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Long-term compressive strength and some other properties of controlled low strength materials made with pozzolanic cement and Class C fly ash

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Abstract

Controlled low strength material (CLSM) is a flowable mixture that can be used as a backfill material in place of compacted soils. CLSM (or flowable fill) require no tamping or compaction to achieve its compressive strength and typically has a load carrying capacity much higher than that of compacted soils, but can be proportioned to allow future excavation. In this study, several different CLSM mixtures containing Class C fly ash (FA) obtained from Soma Thermal Power Plant in Turkey, crushed limestone sand (CLS), and a minimal amount of pozzolanic cement (PZC) were produced. The mass of PZC was kept constant for all mixtures at 5% of FA by mass. The mechanical and physical properties of CLSM mixtures such as unconfined compressive strength, water absorption by capillarity and EP toxicity were investigated by a series of laboratory tests. CLSM mixtures with low PZC contents and high Class C FA and CLS contents can be produced with excellent flowability and low unconfined compressive strengths in the range of 1.16–2.80 MPa at 365-days age when re-excavation at later ages might be needed. The results presented here show a new field of application for Soma FA in CLSM mixtures, resulting in great advantages in waste minimization, as well as, conservation of resources and environment.

Keywords: Controlled low strength material; Fly ash; Unconfined compressive strength; Capillarity; Toxicity; Waste minimization

1. Introduction

The use of controlled low strength materials (CLSM) has increased in many countries within the last decade. CLSM is not a structural material and therefore cannot be described as concrete. It is a cementitious material used primarily as a backfill as an alternative to compacted fill. CLSM is also known by other names such as controlled density fill, flowable mortar, flowable fill, and lean mix backfill. CLSM requires no tamping or compaction and therefore, can be designed to be fluid, it is ideal for use in tight or restricted-access areas where placing and compacting fill is difficult. Its mechanical properties have been deliberately kept low so that it can be easily excavated. For design and application purposes, flowable fill materials usually have a compressive strength of about 8.3 MPa or less. However, most current flowable fill applications require a 28-day compressive strength of 0.7 MPa. If future excavation is anticipated, the maximum long-term compressive strength should generally not exceed 2.1 MPa [1].

Conventional CLSM mixtures usually consist of Portland cement, FA or similar industrial by-products, fine and coarse aggregate or both, and water. Other industrial by-products have been used sporadically in CLSM production, for example spent foundry sand [2,3], acid mine drainage (AMD) [4] and recycled glass [5].

Some properties of CLSM mixtures such as ease of placement, compressive strength, and lower in-place costs make CLSM superior to conventional backfilling methods. These mixes are economical, not labor intensive, and are not adversely affected by varying moisture contents as presented by Landwermeyer and Rice [6]. CLSM can be easily manufactured and delivered to the jobsite by a ready-mixed concrete producer. Its uses include, but are not limited to, placement under existing bridges, around and within box culverts or culvert pipes, in open trenches, in open mine fills liners and other specified filling purposes.

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CLSM mixtures for most fill applications achieve compressive strengths ranging from 0.35 to 2.00 MPa. Higher compressive strength values can be obtained by proper proportioning of the quantity of constituent materials. However, these higher strength values far exceed most natural soils, therefore the CLSM replacement would be stronger than the surrounding in situ materials. Nevertheless, CLSM fills can still be excavated with conventional methods where it becomes necessary. Higher strength may be a problem in mixtures when re-excavation at later ages might be needed, and this should be considered [7].

2. CLSM materials

Some CLSM mixtures use coal-combustion FA as the major constituent of the mixture. FA is a by-product of the coal burning in electric power-generating plants. Coal burning power plants annually produce millions of tons of FA as a waste product world-wide. The Soma Thermal Power Plant in western Turkey produces 4,000,000 t of fly ash annually, but only 0,49% is productively employed, the rest is disposed in landfills [8]. Both of the fly ash types (Class F and Class C) described in ASTM C 618 are produced in Turkey. The amount of Class C FA is predominantly produced in Turkey is more than that of Class F ash. FA consists of fine particles that contain leachable heavy metals and is therefore, classified as a toxic waste by Carlson and Adriano [9] and Ferreira et al. [10]. The environmentally acceptable disposal of the material has become of increasing concern. Past and recent research has established the potential of using FA in a variety of construction applications due to its pozzolanic properties. However, there is still a need to find new environmentally acceptable uses and increase utilization, so less FA will need to be disposed. The use of FA in large volumes in CLSM mixtures seems to be a perfect utilization method. Several successful application of FA in CLSM have recently been reported [4,11,12].

