Center for By-Products Utilization

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Abstract

Significant amount of ash is generated from burning wood with supplementary fuels such as coal, oil, natural gas, and coke by pulp and paper mills and wood-products manufacturers. Thus, the ash generated from such facilities is a mixture of wood ash and other ashes generated from such supplemental fuels. In this investigation, such wood ash is referred to as a combined-fuel ash (CFA). This investigation was carried out to develop Controlled Low-Strength Materials (CLSM) mixtures using various sources of CFAs. Three different series of CLSM mixtures were manufactured using five sources of CFAs. Each series of CLSM mixtures was designed for a different long-term compressive strength, <0.7 MPa (<100 psi), 0.7 to 3.4 MPa (100 to 500 psi), and 3.4 to 8.3 MPa (500 to 1,200 psi). All CLSM mixtures were tested for flow, bleedwater, settlement, shrinkage and cracking, setting characteristics, density, compressive strength, and permeability. The results revealed that CLSM, meeting ACI 229 requirements, can be manufactured using substantial amounts of CFAs.

Introduction

Wood ash is usually generated by saw mills, pulp mills, and the wood-products industry, by burning a combination of wood products, such as bark, twigs, knots, chips, etc. with other supplementary fuels such as coal, oil, natural gas, and coke to generate electricity and/or steam required for their manufacturing processes. Therefore, the resulting ash is sometimes referred to as combined-fuel ash (CFA). A majority of such CFAs generated in the USA is either landfilled or applied on land as a soil supplement. Landfilling is becoming very restrictive and costly while land application is also restricted because of the presence of undesirable elements and/or high alkalinity. Some studies [1-8] have been reported toward evaluating physical and chemical properties of wood ash or CFAs. Based on these properties, a number of constructive use options such as

pollution control [3], land application [9,10,11], construction materials [13,14], have been reported. However, most of these applications consume very limited amounts of CFAs due to low-volume uses resulting from environmental restrictions or low economic benefits. More recently, Naik and his colleagues [8,15] indicated that large amounts of CFAs can be used in cement-based materials such as CLSM, low and medium-strength concrete, masonry products, roller-compacted concrete (RCC) pavement, road base materials, blended cements, etc. However, technology for manufacturer of these materials using CFAs is yet to be established.

Large volumes of CFAs would be consumed in the manufacture of CLSM. Depending upon intended use, CLSM can be proportioned for compressive strength up to 8.3 MPa (1,200 psi) at the age of 28 days. CLSM can be used for foundations, bridge abutments, buildings, retaining walls, utility trenches, etc. as backfill; as embankments, grouts, abandoned tunnels and mine fillings for stabilization of such cavities, etc. CLSM mixture flows like a liquid, and supports like a solid due to its self-setting and hardening behavior. It can typically harden within a few hours of placement. For excavatable CLSM, mixtures should be proportioned to attain compressive strength in the range of 0.4 to 0.7 MPa (50 to 100 psi) at the 28-day age. CLSM can provide cost-effective alternatives to conventional compacted granular backfill or structural fill materials (soil or other granular materials). This is primarily due to lower cost of labor and significantly reduced time required for placement compared to the cost of placing and compacting conventional granular fill materials. The placement of conventional granular fill material requires testing after each lift of 305 to 310 mm (12 to 24 in.), while this is not required for CLSM due to its self-compacting behavior. Since CLSM mixture exhibits very low to negligible settlement after hardening, it provides better support for overlying structures (and/or pavements) and avoids the damage associated with the base/support settlement.

Substantial amount of work has been done concerning the use of coal ash in the manufacture of CLSM [16-20]. However, activities have not been reported concerning the use of CFAs in the manufacture of CLSM. Therefore, this investigation was carried out to develop CLSM mixtures for various applications incorporating high volumes of CFAs derived from various sources.

Experimental Program

Three series (L, M, and H) of experiments were designed and conducted. Each of these series was developed to obtain a different long-term compressive strength levels at later ages (28 to 91 days). CLSM mixtures developed for the project were 0.3 to 0.7 MPa (50 to 100 psi) for Series L, low-strength mixtures; 0.7 to 3.4 MPa (100 to 500 psi) for Series M, medium-strength mixtures; and 3.4 to 8.3 MPa (500 to 1200 psi) for Series H, high-strength mixtures.

Materials

Materials utilized for this project consisted of CFA, cement, fine aggregate, coarse aggregate, and coal fly ash. Each material was characterized for physical and chemical properties in accordance with the appropriate ASTM standards. The detailed data on properties of these materials are reported elsewhere [14]. Summary data is provided in Tables 1 and 2.

Five different sources of CFA were used for this project. Each CFA was characterized for physical properties such as fineness (ASTM C 430), strength activity index with cement (ASTM C 109), water requirement (ASTM

C 109), autoclave expansion (ASTM C 151), and specific gravity (ASTM C 188). Each CFA was also tested for chemical properties which included determination of oxides, basic chemical elements, and mineralogy. The physical and chemical properties of CFA are given in Tables 1 and 2, respectively.

