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Strength properties of fly ash based controlled low strength materials

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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. Flowable fill requires no tamping or compaction to achieve its strength and typically has a load carrying capacity much higher than compacted soils, but it can still be excavated easily. The selection of CLSM type should be based on technical and economical considerations for specific applications. In this study, a mixture of high volume fly ash (FA), crushed limestone powder (filler) and a low percentage of pozzolana cement have been tried in different compositions. The amount of pozzolana cement was kept constant for all mixes as, 5% of fly ash weight. The amount of mixing water was chosen in order to provide optimum pumpability by determining the spreading ratio of CLSM mixtures using flow table method. The shear strength of the material is a measure of the materials ability to support imposed stresses on the material. The shear strength properties of CLSM mixtures have been investigated by a series of laboratory tests. The direct shear test procedure was applied for determining the strength parameters Φ (angle of shearing resistance) and C_h (cohesion intercept) of the material. The test results indicated that CLSM mixtures have superior shear strength properties compared to compacted soils. Shear strength, cohesion intercept and angle of shearing resistance values of CLSM mixtures exceeded conventional soil materials' similar properties at 7 days. These parameters proved that CLSM mixtures are suitable materials for backfill applications.

Keywords: Fly ash; Controlled low strength; Backfill; Shear strength

1. Introduction

The use of controlled low strength materials (CLSM) is getting more popular in many countries within the last decade. The material being described is not concrete and it's not soil. The material is also known by other names such as controlled density fill (CDF), flowable mortar, flowable fill and lean mix backfill. Its mechanical properties have been deliberately kept low so that it can be excavated easily. CLSM mixtures usually have a compressive strength of about 8.0 MPa at 28 days or less. However, in many flowable fill applications 28-day compressive strength value may be as low as 0.7 MPa [1].

These strength values far exceed most of the natural soils similar values. This leads to the formation of a stronger replacement than the surrounding soil. Nevertheless, CLSM fills can still be excavated with conventional methods where it becomes necessary. However, rather high strength values may be a problem when re-excavation at later ages due to the pozzolanic nature of the constituents. CLSM requires no tamping or compaction to achieve its strength. Other benefits gained from using flowable fills are, improved construction safety since trench exposure is limited, better durability because it is less permeable than compacted granular backfills. And it can be used in hard-to-reach places [2–5].

CLSM is basically a mixture of cement, a by-product material (usually fly ash), fine aggregate and water that can be used as a backfill material in place of compacted soils with its self leveling property. Recycling of waste material for use in CLSM is also helpful in conservation of the environment. CLSM fills incorporating fly ash has been defined by ACI committee report No. 229 as "Fly ashes, both F or C classes can be utilized in CLSM fills with relatively low proportions of cement to activate pozzolanic reactions". Besides FA, the usage of various by-products such as acid mine drainage (AMD) sludge, quicklime

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(QL), has been also investigated by Gabr and Bowders [3].

Some properties of the CLSM mixtures such as ease in placement, strength and economy make CLSM superior to conventional backfilling materials and methods. They become economically competitive whenever a structural well-compacted fill is required. The ease of placement of CLSM mixture makes them attractive from the standpoint of reduced labour cost. Also, CLSM mixtures do not disintegrate or lose them stability, when the structure comes into contact with water, in contrast to soil. If the material is available, it can be manufactured and delivered by a ready-mix concrete producer [2]. 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.

Spherical shapes of fly ash particles and rather high water/binder ratios improve the fluidity of the CLSM mixtures so that the mortars can be placed with ease requiring no tamping or compaction without segregation. This unique property saves the operation time. For example, a fill of 8 m^3 volume has been realised in just 3 min of working period [6]. Also, there is little or no spreading required. In conventional backfill operations, in tight locations the spreading and compaction is usually accomplished by hand, making the operation time consuming and costly.

Long-term compressive strength and some other properties such as water absorption by capillarity and EP toxicity of CLSM mixtures have been investigated by Türkel [7]. In this study, compressive strength values varied in the range of 1.16–2.80 MPa on 1-year-old specimens. These results indicate that, the mixtures that have lower compressive strength values (∼1.16 MPa) are suitable in terms of excavatability. In addition, based on the test results of this study, CLSM mixtures are environmentally acceptable according to US Environmental Protection Agency (EPA) standards.

Different proportions of fly ash (Class C)–pozzolana cement and crushed limestone sand have been used as the main ingredients of CLSM in this research. According to available technical literature data, Portland cement of type I has been used in various testing programs on CLSM mixtures [3–5]. However, in this study, pozzolana cement has been chosen due to its availability in the local market. The shear strength properties of different CLSM mixtures have been determined. The direct shear test procedure was implemented for determining the strength parameters Φ (angle of shearing resistance) and C_h (cohesion intercept) of the material.

2. Experimental study

The tests performed in this experimental program have been realised according to American (ASTM), Turkish (TS) and other relevant standard test methods. The details of the testing program and test data have been presented in the following sections. A parallel program also has been carried out by Türkel on the same materials aimed at determining other properties of CLSM mixtures [7].

