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Journal of Hazardous Materials 76 (2000) 251–263

Journal of Hazardous Materials

www.elsevier.nl/locate/jhazmat

Controlled low-strength material using fly ash and AMD sludge

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Received 17 April 1999; received in revised form 2 December 1999; accepted 27 December 1999

Abstract

Controlled low-strength material (CLSM) is a cementitious material with properties similar to stabilized soil. After hardening, CLSM provides adequate strength in bearing capacity and support but can also be easily excavated. To be classified as a CLSM, the material must have a compressive strength between 450 kPa (65 psi) and 8400 kPa (1200 psi). Typical CLSM contains coal-combustion fly ash (FA), cement, water and fine or coarse aggregate. In this paper, physical and strength properties of CLSM formed by combining sludge, a by-product from the treatment of acid mine drainage (AMD), with Class F FA are investigated. The sludge is a lime-based waste product that when combined with FA, exhibits self-hardening characteristics similar to cement. A main focus of this research is to develop a CLSM mix in which by-product material utilization is maximized while satisfying workability and performance requirements. A mixture of 10% AMD sludge, 2.5% Portland cement (PC), 87.5% Class F FA (dry wt.%) with water provided unconfined compressive strength values within the range for classification as CLSM. This mixture satisfies the excavatability and walkability requirements as well as the hardening time and stability criteria.

Keywords: Controlled low-strength material; Fly ash; Portland cement; Acid mine drainage; Quicklime

1. Introduction

Controlled low-strength material (CLSM) is a cementitious material which after hardening, allows for future excavation with properties that are similar in characteristics

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PII: S0304-3894(00)00202-8

to stabilized soils. Cement and Concrete Terminology (ACI 116R) defines CLSM as ‘‘a material resulting in a compressive strength of 1200 psi (8.3 MPa) or less.’’ CLSM can be used as a substitute for compacted soil in backfill applications, especially when possessing the desirable properties of flow (without segregation) under gravity for situations where compaction access is challenging. Other desired characteristics include hardening for early walkability and cover application, and low strength to allow excavation in case of temporary construction.

It was demonstrated that cement/lime-stabilized Class F fly ash (FA) compositions exhibit increased strength and durability [9] and reduced permeability and leachability [3]. Gabr et al. [5] demonstrated that an optimized mix of 50% Class F FA and 50% acid mine drainage (AMD) lime sludge provide reduced hydraulic conductivity and acceptable leachate characteristics as a grout material.

Research presented in this paper is focused on evaluating the properties of CLSM mixtures comprised primarily of waste materials. The experimental study included determining index properties of various CLSM mixtures for screening and selecting candidate mixtures for strength testing. Various CLSM mixtures consisting of FA, AMD treatment sludge, quicklime (QL), and Portland cement (PC) were investigated. Measured index properties included specific gravity, density, flowability, viscosity, stability, and hardening time. Unconfined shear strength was evaluated for selected CLSM mixtures to discern walkability within 24 h after installation and long term excavatability. Results are discussed and optimum CLSM mix ratio is recommended for fill applications.

2. CLSM components and characteristics

Typical CLSM mix components include FA, aggregate, cement, and water. Recycling of waste material for use in CLSM benefits the environment. FA, a by-product from coal-burning power plants during the generation of electricity, is the most common waste material used in CLSM. FA improves flowability, increases strength, reduces bleeding, shrinkage, and permeability, and aids in pumpability by acting as a fine aggregate [1]. There are mainly two types of FA produced in the US; Class F, which is commonly described as non-cementitious and Class C, which possess cementitious characteristics (as described in ASTM C 618). In the Appalachian region of the US, Class F FA is predominantly produced while Class C ash is predominant in the mid-west and western regions [8].