CLSM fills incorporating FA have been defined by ACI Committee Report 229R-99. Both ASTM Class F or Class C FA can be incorporated into CLSM fills with relatively low proportions of cement to activate pozzolanic reactions.

The spherical shape of FA particles and rather high water/binder ratios improve the fluidity of the CLSM mixtures so that these mixtures can be placed with ease and require little or no tamping or compaction. This property saves operation time. For example, a void fill of 8 m^3 volume has been completed in just 3 min of working period [13]. Besides, a minimum spread value of 200 mm without noticeable segregation. The spread values of the mixtures used in this study were adjusted to be slightly larger than 200 mm as shown in Table 4. CLSM mixtures require little or no mechanical or hand-spreading to completely fill an inaccessible area. In tight or congested locations, the spreading and compaction of a fill material is usually accomplished by hand, making the operation time consuming and costly.

This research investigated CLSM mixtures with varying proportions of ASTM Class C fly ash, pozzolanic cement, and crushed limestone sand. Basic physical and mechanical properties of the different CLSM mixtures using these local materials were determined. The possible hazardous effects of CLSM mixtures on the environment were also investigated using the EP toxicity test method.

3. Experimental study

Materials and the details of the testing program as well as resultant test results are presented in the following sections.

3.1. Materials

The basic constituent materials used in producing the CLSM mixtures in this investigation were: pozzolanic cement (PZC) and fly ash (FA) as binders, crushed limestone (CLS) as fine aggregate, fly ash (FA), and tap water.

3.1.1. Cement

The purpose of cement in CLSM mixtures is to provide cohesion and strength gain and is also used in pozzolanic reactions.

According to available technical literature data, Portland cement classified by ASTM C150 as Type I, has been used in previous studies on CLSM mixtures. Pozzolanic cement (PZC) has been chosen as the binder in this study. PZC is the most available type in the market due to its lower production costs in Turkey.

The PZC, CEM II/B-P 32.5 (65% clinker + 35% trass) was used in this research. Cement in conformity with Turkish Standards (TS197-1) [14] was manufactured by Batı Anadolu Cement Plant, İzmir, Turkey. The physical and chemical properties of PZC (CEM II/B-P 32.5) provided by the manufacturer are shown in Table 1.

3.1.2. Fine aggregate

Crushed limestone (CLS) fine aggregate (0.0–5.0 mm) was used in the CLSM mixtures in this research. The grading and physical properties of the CLS fine aggregate are presented in Table 2. CLS fine aggregate passing 74 μm (#200 sieve) was 5%.

3.1.3. Fly ash

The FA used in this research was provided by from the Soma Power Plant located in Manisa, Turkey. Some of the chemical and physical characteristics of the FA were determined in Batı Anadolu Cement Plant quality control laboratory and the test results are presented in Table 3.

3.2. Specimen preparation and test procedure

The CLSM mixtures that are used in the experimental studies are presented in Table 4. These mixtures were chosen after a series of pre-trials [15]. From each mixture type, a sufficient number of test specimens of specify sizes and shapes were cast. In these mixtures, the total amount of binder (PZC + FA) was kept constant. The CLS fine aggregate was proportioned in filler/binder ratios by mass. In all mixtures, the ratio of PZC/FA was chosen as 0.05. Krell [16], also recommended 4–5% Portland cement added to the dry mass of the FA with enough

