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Controlled low strength materials incorporating cement kiln dust from various sources

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Abstract

This paper presents the development of controlled low strength materials (CLSM) incorporating cement kiln dust (CKD) from four different sources or manufacturers. A preliminary study (Phase I) was conducted to understand the influence of CKD on fresh and strength properties of 12 selected CLSM mixtures where CKD and cement contents varied from 4% to 45% and 2% to 4% of total mass, respectively. Subsequently, four best CLSM mixtures were selected from Phase I and used in combination with the four types of CKD (from four sources) to provide 16 CLSM mixtures for a detailed study (Phase II). The detailed study investigated fresh and hardened properties, addressed durability issues, compared the performance of different types of CKD, and made recommendations for suitable mix designs for field applications. CLSMs with larger quantities of CKD showed higher drying shrinkage and seemed to have lower freeze–thaw and wetting–drying resistances. CLSM appeared to be less permeable than the well-drained soil. Correlations between properties such as California bearing ratio (CBR), compressive strength, and setting time are also established. The source/type of CKD influenced fresh, mechanical and durability characteristics of CLSM mixes due to variations in chemical compositions. The research suggests suitable CLSM mixes either derived from the combination of CKD (10% maximum) and cement (4% maximum) or CKD (30% maximum) alone. The developed 16 CLSM mixtures from four different types of CKD should provide the user a range of alternatives for the selection of suitable mix for a specific project. Sustainable development in the cement industry can be achieved by producing CKD based CLSM as it reduces the use of cement and consumes a co-generated product.

Keywords: Cement kiln dust; Controlled low strength material; Mix design; Fresh-mechanical properties; Durability

1. Introduction

Controlled low strength material (CLSM) can be defined as a self-compacting, cementitious material used primarily as a backfill instead of a compacted fill in numerous applications [1–10]. CLSM may be used in backfilling walls or trenches; as utility bedding material for pipes; as void fillings including the filling of sewers, tunnel shafts, and basements or other similar underground structures. The self-levelling characteristic allows CLSM to be placed without consolidation that can reduce construction time as well as enhance health and safety at construction site by eliminating noise of vibrators.

A CLSM called 'plastic soil-cement' was first used as pipe bedding on the Canadian River Aqueduct Project in north-western Texas (in 1964) by the US Bureau of Reclamation [3] and its use reduced the project cost by about 40% compared to conventional backfill [1]. In the early 1970s, an Ohio based ready-mix concrete company produced a backfill material called 'flowable fly ash' (primarily fly ash with 4–5% cement) which was used in the Belle River project saving approximately $1 million [4]. A company known as K-Krete patented this CLSM as 'K-Krete' and eventually gave the patent rights to the National

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Ready-Mix Concrete Association (NCRMA) [1]. Subsequently, various CLSMs similar to K-Krete were developed by different companies in North America without disseminating information in order to maintain a competitive edge. CLSM is currently known by a variety of terms including 'flowable fill', 'controlled density fill', 'flowable mortar' and 'soil-cement slurry'. In an effort to promote CLSM and its uses, ACI and ASTM published standards and specifications [2,5].

Portland cement, supplementary cementitious materials (SCM), aggregates and water are the key ingredients of a CLSM mixture. Air entraining or water reducing admixtures can also be used to control fresh, mechanical and durability characteristics. Fine aggregates or fillers are often used in larger quantities while coarse aggregates (however, this is seldom) may also be used. Typical CLSM mix proportions are 80–85% fine aggregate (size ranging from 4.45 to 0.075 mm) or filler, 10–15% supplementary cementing materials, 5–10% cement by mass, 250–400 L/m^3 of water – although the actual mix proportion can vary depending on the application [11,12]. Sand is the most commonly used fine aggregate, although other materials such as quarry fines, asphalt dust and recyclable aggregates have also been used [13]. SCMs such as coal fly ash, bottom ash, foundry sand, and wood ash are used in CLSM mixes [4,7,8,14]. Typically, CLSM has a slump value of about 250 mm or more and a maximum compressive strength of 8 MPa [1] (although different upper bounds have been suggested for the compressive strength). Most current applications used an unconfined compressive strength of 1.4 MPa or less to allow for future excavation of CLSM [1].