Mixes with FA, as the only aggregate source, produced no noticeable segregation when used although they required a higher water content [1]. Quick-setting CLSM, a mixture with higher cement content, develops high early penetration resistance allowing for continuous construction. It also exhibits low shrinkage and compressibility characteristics. These mixes are economical, not labor intensive, and are not adversely affected by varying moisture contents as presented by Landwermeyer and Rice [6]. The unit weight of in-place CLSM ranges from 18 to 23 kN/m^3, a value greater than several compacted materials.

Cement is also used in CLSM to provide cohesion and strength and as a stabilizer for the FA material. Type I or II PC is normally used and conforms to ASTM C 150. Mixes with cement contents from 24 to 60 kg/m^3 are noted as having satisfactory long-term performance. Aggregates, both coarse and fine, provide the bulk of any typical CLSM mixture, with contents varying from 1544 to 1840 kg/m^3 [1].

Water provides the necessary lubrication for high flowability and workability as well as hardening, i.e., reactivity. Water contents from 190 to 340 kg/m^3 are typical in mixes containing aggregate, while those containing only Class F FA and cement can require as much as 590 kg/m^3 to maintain an acceptable flowability (ACI 229R-94, Ref. [1]).

Flowability, a common property used in concrete and grout technology, makes CLSM a unique fill material as it can be installed under gravity flow. In the laboratory, a spread of 229 mm (9 in.), per ACI 229, is considered adequate for CLSM [7]. Permeability of CLSM generally ranges from 10^{-5} to 10^{-6} mm/s and can be further decreased by adding materials such a bentonite [1].

Lovell [7] provided an idealized flow curve for CLSM as shown in Fig. 1, based on the flowability requirement of 0.229 mm (9 in.) spread. The point of minimum water content B is defined as the mixture with a minimum porosity, bleeding, and cement content. Lovell [7] also defined hardening time as the time required for CLSM to reach a hardened state with sufficient strength to support the weight of a person. Bhat and Lovell [2] developed a correlation between the hardening adequate for walkability and

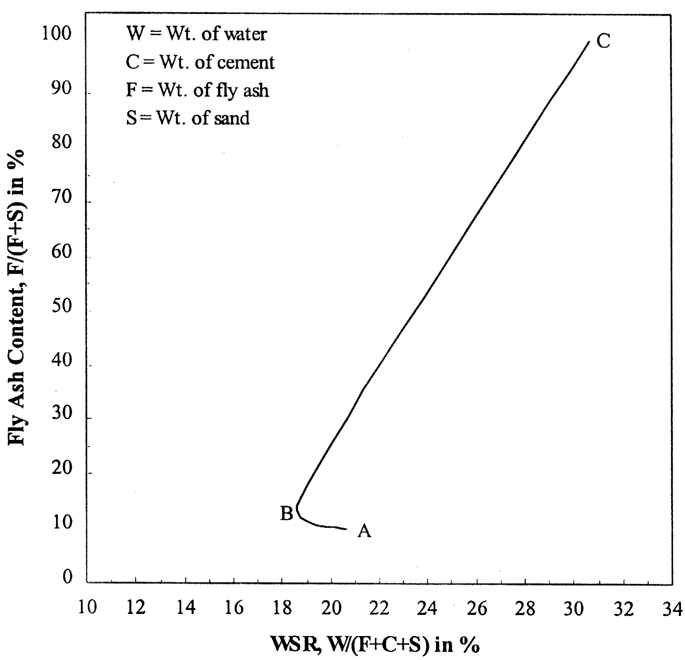

Fig. 1. Idealized flow curve for CLSM [7] (WSR = water-to-solids ratio).