Table 1
Chemical and physical properties of CEM II/B-P 32.5 cement

Chemical properties	
Element	%
SiO_2	3.49
Al_2O_3	8.50
Fe_2O_3	3.53
CaO	45.78
MgO	0.79
SO_3	2.10
Na_2O	0.87
K_2O	1.51
Insoluble residue	29.57
Loss on ignition	2.74
Free lime	1.20
Physical properties	
Specific gravity	2.88
Blaine (cm^2/g)	4609
% retained on 90 μm sieve	0.9
% retained on 90 μm sieve	0.1
Setting time	
Initial (min)	135
Final (min)	215
Compressive strength (MPa)	
2 days	17.9
7 days	29.8
28 days	37.1

Table 2
Grading and physical properties of crushed limestone fine aggregate

Sieve size (mm)	% passing
8	100
4	96
2	66
1	40
0.5	23
0.25	11
Physical properties	
Bulk specific gravity	2.66
Unit weight (kg/m^3)	
Loose	1620
Compacted	1860

Table 3
Properties of fly ash

Property	Soma fly ash
Specific gravity	2.12
pH	11.86
Moisture content (%)	0.72
Strength activity	
Index (%)	78
CaO	14.63
SiO_2	49.08
Al_2O_3	22.99
Fe_2O_3	5.20
$SiO_2 + Al_2O_3 + Fe_2O_3$	77.27
SO_3	1.28
MgO	2.15
Loss on ignition	1.45

Cured 1 day at 23 °C plus 27 days at 38 °C.

mixing water to maintain the necessary fluidity and pumpability of CLSM mixtures for the application. Water/solid materials ratio has been chosen as 0.2 as a minimum value according to GAI Consultants recommendations [17].

The flowability was measured by using an open-ended cylinder as described in ASTM D6103 [18]. Resultant CLSM mixtures were cast into molds without compaction or vibration.

The CLSM mixture types with high FA contents could not be demolded at 24-h age due to low or insufficient strength gain. These test specimens were kept in molds for seven days in a humid environment under wet burlap covers. After demolding, specimens were cured at 20 ± 2 °C and minimum relative humidity of 80%. The densities of CLSM mixtures were determined to be between 1.95 and 2.15 g/cm^3 according to the ASTM D854-92 [19].

Unconfined compressive strength tests were performed on six 50 mm × 50 mm cube specimens as described in ASTM D4832 at various ages (7-, 28-, 56-, 120-, and 365-days age). A compression test machine of 0.2 N sensitivity was used in the test. Smooth metal sheets were placed at the bottom and top of the specimens during the unconfined compression test to minimize end effects.

40/40/160 mm prisms were prepared to determine the water absorption of CLSM mixtures by capillarity according to the TS 4045 [20]. After 28 days of casting, test prisms were dried in the oven at 105 °C to constant weight. The test specimens were placed in a container in the vertical position with the bottom in contact with water.

Table 4
Mix proportions of various CLSM mixtures

Mixture	Materials batch weight (kg/m^3)				CLS/(PZC + FA)	W/(PZC + FA)	Total weight (kg/m^3)	Spread (mm)
	PZC	FA	CLS	Water				
M1	19	370	1166	389	3:1	1.00	1944	220
M2	17	346	1272	363	3.5:1	1.00	1998	210
M3	16	314	1319	363	4:1	1.10	2012	207
M4	13	268	1407	352	5:1	1.25	2040	210
M5	13	250	1444	341	5.5:1	1.30	2048	210
M6	12	234	1474	344	6:1	1.40	2064	205

To analyze hazardous heavy metal existence in CLSM mixtures, selected CLSM mixtures were subjected to Extraction Procedure (EP toxicity tests). Test methods are prescribed by U.S. Environmental Protection Agency [21].

4. Results and discussions

4.1. Compressive strength

Fig. 1 represents the unconfined compressive strength test results in graphical form.

The following situations are observed with respect to the compressive strength behavior of the CLSM mixtures in this investigation.

As expected, lower W/(PZC + FA) ratios resulted in higher strengths. For example, W/(PZC + FA) ratio of M1 is 1.0 and its 28-day compressive strength 1.15 MPa. On the other hand, W/(PZC + FA) ratio of M6 is 1.40 and its 28-day compressive strength is 0.85 MPa.