As the volume of waste and by-product materials generated in society increases, there are numerous pressures and incentives to reduce, reuse and recycle. The use of wastes and by-products in the development of CLSM can help to decrease environmental hazards which can lead to sustainable development. CLSM offers an excellent opportunity for the use of industrial by-products or recycled materials as fine aggregate and/or cementing materials [4,7,13–16]. Cement kiln dust (CKD) is a voluminous co-generated by-product of the cement manufacturing process. It is estimated that approximately 30 million tonnes of CKD is generated worldwide each year [17]. Although CKD has been used as a soil stabilizer [18–20], a mineral filler in asphalt concrete mixes [20] and a raw material for the production of artificial aggregate for asphalt concrete pavements [21] – approximately 80% of the CKD remains stockpiled or landfilled which pose an environmental problem. Research has been conducted to explore the viability of incorporating CKD in producing "green" cement [22] and self-consolidating concrete [23].

Limited research has been conducted on the manufacture of CLSM incorporating CKD as a replacement of Portland cement [6,24] but no research has been done on the comparative performance of CKD from various sources. Chemical composition of CKD can vary depending on the kiln process (dry or wet), raw materials and the method/location of dust collection system used by different manufacturing companies [25].

This paper presents the results of a comprehensive research studying mix design, fresh and mechanical properties as well as durability characteristics of CLSM mixtures incorporating CKD from four different sources/manufacturers having varying chemical compositions [26]. Development of non-expensive and environmentally friendly CKD based CLSMs is a step forward towards future sustainable development. The recommendations of this research can be of special interest to owners, manufacturers and engineers considering the use of CLSMs in construction.

2. Investigations on the development of CKD based CLSM mixtures

A comprehensive experimental program was planned to develop CLSM mixtures with acceptable properties incorporating CKD from four different sources/manufacturers designated as Types A, B, C and D. The experimental program was divided into two phases.

Phase I: Development of basic CLSM mixes – 12 CLSM mixes were designed based on the experience of previous research studies [6,10,13,24]. In this phase, only CKD 'D' was incorporated in the 12 CLSM mixes and were tested for fresh and strength properties. From these mixes, four basic mixes with acceptable fresh and mechanical properties were selected.

Phase II: Detailed investigation – This phase covered a detailed study of four basic mixes selected from Phase I but incorporating four CKDs – A, B, C and D (a total of 16 mixes). Phase II investigated fresh and hardened properties of 16 CLSM mixes with four different CKDs, addressed durability issues, studied comparative performance/suitability of CKDs from various sources and made recommendations for suitable mix designs to develop CKD based CLSM for field applications.

2.1. Materials and properties

CSA-GU (Canadian Standard Association-General Use), equivalent to ASTM Type I, Portland cement (PC) with specific gravity of 3.15 and Blaine fineness of 3740 cm^2/g was used. Physical properties and chemical compositions of PC and four CKDs supplied by different local cement manufacturing companies designated as A, B, C, and D are presented in Table 1. All CKDs have similar oxide compounds but their contents vary from source to source. Fineness of CKD (>4000 cm^2/g) is higher compared with PC. The chemical compositions of CKD's vary from source to source and the variability is well illustrated in Table 1 which summarizes statistics of 63 different CKDs [27]. A local natural sand with a bulk specific gravity of 2.73 and water absorption of 1.83% was used. Table 2 presents the particle size distribution as per ASTM C 136 as well as physical properties of sand.

Table 1
Chemical compositions and physical properties of cement and CKD

	Cement	CKD				
	CSA GU	A	B	C	D	63 CKD's from various sources [27]
Chemical compositions						
Silicon dioxide (SiO_2)	19.4	16.0	18.6	10.0	13.1	2.2–34.3
Aluminium oxide (Al_2O_3)	5.3	4.5	5.5	3.4	4.2	1.1–10.5
Ferric oxide (Fe_2O_3)	2.3	1.9	2.4	2.1	2.3	0.2–6.0
Calcium oxide (CaO)	61.8	52.0	60.1	51.3	58.1	19.4–61.3
Magnesium oxide (MgO)	2.3	1.9	2.4	1.6	3.3	0.5–3.5
Sodium oxide (Na_2O)	0.2	0.8	0.2	0.2	0.7	0.0–6.3
Potassium oxide (K_2O)	1.1	14.3	4.1	3.7	2.8	0.1–15.3
Phosphorous oxide (P_2O_5)	0.1	0.1	0.1	0.1	0.2	–
Titanium oxide (TiO_2)	0.3	0.3	0.2	0.2	0.3	–
Sulphur trioxide (SO_3)	3.8	6.0	4.0	11.1	10.6	0.02–17.4
Loss on ignition	2.1	12.5	3.3	13.5	3.1	4.2–42.4
Free CaO	–	13.3	20.6	12.0	20.1	0.0–27.2
Chloride (Cl)	0.1	6.4	2.4	–	–	–
Physical properties						
Specific gravity	3.1	3.2	3.2	3.3	3.2	
Blain fineness (cm^2/g)	3740	4000	4150	4050	4100	
Compressive strength (MPa)						
7 day	33.8	–	–	–	–	
28 day	41.0	–	–	–	–	
Setting time (min)						
Initial	121					
Final	–					
Air content of mortar (vol%)	8.1	–	–	–	–	