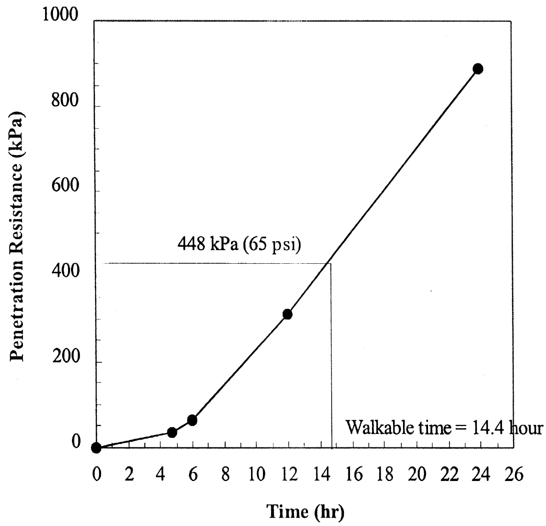

Fig. 2. Penetration resistance versus time [2].

the penetration resistance (shown in Fig. 2). Walkability was defined at penetration resistance of 448 kPa and was obtained in 14.4 h using their mix.

The penetration resistance (p) was measured using a mortar penetrometer as described in ASTM C 403. Lovell defined the relationship between the unconfined compressive strength (q_u) and the penetration resistance as $q_u = 0.162 p$ with both q_u and p being in stress units.

3. Material properties

CLSM mixtures used in this research consisted of various proportions of Class F FA, AMD treatment sludge, QL, PC and water. The major constituent in each mixture was Class F FA. This was performed in order to maximize the utilization of waste as the percent FA was maintained at or above a minimum of 80% (dry wt. basis).

3.1. Fly ash

The FA was obtained from Hatfield electric power generating station in Pennsylvania located near Waynesburg. The ash was from the #1 boiler unit and has low-calcium (1–2% CaO) with no appreciable self-hardening characteristics. The range and type of oxide composition of the FA include 45–50% SiO_2, 22–28% Al_2O_3, 14–22% Fe_2O_3, 1.2–1.4% CaO, 1–1.2% MgO, and 1.2–1.4 SO_3. The FA particles ranged in size from 5 to 100 μm with 91% of the material passing the #200 sieve (0.074 mm). The specific gravity of the ash was 2.55.

Table 1
Elemental composition of AMD used in testing [4]

Chemical	Percent composition (%)
Iron	5.0
Manganese	0.1
Aluminum	0.3
Calcium	22.0
Silicon	0.5
Sulfur	23.2

3.2. AMD sludge

The AMD treatment sludge was obtained from a 20-acre settling pond in northern West Virginia where water from underground mines is treated with hydrated lime. The AMD sludge from this site was analyzed using X-ray diffraction by Brown et al. [4] and the chemical composition of the solids content is shown in Table 1. The average moisture content of the sludge used in testing was 207% and the material had a specific gravity of 3.02. The percent AMD sludge in the test mixtures was varied from 0% to 10% (all percentages are reported on a dry weight basis).

3.3. Lime

Lime used in CLSM mixtures was high-calcium QL (CaO). The chemical composition of the lime as provided by the manufacturer is shown in Table 2. QL, rather than hydrated lime, was used for its higher percent calcium content. The specific gravity of the QL was 3.31. The percent lime in the test mixes was varied from 0% to 10%.

3.4. Cement

Type I PC complying with ASTM C150 was used for the preparation of the test specimens. The specific gravity of the cement was 3.11 with an average hygroscopic moisture content of 0.033%. The percent cement in the test mixes was varied from 0% to 10%.

Table 2
Elemental composition of QL (Germany Valley Limestone)

Element	Percent	Notes
Total Ca as CaO	97.5	loss on ignition = 0.38%
Total Mg as MgO	1.1	available CaO = 95.50%
Total Si as Si02	0.61	reactivity: 40°C rise in 30 s
Total Al as A1203	0.33	60°C rise in 3 min
Total Fe as Fe203	0.14	
Total Sulfur as S	0.026	
Arsenic	< 1.0 ppm	

4. Specimen preparation and testing methods

The testing program was performed on 21 CLSM mixtures. Table 3 shows the mix ratios of the specimens used in the testing program. Mixing of the various constituents was performed with Hobart Manufacturing's Model A120 mechanical mixer.

Specific gravity tests were performed in accordance with ASTM D854 Test Method B — Procedure for Moist Specimens. All tests were performed using AMD sludge in slurry state while accounting for its moisture content contribution to the mixture moisture content.