One source of fine aggregate was utilized in this investigation for the high-strength (Series H) CLSM mixtures. Physical properties of the sand were determined per ASTM C 33 requirements for the following properties: unit weight (ASTM C 29), specific gravity and absorption (ASTM C 128), fineness (ASTM C 136), material finer than #200 sieve (ASTM C 117), and organic impurities (ASTM C 40).

Type I cement was used throughout this investigation. Cement was tested per ASTM C 150 requirements for air content (ASTM C 185), fineness (ASTM C 204), autoclave expansion (ASTM C 151), compressive strength (ASTM C 109), time of setting (ASTM C 191), and specific gravity (ASTM C 188).

All CLSM mixtures were batched in the laboratory of the UWM Center for By-Products Utilization. The low-strength CLSM (Series L) mixtures consisted of CFA, ASTM Type I cement, and water. The medium-strength CLSM (Series 2) mixtures consisted of CFA, an increased amount of ASTM Type I cement, and water. The high-strength CLSM (Series H) mixtures consisted of CFA, ASTM Type I cement, sand, and water. These CLSM mixtures were proportioned to maintain a practical value of flow in the range of approximately 250 mm ± 50 (10 ± 2 in.).

Manufacturing of CLSM

All CLSM ingredients were manually loaded in a 2.7 m^3 (9 ft^3) rotating drum concrete mixer. The required amount of cement together with one-half the specified quantity of fly ash or sand was loaded into the mixer and mixed for three minutes. Three-quarters of the specified water was then added to the mixer and then mixed for an additional three minutes. The remaining CFA or sand, and water was added to the mixer and then mixed for five more minutes. Additional water was added in the mixture as needed for achieving the desired flow, prior to discharging the CLSM for testing. Whenever additional water was added to obtain the specified fresh CLSM characteristics, the CLSM mixture was mixed for an additional five minutes. The resulting mixture was then discharged into a pan for further testing and evaluation.

Specimen Preparation and Testing

Fresh CLSM mixtures was tested for properties such as air content (ASTM D 6023), flow (ASTM D 6103), unit weight (ASTM D 6023), and setting (ASTM D 6024). Ambient air temperature was also measured and recorded. For each mixture, CLSM test specimens were prepared for compressive strength (ASTM D 4832), water permeability (ASTM D 5084), and setting and hardening tests. Compressive strength of 150 x 300-mm (6 x 12-in) cylindrical specimens was determined at the 3-, 14-, 28-, and 91-day ages. Permeability was tested at the ages of 28 and 91 days using 100 x 100-mm (4 x 4-in) cylindrical specimens. The amount of bleed water and level of the solids (settlement) of CLSM mixtures were also measured in a 150 x 300-mm (6 x 12-in.) cylinder. All test specimens were cast in accordance with ASTM D 4832. These specimens were typically cured for one day in their molds in the UWM-CBU laboratory at about 24° ± 2°C (75° ± 3°F). These specimens were then demolded and placed in a standard moist-curing room maintained at 100% R.H. and 23° ± 1° C (73° ± 2° F), temperature until the time of test (ASTM D 4832). The setting characteristics of the CLSM mixtures were determined using specimens cast in molds, approximately 300 x 300 x 75-mm (12 x 12 x 3-in.). The CLSM was cast directly into the mold and left uncovered for the entire measurement period. The setting characteristics were

determined in accordance with ASTM D 6024. This method measures diameter of an impression by a spherical steel ball of the Kelly Ball apparatus. Per ASTM D 6024, a CLSM mixture becomes suitable to support load when a maximum diameter of impression of 76 mm (3 in.) is reached. This value was considered too high for the cylinders to be safely demolded without damaging the test specimens. Based upon comparing the setting consistency of the CLSM, as cast in the cylinder molds, a more reasonable value was considered to be approximately 50 mm (2 in.).

Conclusions

Based on data collected in this investigation, the following conclusions may be drawn.

- The physical and chemical properties of the combined fuel ashes were significantly influenced by their source.
- Although all combined fuel ashes used in this work did not conform to the requirements of ASTM C 618 Class C or Class F coal fly ash, they are suitable for use as a primary ingredient of flowable CLSM.
- Fresh CLSM unit weight generally decreased when CFA content or water to cementitious materials ratio was increased.
- Compressive strength of CLSM mixtures increased with age. CLSM mixtures meeting ACI 229 requirements can be proportioned using large amounts of CFA for strength levels up to 8.3 MPa (1,200 psi) at the age of 28 to 91 days.
- The permeabilities of the CLSM mixtures made with CFA decreased with increasing age and compressive strength. The permeability values of the CLSM mixtures incorporating CFA was generally lower than that normally observed for compacted clay.