Table 2
Particle size distribution and properties of fine aggregate

Sieve size	% Passing by mass
Particle size distribution	
9.5 mm	100.00
4.75 mm	99.28
2.36 mm	90.87
1.18 mm	89.65
600 μm	76.36
300 μm	63.78
150 μm	84.52
Properties	
Fineness modulus	2.5
Dry loose bulk density (kg/m^3)	1780
Specific gravity – SSD	2.78
Specific gravity – bulk	2.73
Water absorption (%)	1.83

2.2. Testing procedures for the fresh properties of CLSM

CLSM ingredients, placing technique and handling are similar to those of concrete; its applications and uses are comparable to those of soils. Fresh properties of CLSM such as slump flow, flow time and filling capacity were determined by procedures used for self-consolidating concrete (SCC) [28].

Flowability of CLSM was measured by cylinder slump flow as per ASTM D 6103. A CLSM with good flowability should show a horizontal spread (slump flow) of at least 200 mm in diameter without noticeable segregation. However, stiff CLSM mixes can have a slump flow of less than 150 mm; whilst a fluid CLSM can have as high as 300 mm or greater.

The flowability of CLSM in the presence of obstructions was also measured using a slump flow cone with J-ring [29]. A standard slump cone was used for the test and the CLSM was poured in the cone without consolidation. The J-ring consists of vertical 100 mm long reinforcing bars attached to a steel ring of 300 mm diameter. The spacing of bars is adjustable, depending on the size of aggregate used. Slump flow value represented the mean diameter (measured in two perpendicular directions) of CLSM spread after lifting the standard slump cone. Fig. 1 shows the test setup of slump flow with J-ring and a typical CLSM spread after the test. CLSM should exhibit good flowability and passing ability if slump flow value with J-ring ranges between 500 and 700 mm. Also, the difference in height of the CLSM spread just inside and just outside the J-ring bars was measured at four locations. A smaller difference in heights (ranging from 0 to 10 mm) is an indication of greater passing ability and lower viscosity of CLSM. The slump flow with and without the J-ring can also be compared as a measure of passing ability of CLSM [29,30].

The V-funnel test was used to measure the viscosity and deformability of CLSM [29]. In this test, a V-funnel was filled completely with CLSM and the bottom outlet was opened, allowing the CLSM to flow out. The time of flow from the opening of outlet to the seizure of flow was recorded. For CLSM, the flow time should be less than 10 s.

Fig. 1. Cone slump flow of CLSM with J-ring.

The filling capacity (FC) of CLSM was determined by 300 × 500 × 300-mm transparent box apparatus [28,29]. The box had two chambers: one with closely spaced, smooth, horizontal, 20-mm diameter copper tubes as obstacles and the other without obstacles (Fig. 2). CLSM was poured at a constant rate into the chamber without obstacles (with the gate between two chambers closed). Once the chamber was full, the gate between the chambers was lifted allowing CLSM to flow through the obstacles. When the flow of CLSM ceased, the height of the CLSM at the two ends of the box was measured and the mean filling capacity expressed as percentage or ratio was calculated. Any filling capacity percentage ranging between 80% and 100% was considered acceptable for CLSM.

Bleeding was measured according to ASTM C 940. Freshly mixed CLSM was placed in a graduated cylinder and kept covered to prevent evaporation of bleed water. Accumulation of bleed water if any on the surface of CLSM was observed over a period of time.

Fig. 2. Box apparatus for FC.

Subsidence/settlement is the reduction in volume or vertical dimension from the time of placement to the initial set as per the American Concrete Pavement Association (ACPA). This was measured by filling a 150 mm by 300 mm cylinder mould with fresh CLSM and then calculating the percentage reduction of the vertical dimension at the time of initial set as a measure of settlement. CLSM typically has a final bleeding of less than 2% (retaining 98% of its original placement height) or a settlement of 3–6 mm per 300 mm of depth for a CLSM with high water content. CLSM with lower fluidity shows little or no subsidence [16].