This was necessary since oven-drying of the AMD sludge, alone or in a mixture, resulted in a hardened material due to its excess lime's pozzolanic reactions. The measure of flowability was determined in accordance with the procedure described in ACI 229R-94 [1] using an open-ended cylinder. Hardening time was determined using a pocket penetrometer Gilson Model HM500, with a penetration needle area of 31.7 mm^2, and adapter foot area of 1506.7 mm^2. Readings were taken after the penetrometer was held in a vertical position and applied to the CLSM at a relatively constant rate of penetration of approximately 1 mm/s.

Viscosity of the different mixes, defined as the ratio between shear stress and the rate of shear, was measured using Brookfield viscometer following the procedure outlined by ASTM D4016. The SI unit of viscosity is pascal second, which is equal to 1000 cP.

Table 3
Mix ratios of specimens used in the testing program
FA = Fly ash; PC = Portland cement; QL = quicklime; AMD = acid mine drainage sludge; WSR = water-to-solids ratio.

Mix	Sample	FA	PC	QL	AMD	WSR	γ_{dry} (kN/m^3)
1	A	100	0	0	0	1:3.10	12.47
	B	95	0	0	5	1:3.10	12.13
	C	90	0	0	10	1:3.10	12.90
2	A	97.5	2.5	0	0	1:2.80	13.02
	B	92.5	2.5	0	5	1:2.58	13.00
	C	87.5	2.5	0	10	1:2.28	12.25
3	A	95	5	0	0	1:2.80	13.47
	B	90	5	0	5	1:2.50	12.91
	C	85	5	0	10	1:2.20	11.65
4	A	90	10	0	0	1:2.70	13.45
	B	85	10	0	5	1:2.25	12.43
	C	80	10	0	10	1:2.00	11.79
5	A	97.5	0	2.5	0	1:2.75	13.10
	B	92.5	0	2.5	5	1:1.91	10.93
	C	87.5	0	2.5	10	1:1.81	10.45
6	A	95	0	5	0	1:2.25	12.32
	B	90	0	5	5	1:1.91	11.26
	C	85	0	5	10	1:1.81	11.34
7	A	90	0	10	0	1:2.54	11.88
	B	85	0	10	5	1:1.90	11.73
	C	80	0	10	5	1:1.75	11.00

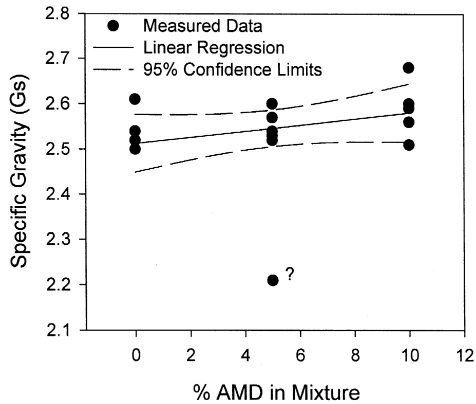

Fig. 3. Specific gravity with varying percent AMD in the mix.

Brookfield viscometer model LVT was used with spindle #2 LV for all CLSM mixes with the exception of mix 3A, which used spindle #3 LV.

CLSM stability, defined as the potential of the particles within a mixture to remain in suspension, was measured after the mixture was allowed to settle for 2 h. The percent stability was defined as the volume of clear liquid, or bleed water, after 2 h of settling subtracted from the original mix volume and divided by the original CLSM volume.

5. Specific gravity and density

Fig. 3 shows the specific gravity value for the 21 mixes tested in this study as a function of percent AMD sludge. Specific gravity values range from 2.5 to 2.7. This is in comparison to the specific gravity range for common soils of 2.6 to 2.8. As AMD sludge content was increased from 0% to 10%, specific gravity slightly increased. This is due to the increase in solid particles (metal precipitate) which are a major constituent of the AMD sludge. The dry unit weights of the various test mixes are shown in Table 3 along with the water-to-solids ratio (WSR).