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Table 1 - Physical Properties of CFAs

TEST PARAMETER	W-1	W-2	W-3	W-4	W-5	ASTM C 618 SPECIFICATIONS		
						CLASS C	CLASS F	CLASS N
Retained on No.325 sieve (%)	23	60	90	40	12	34 max	34 max	34 max
Strength Activity Index with Cement (% of Control)								
3-day	88.4	38.4	102.0*	53.8	112.3			
7-day	84.2	39.4	83.3*	59.3	72.0	75 min	75 min	75 min
28-day	88.3	33.6	78.7*	59.4	67.0	75 min	75 min	75 min
Water Requirement (% of Control)	115	155	115*	126	130	105 max	105 max	115
Autoclave Expansion (%)	0.2	0.5	-0.63*	-0.22	0.12	±0.8	±0.8	0.8 max
Unit Weight, kg/m^3 (lb/ft^3)	545 (34.0)	412 (25.7)	1376 (85.9)	509 (31.8)	162 (10.1)	-	-	-
Specific Gravity	2.26	2.41	2.60	2.26	2.33	-	-	-
Variation from Mean (%)								

Fineness Specific Gravity	N.A. 0.4	N.A. 0.4	N.A. N.A.	N.A. 0.7	N.A. 0.1	5 max 5 max	5 max 5 max	5 max 5 max

*Material passing No. 100 (150 um) sieve was used for this test.

Table 2 - Analysis for Oxides, SO_3, and Loss on Ignition for CFAs

OXIDES, SO_3, AND LOSS ON IGNITION ANALYSIS, (%)								
Analysis Parameter	W-1	W-2	W-3	W-4	W-5	ASTM C-618 Requirements		
						Class C	Class F	Class N
Silicon Dioxide, SiO_2	32.4	13.0	50.7	30.0	8.1	--	--	--
Aluminum Oxide, Al_2O_3	17.1	7.8	8.2	12.3	7.5	--	--	--
Iron Oxide, Fe_2O_3	9.8	2.6	2.1	14.2	3.0	--	--	--
SiO_2 + Al_2O_3 + Fe_2O_3	59.3	23.4	61.0	56.5	18.6	50.0 Min	70 Min	70 Min.
Calcium Oxide, CaO	3.5	13.7	19.6	2.2	25.3	--	--	--
Magnesium Oxide, MgO	0.7	2.6	6.5	0.7	4.5	--	--	--
Titanium Oxide, TiO_2	0.7	0.5	1.2	0.9	0.3	--	--	--
Potassium Oxide, K_2O	1.1	0.4	2.8	2.0	2.7	--	--	--
Sodium Oxide, Na_2O	0.9	0.6	2.1	0.5	3.3	--	--	--
Sulfite, SO_3	2.2	0.9	0.1	2.1	12.5	5.0 Max	5.0 Max	4.0 Max.
Loss on Ignition, LOI ($1000^{?}C$)	31.6	58.1	6.7	35.3	32.8	6.0 Max	6.0 Max	10.0 Max.
Moisture	2.4	0.5	0.2	0.4	3.3	3.0 Max	3.0 Max	3.0 Max.
Available Alkali, Na_2O, (ASTM C-311)	0.9	0.4	0.8	1.1	4.2	1.5 Max	1.5 Max	1.5 Max.

Table 3 - Mixture Proportions for the Series L CLSM Mixtures

Mix No.	1-L	2-L	3-L	4-L	5-L
Laboratory Mixture Designation	N-1L	DC-1L	R-1L	B4-1L	B5-1L
Fly Ash Source	W-1	W-2	W-3	W-4	W-5
Fly Ash (%)	90	85	90	90	85
Cement, kg/m^3 (lb/yd^3)	77 (130)	89 (150)	53 (90)	56 (95)	95 (160)
Fly Ash, kg/m^3 (lb/yd^3)	641 (1080)	469 (790)	1187 (2000)	662 (1115)	498 (840)
Water, W kg/m^3 (lb/yd^3)	626 (1055)	635 (1070)	481 (810)	656 (1105)	730 (1230)
[W/(C+A)]	0.82	1.14	0.39	0.91	1.23
Air Temperature, °C (°F)	22.2 (72)	22.2 (72)	22.2 (72)	22.2 (72)	22.2 (72)
Fresh CLSM Temperature, °C (°F)	23.3 (74)	23.3 (74)	23.9 (75)	22.8 (73)	24.4 (76)
Flow, mm (in.)	241 (9 ½)	254 (10)	254 (10)	254 (10)	254 (10)
Air Content (%)	2.4	5	3.5	2.8	1.0
Unit Weight, kg/m^3 (lb/ft^3)	1344 (83.9)	1195 (74.6)	1724 (107.6)	1371 (85.6)	1323 (82.6)