Hardening of CLSM mixtures was measured in terms of initial and final setting times as per ASTM C 403 procedure based on penetration resistance. Ball drop test as per ASTM D 6024 was also used to test the hardening time (hardness) by repeatedly dropping a metal ball onto the in-place CLSM (Fig. 3). The test specimen was a 400 × 400 × 150 mm block. The CLSM was considered suitable for load application if the indentation of the dropped ball was less than 76 mm. In this paper, the time to reach a ball drop indentation of 76 mm is named as 'ball drop setting time'.

The air content and unit weight of CLSM mixtures were determined as per ASTM D 6023. CLSM has a wide range for unit weight from as little as 1440 to as dense as 2300 kg/m^3; however, this is dependent on the materials used and their proportions [3].

Fig. 3. Ball drop apparatus and test measurement for CLSM.

2.3. Tests on mechanical and durability properties of CLSM

The unconfined compressive strength of CLSM was determined as per ASTM D 4832 using 150 mm by 300 mm cylinders cast without compaction. The specimens were demoulded after 7 days, when enough strength had been obtained for proper demoulding without damaging the specimens. During the initial 7 days, the moulds were covered with plastic bags and left in a curing room at a temperature of 23 °C. After demoulding, the specimens were stored in 100% relative humidity curing room at 23 °C. The specimens were tested at 7 and 28 days using a compressive testing machine at a loading rate of 0.1 mm/min.

ASTM C 596 procedure was used to determine the drying shrinkage (DS) using 25 × 25 × 285-mm prisms. After casting, the specimens (three for each mix) were kept in the moulds for 7 days wrapped in plastic. After 7 days, the specimens were demoulded and initial lengths were measured using a length comparator. The specimens were then cured in a controlled storage room at 23 ± 2 °C and 50% ± 4% relative humidities. The drying shrinkage for each specimen was measured daily until no more change was noticed.

Initially, the standard falling head test as per ASTM D 2434 was conducted to determine water permeability of CLSM and was proved unsuccessful as very little change in water height was observed after two weeks. Eventually, a modified version of the falling head test was conducted to speed up the process where the head was increased from 2 m to 6 m and CLSM samples were saturated prior to testing rather than allowing the specimen to absorb water through the system.

The resistance of CLSM to repeated cycles of freezing and thawing was determined as per ASTM D 560 procedure for compacted soil-cement using prism of dimensions 76 mm × 76 mm × 305 mm. The freeze–thaw test was done for 12 cycles to effectively investigate the durability of CLSM.

The wetting and drying tests as per ASTM D 559 were also conducted in concurrence with the freeze–thaw test to study the durability of CLSM mixtures. The CLSM specimens were cured for 7 days in 100% relative humidity after casting. After curing, the specimens were weighed and submerged in water at room temperature (23 °C) for 5 h. They were then oven-dried for 42 h at 71 °C. Material loosened by wetting and drying was then removed using 20 strokes of a wire brush on the sides and 4 on each end. The process was repeated for a total of 12 cycles. At the end of 12 cycles, the samples were put in an oven at 110 °C for 48 h. After this, the specimens were weighed and the amount of disintegration that occurred during the cycles was determined. A passing grade for soil ranges from 14% loss for sandy or gravelly soils down to 7% for clayey soil [31].

The CBR test was conducted as per ASTM D 1883 to evaluate the bearing capacity of CLSM. The specimens were cast in the CBR-mould without compaction and allowed to gain strength by normal hydration process. Penetration testing was then carried out at ball drop time (that corresponds to 76 mm indentation) of CLSM mixtures with the help of a plunger of cross-sectional area of 19.35 cm^2. The CBR value was calculated corresponding to 2.54 and 5.08 mm penetrations.