6. Hardening time

The amount of time each test specimen needed to reach a penetration resistance equal to 440 kPa, as measured by pocket penetrometer, was considered hardening time. Table 4 presents the data for each of the 21 mixes tested.

All nine mixes containing PC hardened in less than 24 h, independent of AMD's sludge content. The hardening time for the nine CLSM mixtures containing QL varied. Those with no AMD sludge took more than 14.5 days (350 h) to harden, while those containing AMD could harden in a period as low as 1 day (24 h). In general, hardening time is a function of the quantity of water added, constituent temperature, particle

Table 4
Mix ratios, hardening time and 2-h settlement

Mix	Sample	FA	PC	QL	AMD	WSR	Hardening time (min)	Percent stability in 2 h (%)
1	A	100	0	0	0	1:3.10	NH	2.1
	B	95	0	0	5	1:3.10	NH	3.0
	C	90	0	0	10	1:3.10	NH	2.0
2	A	97.5	2.5	0	0	1:2.80	150	1.0
	B	92.5	2.5	0	5	1:2.58	240	1.3
	C	87.5	2.5	0	10	1:2.28	405	1.2
3	A	95	5	0	0	1:2.80	345	0
	B	90	5	0	5	1:2.50	255	0
	C	85	5	0	10	1:2.20	615	1.0
4	A	90	10	0	0	1:2.70	1055	2.0
	B	85	10	0	5	1:2.25	1410	1.0
	C	80	10	0	10	1:2.00	1160	1.0
5	A	97.5	0	2.5	0	1:2.75	20,880	0
	B	92.5	0	2.5	5	1:1.91	2400	1.3
	C	87.5	0	2.5	10	1:1.81	2595	2.0
6	A	95	0	5	0	1:2.25	22,635	1.0
	B	90	0	5	5	1:1.91	2805	1.0
	C	85	0	5	10	1:1.81	2670	1.0
7	A	90	0	10	0	1:2.54	NH	0
	B	85	0	10	5	1:1.90	2730	0
	C	80	0	10	5	1:1.75	3915	1.0

NH = No hardening.

fineness as well as any added gypsum. Data in Table 4 show an increase in hardening time with increasing cement content (mixes 2 and 4). The difference in hardening times in this case may be attributed to the lower WSR, as well the FA content, for the higher cement mixes. During the hydration process, lime is released which may lead to the slowing of the set reaction. A higher percent FA, which acts as a pozzolan, will serve to uptake the excess lime and to diminish its effect on the hydration time.

An acceptable hardening time is a function of the construction technique and the intended use of the hardened mix. A relatively quick hardening time of 24 h or less will render the CLSM as a desirable substitute for compacted fill in quick-construction projects such as utility trenches, pipeline foundations, and pavement support.

A CLSM is considered stable if the sedimentation of solids is less than 5% in 2 h. Sedimentation tests were conducted to determine the stability of each CLSM mixture used in this study. Stability results are presented in Table 4 and indicate that all mixtures are deemed stable regardless of the AMD content.

7. Flowability and viscosity

The flowability, measured using an open-ended cylinder as described in ACI [1], is plotted versus the viscosity measured using a Brookfield viscometer (Fig. 4). The

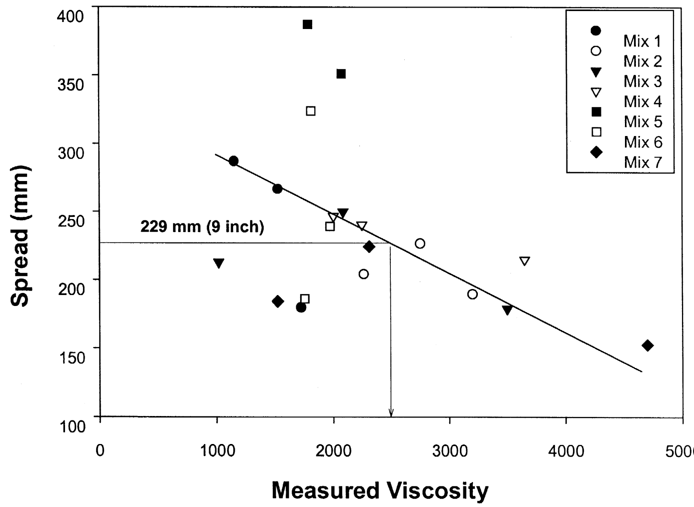

Fig. 4. Relationship between viscosity and spread.