Table 4 - Mixture Proportions for the Series M CLSM Mixtures

Mix No.	1-M	2-M	3-M	4-M	5-M
Laboratory Mixture Designation	N-1	DC-1	R-1	B4-1	B5-1
Fly Ash Source	W-1	W-2	W-3	W-4	W-5
Cement, kg/m^3 (lb/yd^3)	187 (315)	228 (385)	101 (170)	157 (265)	125 (210)
Fly Ash, kg/m^3 (lb/yd^3)	611 (1030)	400 (675)	1133 (1910)	617 (1040)	445 (750)
Water, W kg/m^3 (lb/yd^3)	602 (1015)	596 (1005)	510 (860)	635 (1070)	721 (1215)
[W/(C+A)]	0.75	0.95	0.41	0.82	1.26
Flow, mm (in.)	273 (10 ¾)	260 (10 ¼)	254 (10)	260 (10 ¼)	260 (10 ¼)
Air Content (%)	1.5	5.7	4.4	1.6	1.6
Air Temperature, °C (°F)	25.5 (78)	25.5 (78)	25.5 (78)	26.1 (79)	26.1 (79)
Fresh CLSM Temperature, °C(°F)	22.2 (72)	27.8 (82)	25.5 (78)	31.1 (88)	22.2 (72)
Unit Weight, kg/m^3 (lb/ft^3)	1394 (87)	1234 (77)	1762 (110)	1410 (88)	1298 (81)

Table 5 - Mixture Proportions for the Series H CLSM Mixtures

Mix No.	1-H	2-H	3-H	4-H	5-H
Laboratory Mixture Designation	N-2	DC-2	R-2	B4-2	B5-2
Fly Ash Source	W-1	W-2	W-3	W-4	W-5
Cement, kg/m^3 (lb/yd^3)	169 (285)	205 (345)	196 (330)	175 (295)	157 (265)
Fly Ash, kg/m^3 (lb/yd^3)	427 (720)	205 (345)	537 (905)	392 (660)	353 (595)
Water, W kg/m^3 (lb/yd^3)	418 (705)	430 (725)	359 (605)	484 (815)	540 (910)
[W/(C+FA)]	0.7	1.05	0.48	0.85	1.04
SSD Fine Aggregate, kg/m^3 (lb/yd^3)	774 (1305)	828 (1395)	946 (1595)	706 (1190)	611 (1030)
Flow, mm (in.)	273 (10 ¾)	260 (10 ¼)	273 (10 ¾)	260 (10 ¼)	260 (10 ¼)
Air Content (%)	1.4	6.3	1.6	1.3	0.9
Air Temperature, °C (°F)	25.6 (78)	26.1 (79)	25.6 (78)	25.6 (78)	24.4 (76)
Fresh CLSM Temperature, °C (°F)	23.3 (74)	27.8 (82)	28.9 (84)	26.7 (80)	22.8 (73)
Unit Weight, kg/m^3 (lb/ft^3)	1794 (112)	1660 (104)	2035 (127)	1762 (110)	1666 (104)

Table 6 - Bleedwater of the Series L CLSM Mixtures

Mixture No.	Bleedwater mm (in) *						
	1 hour	4 hour	8 hour	24 hour	2 days	3 days	2 days
1-L	9.5 (3/8)	1.6 (1/16)	0	0	0	0	0
2-L	3.2 (1/8)	1.6 (1/16)	0	0	0	0	0
3-L	9.5 (3/8)	1.6 (1/16)	1.6 (1/16)	1.6 (1/16)	1.6 (1/16)	1.6 (1/16)	0
4-L	4.8 (3/16)	3.2 (1/8)	0	0	0	0	0
5-L	1.6 (1/16)	0	0	0	0	0	0

*Average of three readings

Table 7 - Bleedwater of the Series M CLSM Mixtures

Mixture No.	Bleedwater, mm (in) *						
	1 hour	4 hour	8 hour	24 hour	2 days	3 days	7 days
1-M	12.7 (½)	9.5 (3/8)	6.4 (1/4)	3.2 (1/8)	1.6 (1/16)	0	0
2-M	0	0	0	0	0	0	0
3-M	3.2 (1/8)	0	0	0	0	0	0
4-M	3.2 (1/8)	9.5 (3/8)	9.5 (3/8)	9.5 (3/8)	9.5 (3/8)	9.5 (3/8)	0
5-M	12.7 (1/2)	11.1 (7/16)	6.4 (1/4)	1.6 (1/16)	0	0	0

*Average of three readings

Table 8 - Bleedwater of the Series H CLSM Mixtures

Mixture No.	Bleedwater, mm (in.) *					
	1 hour	4 hour	8 hour	24 hour	2 days	3 days
1-H	4.8 (3/16)	3.2 (1/8)	1.6 (1/16)	0	0	0
2-H	9.5 (3/8)	6.4 (1/4)	1.6 (1/16)	0	0	0
3-H	9.5 (3/8)	6.4 (1/4)	3.2 (1/8)	0	0	0
4-H	4.8 (3/16)	7.9 (5/16)	9.5 (3/8)	12.7 (1/2)	9.5 (3/8)	9.5 (3/8)
5-H	6.4 (1/4)	9.5 (3/8)	9.5 (3/8)	6.4 (1/4)	0	0