As shown in Fig. 2, the ratio of 365-day to 28-day strengths was lower for mixtures with higher W/(PZC + FA) ratios. According to the test results, these ratios ranged from 1.36 to 2.43 from M1 to M6, respectively.

As shown in Fig. 3, compressive strengths–time relationships of CLSM mixtures established in logarithmic equations in the form of $f_c = a\ln(t) - b$. The correlation coefficients were computed between 0.93 and 0.97 for these logarithmic equations. These coefficients had been showed that the logarithmic equations more reliable than the others equations. The coefficients of the logarithmic equations (a, b, and regression R) for six CLSM mixtures are also given in Fig. 3.

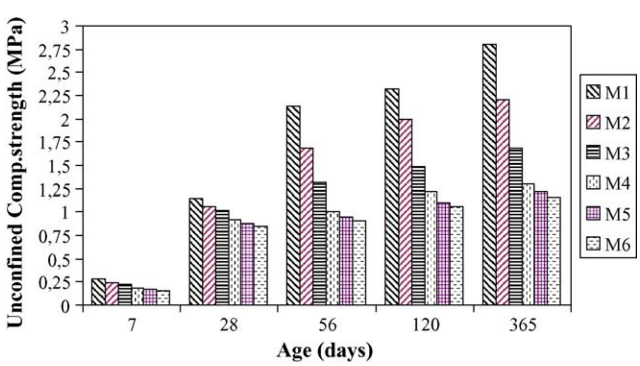

Fig. 1. Unconfined compressive strength of various type of CLSM mixtures.

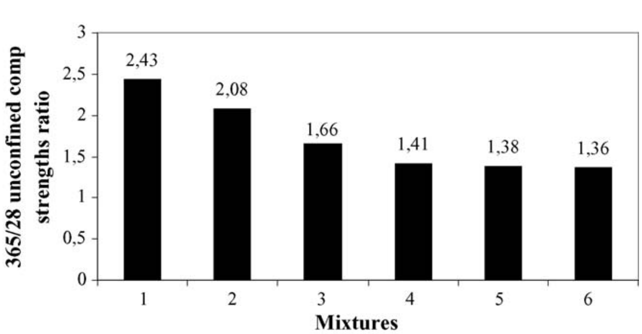

Fig. 2. 365/28 days unconfined compressive strength ratios.

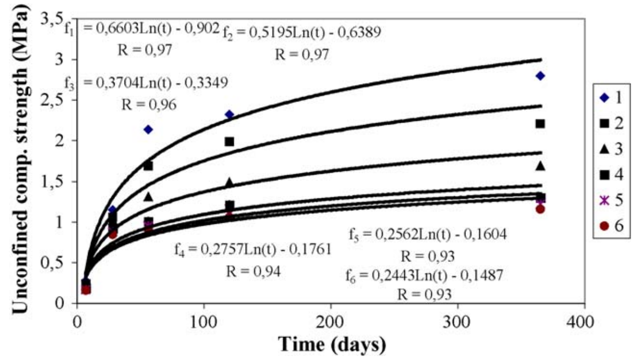

Fig. 3. Unconfined compressive strength–time relationship.

FA gains strength at a slower rate than cement. This factor became very important for the current investigation because of the high FA content of the CLSM mixtures. The following observations were made with regard to compressive strength gain with time.

(a) The rate of strength gain decreased slowly after 56-days for M1, M2 and M3 mixtures. However, the rate of strength gain decreases after 28-days for M4, M5 and M6 mixtures.
(b) The strength gain continued steadily up to 365 days of testing period.
(c) Increase in fine aggregate content showed a decrease in the rate of later strength gain. This trend was logical because more fine aggregate provided more inert material that did not hydrate with time [22]. This behavior should be the reason why the rate of strength gain of M4, M5 and M6 mixtures started to decrease after 28-days.

The amounts of FA and fine aggregate had a higher influence on strength at lower W/(PZC + FA) ratios. Based on the test results obtained in this investigation, fine aggregate to cementitious material ratio of 6 could be used for W/(PZC + FA) ratios of 1.40 for situations where low compressive strengths are desired. If higher strengths are desired, fine aggregate to cementitious materials ratio of 3 and W/binder material ratio of 1.0 seem to provide the best results.