measured data are also presented in Table 5. Based on the data in Fig. 4, a viscosity of approximately 2500 cP can be correlated to the 229 mm (9 in.) spread and considered acceptable for the stable delivery of the CLSM mix.

Table 5
Viscosity and spread data for the tested mix ratios

Mix	Sample	FA	PC	QL	AMD	WSR	Spread (mm)	Viscosity (cP)
1	A	100	0	0	0	1:3.10	287	1150
	B	95	0	0	5	1:3.10	267	1525
	C	90	0	0	10	1:3.10	180	1725
2	A	97.5	2.5	0	0	1:2.80	227	2750
	B	92.5	2.5	0	5	1:2.58	204	3200
	C	87.5	2.5	0	10	1:2.28	213	2263
3	A	95	5	0	0	1:2.80	179	1020
	B	90	5	0	5	1:2.50	250	3500
	C	85	5	0	10	1:2.20	215	2088
4	A	90	10	0	0	1:2.70	247	3650
	B	85	10	0	5	1:2.25	240	2006
	C	80	10	0	10	1:2.00	1160	2250
5	A	97.5	0	2.5	0	1:2.75	133	N/P
	B	92.5	0	2.5	5	1:1.91	387	1788
	C	87.5	0	2.5	10	1:1.81	352	2075
6	A	95	0	5	0	1:2.25	186	1755
	B	90	0	5	5	1:1.91	324	1813
	C	85	0	5	10	1:1.81	239	1975
7	A	90	0	10	0	1:2.54	184	1525
	B	85	0	10	5	1:1.90	152	4700
	C	80	0	10	10	1:1.75	224	2313

N/P = Not possible to measure by the available viscometer blade.

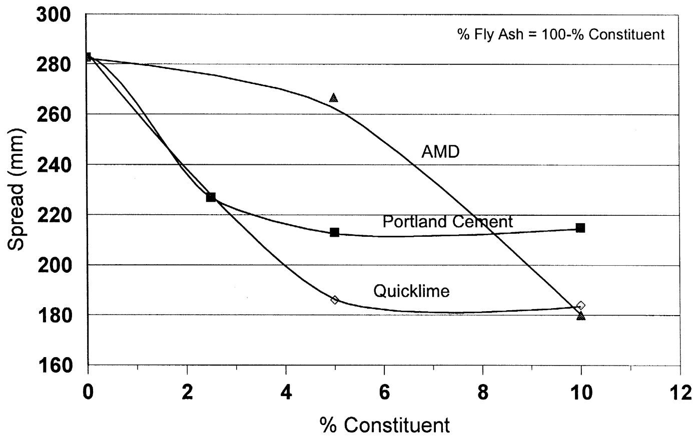

Fig. 5. Spread as a function of percent constituent.

A measure of viscosity, as opposed to spread, may be more reliable for defining the phase transitions, specifying the delivery equipment, as well as the mix resistance to flow under its own weight. The use of in-line viscometers can automate the mixing process, and since viscosity is a measure of the internal friction produced by the mix, it can potentially serve as an indicator of how the material will perform once set. This is however an area for future research since spread is currently the most common construction measure of flowability.

The flowability of the test mix was affected by the percent AMD as shown in Fig. 5. Scattered data points were mainly associated with mixes having lime as a component. As the percent AMD is increased, the spread decreased. This may be explained by the influence of AMD on ettringite formation, which lends a structure to the formed mix, therefore decreasing the spread. This explanation is supported by the data in Fig. 6, which shows an increase in shear strength with increasing percent AMD. Such an increase in strength maybe attributed to increased structure within the mix due to the ettringite crystal formation.