* Average of three readings

Table 9 - Settlement of the Series L CLSM Mixtures

Mixture No.	Settlement, mm (in.)*							
	1 hour	4 hour	8 hour	24 hour	2 days	3 days	7 days	14 days
1-L	9.5 (3/8)	--	--	--	9.5 (3/8)	9.5 (3/8)	--	9.5 (3/8)
2-L	27.0 (1-1/16)**	--	49.2 (1-15/16)**	46.0 (1-13/16)**	46.0 (1-13/16)**	49.2 (1-15/16)**	49.2 (1-15/16)**	--
3-L	9.5 (3/8)	1.6 (1/16)	--	1.6 (1/16)	1.6 (1/16)	1.6 (1/16)	1.6 (1/16)	0
4-L	4.8 (3/16)	4.8 (3/16)	4.8 (3/16)	4.8 (3/16)	4.8 (3/16)	4.8 (3/16)	4.8 (3/16)	4.8 (3/16)
5-L	3.2 (1/8)	4.8 (3/16)	4.8 (3/16)	4.8 (3/16)	4.8 (3/16)	4.8 (3/16)	4.8 (3/16)	4.8 (3/16)

*Average of three readings
**Values indicate CLSM expansion

Table 10 - Settlement of the Series M CLSM Mixtures

Mixture	Settlement, mm (in.) *							
	1 hour	4 hour	8 hour	24 hour	2 days	3 days	7 days	14 days
1-M	12.7 (1/2)	9.5 (3/8)***	6.4 (1/4)***	6.4 (1/4)***	6.4 (1/4)***	6.4 (1/4)***	6.4 (1/4)***	6.4 (1/4)***
2-M	42.9 (1-11/16)**	50.8 (2)**	55.6 (2-3/16)**	61.9 (2-7/16)**	61.9 (2-7/16)**	61.9 (2-7/16)**	--	--
3-M	4.8 (3/16)	3.2 (1/8)***	0***	0***	0***	0***	0***	0***
4-M	4.8 (3/16)	12.7 (1/2)	12.7 (1/2)	--	12.7 (1/2)	12.7 (1/2)	12.7 (1/2)	12.7 (1/2)
5-M	12.7 (1/2)	11.1 (7/16)***	9.5 (3/8)***	6.4 (1/4)***	3.2 (1/8)***	6.4 (1/4)***	6.4 (1/4)***	6.4 (1/4)***

*Average of three readings
**Values indicate CLSM expansion
***Reduction in settlement due to CLSM expansion

Table 11 - Settlement of the Series H CLSM Mixtures

Mixture No.	Settlement, mm (in.)*							
	1 hour	4 hour	8 hour	24 hour	2 days	3 days	7 days	14 days
1-H	4.8 (3/16)	--	--	--	--	--	4.8 (3/16)	4.8 (3/16)
2-H	9.5 (3/8)	6.4 (1/4)**	1.6 (1/16)**	0**	0**	0**	0**	0**
3-H	9.5 (3/8)	6.4 (1/4)**	3.2 (1/8)**	0**	0**	0**	0**	0**
4-H	4.8 (3/16)	6.4 (1/4)	9.5 (3/8)	12.7 (1/2)	12.7 (1/2)	12.7 (1/2)	11.1 (7/16)	11.1 (7/16)
5-H	6.4 (1/4)	9.5 (3/8)	9.5 (3/8)	9.5 (3/8)	9.5 (3/8)	9.5 (3/8)	9.5 (3/8)	9.5 (3/8)

*Average of three readings
**Reduction in settlement due to CLSM expansion

Table 12 - Compressive of the Series L CLSM Mixtures

Mixture No.	Compressive Strength, kPa (psi) *				
	3-day	7-day	14-day	28-day	91-day
1-L	100 (15)	170 (25)	210 (30)	380 (55)	480 (70)
2-L	70 (10)	140 (20)	140 (20)	240 (35)	380 (55)
3-L	140 (20)	170 (25)	210 (30)	410 (60)	280 (140)
4-L	100 (15)	170 (25)	210 (30)	280 (40)	1170 (70)
5-L	140 (20)	480 (70)	520 (75)	1170 (170)	1790 (260)

*Average of three readings

Table 13 - Compressive of the Series M CLSM Mixtures

Mixture No.	Compressive Strength, kPa (psi) *				
	3-day	7-day	14-day	28-day	91-day
1-M	310 (45)	340 (50)	480 (70)	1400 (200)	2840 (390)
2-M	450 (65)	550 (80)	720 (105)	970 (140)	2690 (765)
3-M	450 (65)	660 (95)	760 (110)	1280 (185)	1590 (230)
4-M	210 (30)	660 (95)	900 (130)	1450 (210)	2550 (370)
5-M	170 (25)	340 (50)	620 (90)	720 (105)	1140 (165)

