtown Milwaukee. The CLSM flowable fly ash fill covered a length of about 80 ft., width of 14 ft. and a depth of 7 ft. The final top leveling layer was filled with sand (40).

About three hundred cubic yards of CLSM slurry was prepared using 1,950 lb. of dry Class F fly ash, 1,000 lb. of water and 128 lb. of Type 1 Portland cement. This mixture was placed directly into the cavity from ready mix trucks. Though minor shrinkage cracks were observed the following day, no voids or settlement was noticed.

Figure 5-15: CLSM being placed in lifts to manage the load on basement walls.

The site was excavated, using a tractor mounted backhoe, after several months to install a water supply lateral. The hardened slurry was easily rippable and the excavation had straight walls on each side. CLSM slurry with a compressive strength of less than 300 psi at 28 days worked well for this type of an application.

WisDOT Low Permeability CLSM with We Energies Fly Ash (41)

To ensure containment of contaminated soils and groundwater, WisDOT developed a CLSM with low permeability for use as a migration/contamination barrier during normal construction and construction emergencies. Strict physical requirements were specified for the WisDOT low permeability CLSM. The material needed to be flowable, with a maximum compressive strength of 100 psi, a maximum permeability of 1×10^{-6} cm/s and less than a 24-hour set.

Class C fly ash from We Energies' Pleasant Prairie Power Plant (PPPP) was used extensively during WisDOT low permeability CLSM mixture design study. The mixture using We Energies' PPPP Class C fly ash was one of two mixture designs which meet the above engineering properties requirement, as shown in Table 5-20.

Table 5-20: WisDOT Low Permeability CLSM Mixture Design with We Energies Class C Fly Ash

Weight (lbs/yd^3)	Material
50	Type I Portland Cement
700	Class C Fly Ash from We Energies Pleasant Prairie Power Plant
2640	Fine Aggregate per section 501.3.6.3 of the Wisconsin Standard Specifications
390	Water per section 501.3.5 of the Wisconsin Standard Specifications

Precautions to be Taken When Using CLSM Flowable Fly Ash Slurry

When properly mixed and placed, CLSM can provide construction savings by eliminating the need for labor intensive compaction efforts with standard granular materials. However, the following important construction considerations must be followed for success.

Figure 5-16: CLSM compression test cylinders. Note the color difference between those CLSMs based on Class F (dark) and Class C (light).

1. CLSM is placed as a liquid. Hence it exerts fluid pressure. If CLSM is placed against basement walls or other structures, verify that the

structure is capable of taking this lateral pressure. If the structure is not capable of handling this pressure, it can be braced externally until the CLSM slurry solidifies, or the CLSM slurry may be poured in multiple lifts so that one lift hardens before the next is poured.

2. Secure tanks, pipes and cables so they don't float in the excavation.
3. Fresh CLSM flowable fly ash slurry that is placed in deep excavations behaves like "quick-sand" so it must be protected from accidental entry until it hardens.
4. Low-strength CLSM material where re-excavation may be required at a later age should be specified with a maximum strength (or a range of strength) that will allow for easy re-excavation with normal equipment. The addition of coarse aggregate to the mixture generally makes re-excavation more difficult.
5. When transporting CLSM flowable slurry in a ready-mix truck, the driver should be aware of the liquid nature of the material being transported. CLSM may spill out of the back of a ready mix truck with quick stops or while travelling up hills. It is better to transport CLSM stiff and add water at the job site for high flow requirements.

Advantages of Using CLSM Fly Ash Slurry

CLSM fly ash slurry has several advantages when compared to conventional compacted backfill. The slurry mixture can be designed to meet the requirements of particular applications. The following are the major advantages:

Figure 5-17: Filling a tunnel with twin 30" diameter steam mains in Milwaukee, Wisconsin

1. CLSM fly ash slurry is flowable. The flowability can be increased or decreased by varying the water content. Hence, it can be used to fill inaccessible areas like retired sewer mains and tunnels where conventional ways of backfilling are difficult or economically not feasible. The flowable slurry fills voids completely, thus avoiding future settlement.
2. The level of strength can be increased or decreased depending on the application. Where re-excavation is required, the strength may be limited to the range of 50 to 300 psi maximum. Where higher strength is specified, such as base

material for foundations, changing the cementitious and aggregate proportions may increase the strength.

3. Unlike conventional backfilling methods, no tamping or vibration is required to place CLSM.
4. Long-term settlement is virtually nonexistent. Except for the initial shrinkage settlement of less than ⅛ inch per foot, there is no additional settlement after hardening. Hence, on pavement repairs and similar applications, a smoother ride can be expected.
5. There are substantial cost savings in using CLSM slurry, when compared to labor intensive conventional methods of backfilling. Fly ash slurry does not need compaction or vibration.
6. Utilizing fly ash for this application is making beneficial use of a coal combustion product, which is helpful to the environment. It preserves sand and gravel pits, crushed stone quarries, valuable landfill space; saves land that would be otherwise dedicated for these uses; and contributes to sustainable development by completely utilizing this resource and preserving virgin materials for future generations.

Figure 5-18: Volumetric mixer used for production of fast setting and excavatable CLSM in the Chicago area.