The desirable spread value of 229 mm was obtained for mixes containing 2.5% PC as well as mixes containing 2.5% QL. The spread for mixes with PC above 2.5% were approximately 215 mm which may be deemed acceptable. On the other hand, the spread for mixes with QL above 2.5 was approximately 180 mm which is too low to be accepted for construction purposes.

8. Compressive strength

Unconfined compressive strength was measured for test specimens cured for 7, 14, and 28 days. The tests were conducted on mixes with 0% and 10% PC and 0% and 10% AMD content, respectively. These mixes were selected since they satisfied the spread, hardening times less than 24 h, and stability requirements. The average unit weights for

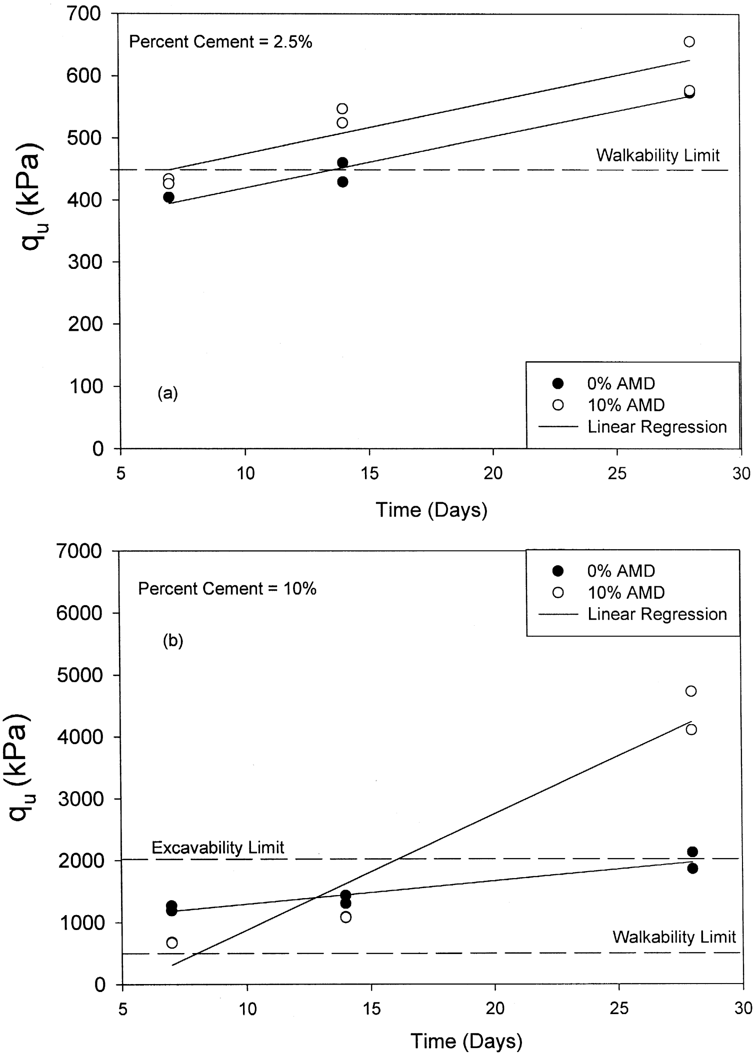

Fig. 6. Compressive strength as a function of time for various percent PC content.

the test specimens were 17.2 and 12.4 kN/m^3 for total and dry unit weights, respectively. ACI 229R-94 [1] recommends an in situ unit weight between 14.4 and 15.7 kN/m^3 for CLSM with only FA, cement, and water and values in the range of 18 to 23 kN/m^3 for CLSM with no FA or by-product material.