*Average of three readings

Table 14 - Compressive of the Series H CLSM Mixtures

Mixture No.	Compressive Strength, kPa (psi)*				
	3-day	7-day	14-day	28-day	91-day
1-H	830 (120)	1380 (200)	2340 (340)	3240 (470)	6650 (965)
2-H	720 (105)	1070 (155)	1140 (165)	1590 (230)	8620 (1250)
3-H	1900 (275)	2280(330)	2480 (360)	3100 (450)	4000 (580)
4-H	850 (120)	1520 (220)	2520 (365)	3590 (520)	6960 (1010)
5-H	660 (95)	1480 (215)	2210 (320)	2210 (320)	4240 (615)

*Average of three readings

Table 15 - Permeability of the Series L CLSM Mixtures

Mixture No.	Permeability (cm/sec)*
	28-day
1-L	100×10^{-6}
2-L	54×10^{-6}
3-L	15×10^{-6}
4-L	35×10^{-6}
5-L	110×10^{-6}

*Average of three readings

Table 16 - Permeability of Series M CLSM Mixtures

Mixture No.	Permeability (cm/sec)*	
	28-day	91-day
1-M	6×10^{-6}	0.1×10^{-6}
2-M	510×10^{-6}	350×10^{-6}
3-M	20×10^{-6}	2.4×10^{-6}
4-M	5×10^{-6}	3.0×10^{-6}
5-M	74×10^{-6}	7.0×10^{-6}

*Average of three readings

Table 17 - Permeability of Series H CLSM Mixtures

Mixture No.	Permeability (cm/sec)*	
	28-day	91-day
1-H	12×10^{-6}	4×10^{-6}
2-H	2×10^{-6}	1×10^{-6}
3-H	120×10^{-6}	38×10^{-6}
4-H	19×10^{-6}	14×10^{-6}
5-H	4×10^{-6}	3×10^{-6}