4.2. Water absorption by capillarity

The coefficient of capillary absorption of the mixtures at 28 days was calculated by using $(Q/A)^2 = kt$ equation [23]. Where Q is the water absorption at 24 h (cm^3), A the cross-sectional area (cm^2), t the time (s), k is the coefficient of capillary absorption (cm^2/s). The water absorption by capillarity test results has been presented in Fig. 4.

The capillary water absorption values ranged from 1.43×10^{-3} to 2.08×10^{-3} cm^2/s at 28 days. The lowest water absorption 1.43×10^{-3} cm^2/s was obtained for M1 mixture, the highest for M6 mixture. According to the test results, an increase in fine aggregate content and also increasing W/(PZC + FA) ratio showed an increase in the capillarity coefficient.

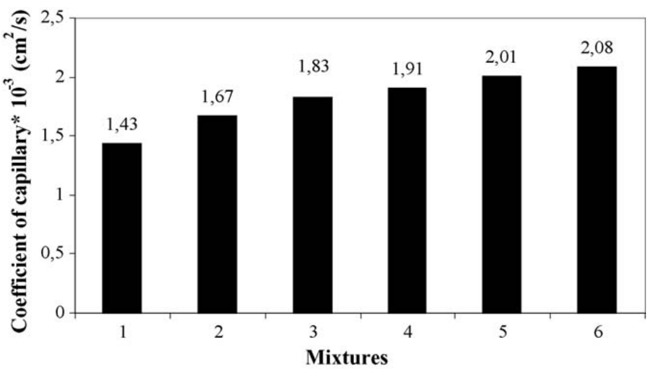

Fig. 4. Capillary water absorption test results for 28-days old CLSM mixtures.

Table 5
EP toxicity test results for selected CLSM mixtures

Element	Concentration (ppm)			
	M1	M4	M6	EPA limits
Arsenic	2.54	2.23	2.08	5.0
Barium	17.84	17.34	17.06	100.0
Cadmium	0.12	0.10	0.09	1.0
Chromium	0.08	0.05	0.03	5.0
Lead	0.39	0.33	0.28	5.0
Mercury	0.11	0.095	0.085	0.5
Selenium	0.32	0.25	0.22	1.0
Silver	0.00	0.00	0.00	5.0

4.3. EP toxicity test

Since CLSM mixtures are rather permeable materials and are used in applications such as fillings or as liner materials in a landfill, their possible effects on environment were also investigated.

The main environmental concern surrounding utilization of CLSM mixtures is the chance of certain constituents leaching into the groundwater at concentrations determined to be potentially hazardous to human health.

After application of the EP toxicity test, eight heavy metal concentrations, namely arsenic, barium, cadmium, chromium, lead, mercury, selenium and silver were measured. The test results are given in Table 5.

The test results showed that the concentrations of all heavy metals for selected CLSM mixtures were lower than the stated EPA limits. Thus, the CLSM mixtures are not hazardous to groundwater.

These results indicate that CLSM mixtures are environmentally acceptable filling materials and ideal compositions for liners.

5. Conclusions

The results obtained from experimental studies can be summarized as follows:

The present study evaluated the use of Soma Power Plant FA, low pozzolanic cement and crushed limestone fine aggregate in flowable fill mixes. CLSM mixtures with a low PZC content and high Class C FA and CLS content can be produced with excellent flowability and a compressive strength in the range of 1.16–2.80 MPa at 365-days age. These results indicate that mixtures M3–M6 (1.69–1.16 MPa at 365-days) are suitable when the re-excavatability of the CLSM is of concern.

The PZC content may be kept about 5% of FA by weight. Acceptable long-term performance has been achieved with PZC contents from 12 to 16 kg/m^3 and Class C FA contents up to 314 kg/m^3. Higher strengths can be achieved by increasing PZC content or by decreasing the amount of mixing water. FA, PZC, and CLS fine aggregate ratios should be chosen carefully to satisfy removability requirements.

In addition, CLSM mixtures are environmentally acceptable according to EPA standards.

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