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

Element	%
Chemical properties	
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

2.1. Materials

The raw materials used in the controlled low strength materials (CLSM) compositions; were pozzolana cement, crushed limestone, fly ash and tap water. Admixtures were not included into the test program due to their rather high costs. And their beneficial effect was negligible in terms of flowability. The physical and chemical properties of these ingredients have been presented in Tables 1–3.

2.1.1. Cement

The purpose of using cement in CLSM mixtures is to provide proper values of cohesion and strength besides pozzolanic

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 ashes

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.

reactions. The pozzolana cement CEM II/B-P 32.5 (with up to 35% of natural pozzolana) was used in this research. The physical and chemical properties of pozzolana cement (CEM II/B-P 32.5) are presented in Table 1. The test data was provided by the cement manufacturer. This type of cement was chosen due to its lower mechanical properties and availability in Turkish market.

2.1.2. Fine aggregate

Fine aggregate, basically limestone powder makes up the major portion of a typical CLSM mixture. A non-standard rejected filler aggregate for concrete (ASTM C33) has proven to be more economical [8]. A fine crushed limestone fine aggregate that was not suitable for concrete production has been used as a filler in all CLSM mixtures. The properties of crushed limestone have been presented in Table 2.

2.1.3. Fly ash

The fly ash (FA) was procured from Soma B power plant of Turkey. Fly ash used in Portland cement concrete should comply to the national standards such as Turkish Specifications for Fly Ashes (TS EN 450) and ASTM C618. The same fly ash specifications may be applicable for the manufacture of CLSM.

Some of the chemical and physical properties of the fly ashes were determined in Batı Anadolu Cement Plant quality control laboratory and the test results are presented in Table 3.

Table 4
Typical mixes

Mixture	Mixture type		Water to solid ratio (W/SR)	Spread (mm)
	F/(C + FA)	W/(C + FA)		
M1	3:1	1.00	0.25	220
M2	3.5:1	1.00	0.22	210
M3	4:1	1.10	0.22	207
M4	5:1	1.25	0.21	210
M5	5.5:1	1.30	0.20	210
M6	6:1	1.40	0.20	205

2.2. Preparation and curing of specimens

The CLSM compositions used in the experimental studies are presented on Table 4. These compositions were chosen after a series of pre-trials. In these compositions, the total amount of binder (pozzolana cement + fly ash) was kept constant. In all compositions the ratio of pozzolana cement/fly ash was chosen as 5%. Krell also recommends a value of 4–5% for normal Portland cement usage [9]. Limestone powder as filler material was added to the mixtures in different filler/binder ratios by weight. The amount of mixing water has determined based on maintaining the fluidity and pumpability of CLSM mixtures. Water/solid materials ratio has been chosen to be about 0.2 as a minimum value according to GAI consultants recommendations [10].

The flowability was determined by using an open-ended cylinder as described in ASTM D6103. Spread values are also presented in Table 4 for every composition. Fluidity ratio of CLSM mixtures varies between 105% and 120% for different mixture types. Water to solid ratio had a high influence on fluidity ratios. It can be seen from Table 4, decreasing water to solid ratio also decreased fluidity ratios of CLSM. CLSM mixtures have been cast into moulds without compaction or vibration.

The samples with high fly ash contents could not be demoulded 24 h after casting day due to low and late gain of strength. These test specimens were kept in moulds for seven days in a humid environment under wet burlap covers. Mix proportions and batch unit weights of test specimens for every CLSM mixture are presented in Table 5. The densities of CLSM mixtures have been measured between 1.95 and 2.15 g/cm^3 by ASTM D 854-92.

Table 5
Mix proportions of CLSM mixtures

Mixture number	Materials				Total weight (kg/m^3)
	Batch weight (kg)	Fly ash (class C)	Crushed limestone	Water	
1	19	370	1166	389	1944
2	17	346	1272	363	1998
3	16	314	1319	363	2012
4	13	268	1407	352	2040
5	13	250	1444	341	2048
6	12	234	1474	344	2064

Table 6
Compressive strengths of various type of mixtures

Mixture	W/(C + FA)	Compressive strength (MPa)			
		7 days	14 days	21 days	28 days
M1	1.00	0.28	0.58	0.84	1.15
M2	1.00	0.24	0.38	0.65	1.06
M3	1.10	0.22	0.37	0.63	1.02
M4	1.25	0.19	0.39	0.72	0.92
M5	1.30	0.17	0.34	0.64	0.88
M6	1.40	0.16	0.31	0.61	0.85

3. Results and discussions

3.1. Compressive strength

The proper control of strength development in a flowable mix is the most important criteria in developing the design mix. Strength development must meet not only the minimum value to provide structure support, but also, the maximum strength development must be controlled since in the cases of backfill applications, often times it may be desired to return to the site and excavate a portion of the backfill to expose buried sub-structures, pipes, etc.

50 mm × 50 mm cube specimens were cast for every mixture for unconfined compressive strength test. Unconfined compression tests were performed on six specimens of various ages (7, 14, 21 and 28 days) as described in ASTM D4832. A compression testing machine of 0.2 N sensitivity was used in the test. Average values for unconfined compressive strength are shown in Table 6.