*Average of three readings

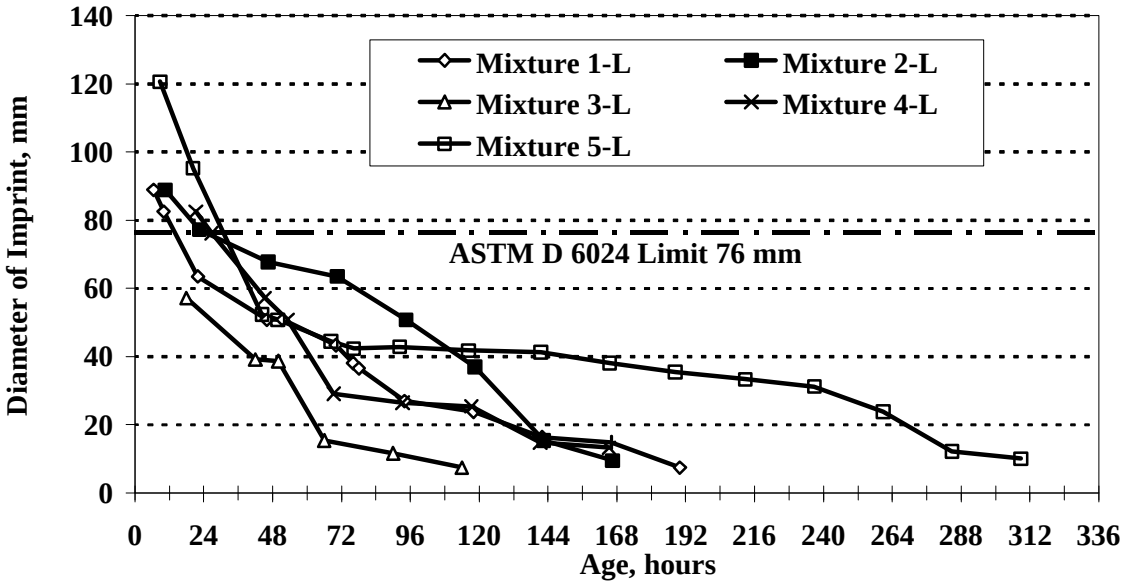

Fig. 1 - Setting Characteristics for the Series L CLSM Mixtures

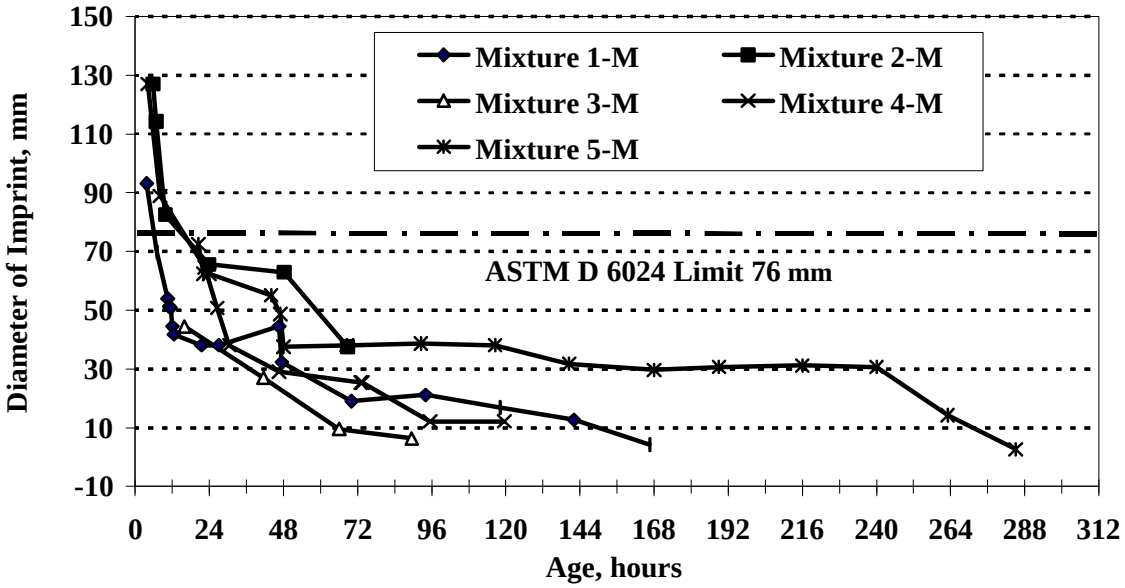

Fig. 2 - Setting Characteristics for the Series M CLSM Mixtures

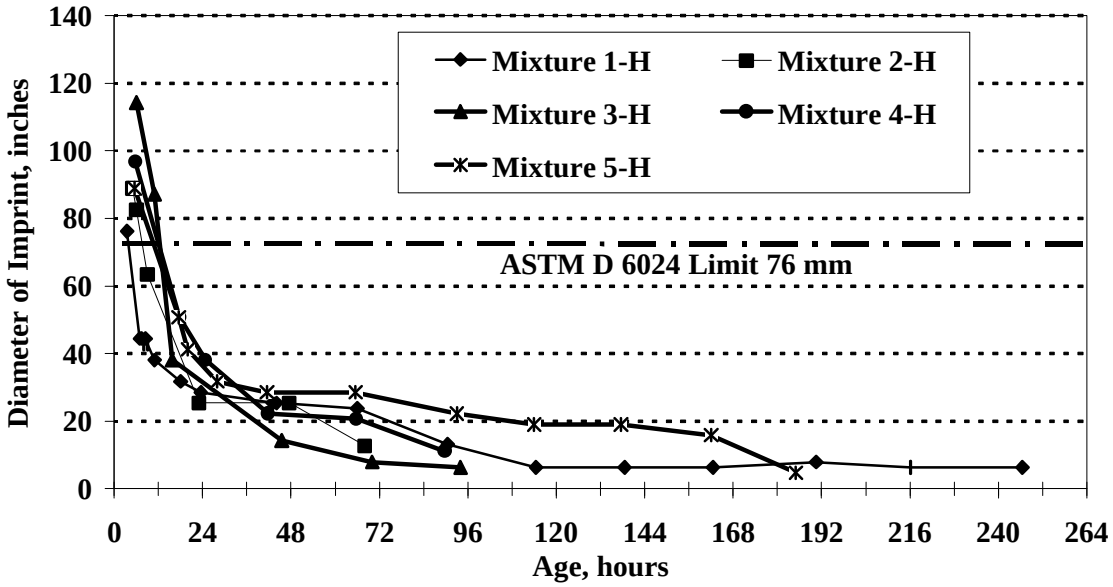

Fig. 3 - Setting Characteristics for the Series H CLSM Mixtures