Fig. 6a shows that CLSM specimens tested after 7, 14, and 28 day curing periods yielded a 10% to 70% higher unconfined compressive strength for mixtures containing AMD sludge as compared to those without AMD sludge. These mixes achieved approximately 70% of the 28-day unconfined compressive strength (590 kPa) within 7 days. As shown in Fig. 6b, the two mixes with 10% cement displayed greater unconfined compressive strengths than those with 2.5%. The CLSM mixture containing 10% cement and no AMD sludge followed a similar trend. After curing for 7 days, the 10% PC, 0% AMD mix reached an unconfined compression strength of 1227 kPa, achieving approximately 60% of its 28 day strength (1990 kPa).

For test samples containing 10% of both cement and AMD sludge (Fig. 6b), the unconfined compressive strength increased from 640 kPa at 7 days to 4420 kPa at 28 days. This continual increase in strength, as shown in Fig. 6b, can be explained by the FA/cement/AMD sludge interaction. The sludge acts as an accelerator using the readily available unreacted calcium (remaining in the AMD sludge from the AMD lime treatment process) to increase pozzolanic reactions.

It should be noted that while the average moisture content for specimens tested with 0% AMD sludge was 35%, the average moisture content for 0%AMD sludge (10% cement) specimens was approximately 46%. This difference in moisture content value may explain the higher early gain in strength for mixes with 0% AMD as compared to mixes with 10% AMD sludge content (see Fig. 6b). This trend was not observed in Fig. 6a (data for 2.5% PC content). However, in this case, the difference in moisture content of the tested specimens, with and without AMD sludge, was less than 3% (35% for specimens without sludge versus 38% for specimens with sludge).

All CLSM mixtures are within the ACI 28-day unconfined compressive strength specification of 8275 kPa to qualify as low strength material. However, the 28-day strength for the mix with 10% of both cement and AMD sludge is over twice the maximum limit for excavatability and should only be used for permanent fill structures. Both mixes containing 2.5% cement meet the manual excavation limit of approximately 2000 kPa. Walkability limits of 450 kPa was also achieved based, as indicated, on the unconfined compressive strength shown in Fig. 6.

9. Conclusions

The main focus of this research was to develop a CLSM mix while maximizing by-product material utilization and satisfying workability and performance requirements. Results of this research demonstrated that CLSM composed upwards of 90% waste by-products, specifically Class F FA and AMD treatment sludge, can be utilized as structural fill. Based on the results obtained in this research, the following specific conclusions can be made.

1. Mixes containing PC hardened in less than 24 h, independent of AMD's sludge content. The hardening time for CLSM mixtures containing QL varied from less than 2 days for those containing AMD sludge to 14.5 days for those with no AMD sludge.

2. A correlation between CLSM spread and viscosity exists. For mixes using PC as the stabilizing agent, flowability corresponding to 229 mm spread occurred when viscosity was between 2200 and 2650 cP. For mixes containing QL, the viscosity range corresponding to 229 mm flowability was from 1500 to 3375 cP.

3. All CLSM mixes maintaining a spread of 229 mm were stable, that is, a settlement of less than 5%, by volume, occurred within 2 h independent of stabilizing agent or AMD sludge content.

4. For test specimens containing 10% of both cement and AMD sludge, the unconfined compressive strength increased from 640 kPa at 7 days to 4420 kPa at 28 days. This continual increase in strength can be explained by the fact that sludge acts as an accelerator with the readily available unreacted calcium increasing pozzolanic reactions.

5. The 28-day unconfined compressive strength for all mixes was greater than the required 440 kPa for walkability. The mix containing 10% of both cement and AMD sludge exceeded the maximum excavatability limit.

6. Recommended mix ratio for flowable fill is 10% AMD, 2.5% PC, 87.5% FA with water content on the order of 40%. This mix ratio satisfies the excavatability and walkability requirements as well as the hardening time and stability criteria.

Acknowledgements

The assistant of Ms. Tonya Monson Hart in conducting the laboratory experiments is greatly appreciated. Undergraduate student Jen Peterson assisted in the preparation of samples and data collection. The quicklime was provided by Germany Valley Limestone.

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