As expected generally mixtures with lower W/(C + FA) ratios and lower filler contents developed higher strengths. For example, M1 (three part filler, one part (C + FA)) and W/(C + FA) ratio 1.0 had a 28-day compressive strength value of 1.15 MPa. On the other hand, M6 (six parts filler, one part (C + FA)) and W/(C + FA) ratio 1.40 had a compressive strength value of 0.85 MPa at the same age. The compressive strength of M4 mixture for 14 and 21 days has been found greater than M2 and M3 mixtures. This unexpected result may be attributed to unavailable experimental errors and to the limited number of test specimens. All CLSM mixtures are in accordance with the ACI 28-day unconfined compressive strength specification of less than 1.15 MPa to qualify as a low strength material.

3.2. Direct shear

Direct shear tests were performed for determining the strength parameters Φ (angle of shearing resistance) and C_h (cohesion intercept) of the material. The shear strength of the material is a measure of the materials ability to support imposed stresses on the material. It is a function of intergranular frictional resistance and cohesion. From each mixture three 60/60/20 mm specimens were tested at 7 days. The shear strength of test specimens was determined according to the procedures of ASTM D 3080-98 for direct shear testing. A single shear apparatus was used to testing [11]. The rate of strain was 0.300 mm/min with a dial gauge reading of 0.12 mm/div. The values of shearing load and shearing strain were recorded simultaneously under various normal loads. The shear stress was determined at failure for each normal load. Shear stress at failure versus normal stress was plotted with the same scale for both the ordinate and abscissa on the chart. A best-fit straight line was constructed through the plotted points. This straight line intercepts with the vertical axis. The ordinate of the intersection points is the cohesion intercept value and the angle with horizontal is angle of shearing resistance [11]. Direct shear test data and result of calculations are given in Table 7. Cohesion and internal angle of friction results are also given in Table 7 for 7 days old specimens. Normal and shear stresses were computed by Eqs. (1)–(3) as

$$\sigma = \frac{P_v}{A_c} \tag{1}$$

$$\tau = \frac{P_h}{A_c} \tag{2}$$

$$A_c = A_o - \text{horizontal dial reading} \times 0.12\,\text{mm/div} \tag{3}$$

where P_v is the vertical (normal) load, P_h the horizontal (shear) load, A_o the original sample area and A_c is the corrected area of the sample.

According to the test results, cohesion values ranged from 0.038 to 0.047 MPa and angle of shearing resistance ranged from 43° to 54°. The value for angle of shearing resistance ranges between 40° and 55° for consolidated-drained medium size gravely soil while minimum value is changed 20–22° for unconsolidated-undrained silty sand soil [11]. From this point of view CLSM mixtures have almost similar angle of shearing resistance values with the medium size gravely soil.

For a good soil, the cohesion intercept value is about 0.2–0.25 MPa [12]. In 7 days, cohesion values of CLSM mixtures are lower than the compacted soils due to the low rate and strength gain. However, direct shear test could not be performed on 28 days old CLSM specimens due to the high gain of strength. The test apparatus is basically designed for soils. Shear strength values over 0.35 MPa cannot be measured. FA gains strength at a slower rate than cement. This factor became very important for the development of shear strength similar to compressive

Table 7
Direct shear test results for CLSM mixtures at 7 days

Parameters	Mixture					
	M1	M2	M3	M4	M5	M6
Cohesion intercept (MPa)	0.047	0.045	0.044	0.041	0.040	0.038
Angle of shearing resistance (°)	54	52	51	47	45	43

strength because of the high FA content of CLSM mixtures [7].

Based on the test results obtained from this investigation, it can be stated that, water to cementitious materials ratios had a high influence on compressive and shear strength. It may be assumed that, increasing values of water/binder ratios also increased the porosity of the CLSM mixtures. Consequently, CLSM samples with high water/binder ratios gave low strength values. Besides, the capillary water absorption values ranged from $1.43 \times 10^{-3}\,\mathrm{cm}^2/\mathrm{s}$ (for mixture number 1) to $2.08 \times 10^{-3}\,\mathrm{cm}^2/\mathrm{s}$ (for mixture number 6) at 28 days [7]. According to these results, an increase in fine aggregate content and also by increasing water/binder ratios caused an increase in capillarity coefficient values.

4. Conclusions

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

CLSM mixtures with a low pozzolanic cement content and high Class C fly ash and limestone filler content can be produced with excellent flowability and compressive strength values in the range of 0.85–1.15 MPa at 28 days. All CLSM mixtures are within the ACI 28-day unconfined compressive strength specification of 1.15 MPa to qualify as a low strength material. In many cases, CLSM mixtures may be economical and feasible due to the low cost of the constituents.

Shear strength, cohesion intercept and angle of shearing resistance values of CLSM mixtures exceed the most conventional soil materials' similar properties at 7 days. These properties are especially favourable for using of CLSM mixtures behind the retaining walls besides other filling jobs. CLSM mixture seems to be a promising alternative to many compacted soil applications due to its positive properties.

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