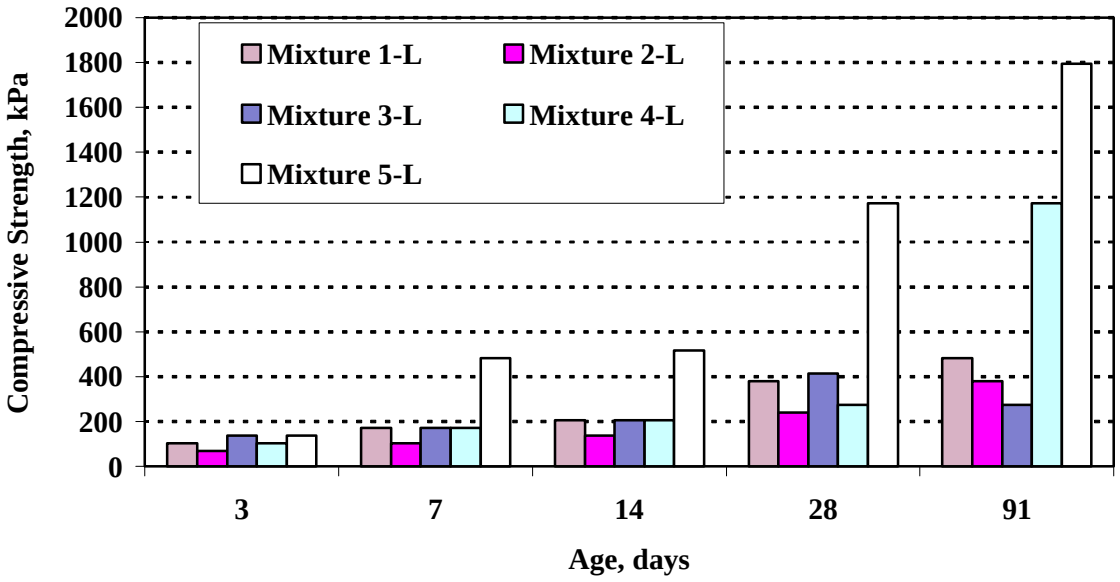

Fig. 4 - Compressive Strength for the Series L CLSM Mixtures

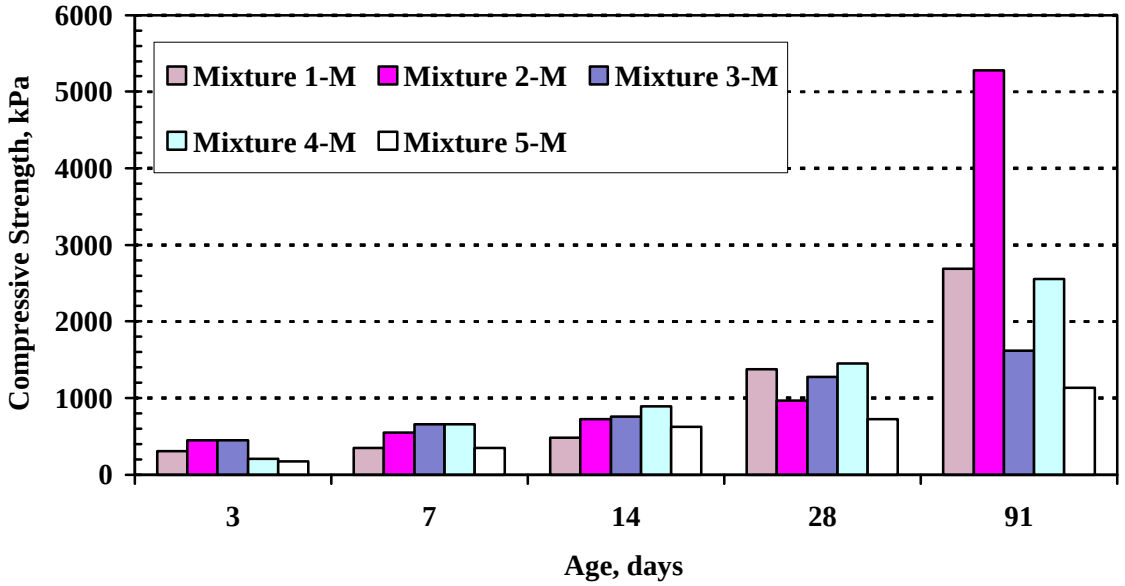

Fig. 5 - Compressive Strength for Series M CLSM Mixtures

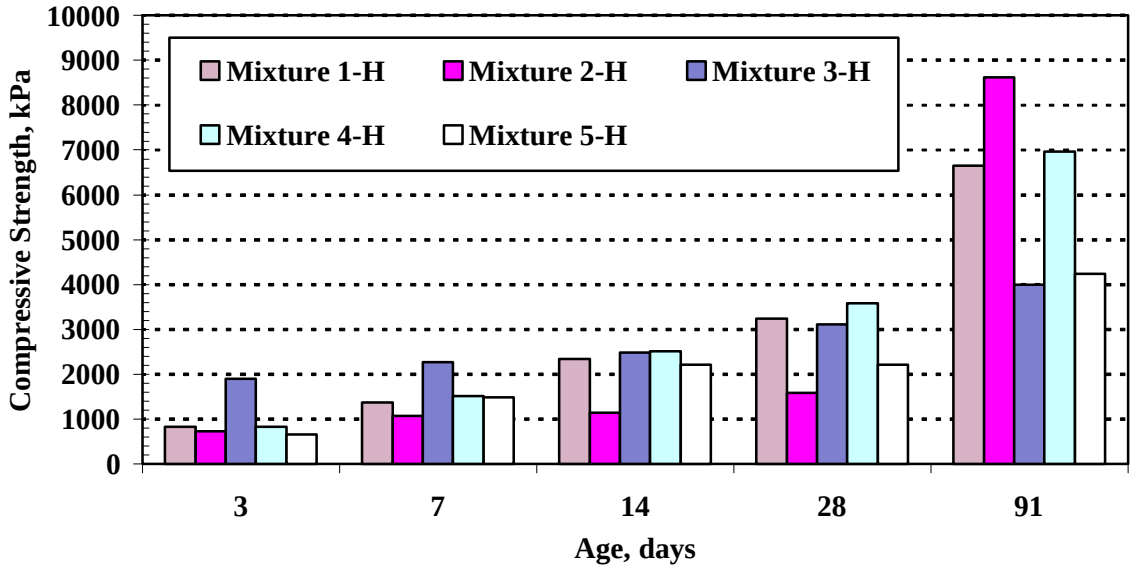

Fig. 6 - Compressive Strength for Series H CLSM Mixtures