2.4. Phase I – Development of basic CKD based CLSM mixes

2.4.1. CLSM mix designs

Mix details for 12 CLSM mixtures for Phase I are presented in Table 3. The principal criteria in picking these mixtures were to select a wide range of possible CLSM mixes whilst trying to keep the density in the range of 1600–2200 kg/m^3. The CLSM mixes were divided into

Table 3
Mix details for CLSM mixtures in Series I and Series II (Phase I)

	Cement (kg/m^3)	Cement (%)[a]	CKD (kg/m^3)	CKD (%)[a]	Water (kg/m^3)	W/B[b]	Fine aggregate (kg/m^3)
Series I							
Mix 1D[c]	80	4	80	4	300	1.9	1500
Mix 2D	40	2	120	5	300	1.9	1550
Mix 3D[c]	40	2	200	10	341	1.4	1470
Mix 4D	40	2	410	20	394	0.9	1260
Mix 5D	40	2	600	30	412	0.6	1070
Mix 6D	40	2	990	45	593	0.6	680
Series II							
Mix 7D	0	0	200	10	340	1.7	1510
Mix 8D[c]	0	0	300	15	361	1.2	1410
Mix 9D	0	0	410	20	392	1.0	1300
Mix 10D[c]	0	0	600	30	437	0.7	990
Mix 11D	0	0	860	40	509	0.6	800
Mix 12D	0	0	1034	45	690	0.7	550

[a] % of total mass.
[b] B = PC + CKD.
[c] Mixes selected for Phase II investigation.

two series: Series I with a combination of cement and CKD and Series II without cement (CKD only).

In Series I, Mix 1 had a cement and CKD content of 4% of the total mass and a water-to-binder ratio (W/B) of 1.9. Mixes 2–6 had a constant cement content of 2% of the total mass, CKD content varied from 5% to 45% of the total mass and W/B varied from 1.9 to 0.6. The remaining six mixes in Series II (Mixes 7–12) had no cement (0%); CKD content ranged from 10% to 45% and W/B ranged from 1.7 to 0.6. Water requirement of the mixes was controlled by the desired flowability requirement and ranged from 300 to approximately 700 kg/m^3. The quantity of fine aggregate (sand) in the mixes ranged from 550 to 1550 kg/m^3 (Table 3).

2.4.2. CLSM mixing procedure

The mixing procedure included placement of fine aggregate, cement (if used) and CKD in the mixer (in that order), prior to starting the mixer. Then, the ingredients were blended in the mixer for 30 s – this provided a good homogenous blend of ingredients which prevented the formation of lumps. Subsequently, half of the mixing water was added and mixed for $1\frac{1}{2}$ min. During the next $1\frac{1}{2}$ min, without stopping the mixer, the remaining water or sufficient water to give the CLSM the desired slump was added. Thereafter, mixing was continued for additional 2 min to have a total of 5 min of mixing. Then, the mixer was stopped and the CLSM was allowed to rest for 2 min. After that, the ingredients were mixed for another 2 min and then stopped and kept at rest for another 2 min. Immediately, after the 11 min which included the 2-min period of resting, the testing on fresh properties as well as the casting of CLSM test specimens for strength and durability tests was performed.

2.4.3. Results, discussion and basic mix selection (Phase I)

Table 4 summarizes the results of Phase I. The results are analyzed in two categories based on CKD based CLSM mixes with cement (Series I) and without cement (Series II).

For both Series I and II, cylinder slump flow with the exception of Mix 6 provided acceptable flowability of more than 250 mm [2,13]. For a constant W/B and a cement content of 0.6% and 2%, respectively (as is the case for Mixes 5 and 6 in Series I), slump flow value decreased from 420 mm (in Mix 5) to 0 mm (in Mix 6) with the increase of CKD content from 30% (in Mix 5) to 45% (in Mix 6). This can be attributed to the fact that the increase in CKD content demands more water to be added in Mix 6 to generate flowability similar to that of Mix 5. This confirms the CKD's affinity for water (as expected) and its slump flow reducing characteristics. Hence, the water demand of CLSM mixes increased with the increase of CKD content to achieve a flowable mix.

V-funnel flow times of CKD based CLSM mixes of both Series I and Series II were within the acceptable range of 2–5 s with the exception of Mix 2 (Table 4). V-funnel flow time increased with the decrease of W/B. The results also illustrates the possibility of developing CKD based CLSM mixes having more or less similar flow times by varying the proportions of ingredients.

For CKD based CLSM mixtures with cement (Series I), air content ranged between 1.2% and 2.8% compared with 1.5% and 2.8% of CLSM mixtures without cement (Series II). The unit weight of CLSM mixes in Series I and II ranged from 1700 to 2000 kg/m^3 (Table 4) – all within the ACI prescribed limits for CLSM [2].

The filling capacities of CLSM mixes with or without cement were within the acceptable range of 85% or greater except for few mixes (Mixes 2 and 6) (Table 4). As expected, an increase in slump flow increases the filling capacity of the CLSM as long as there is no segregation (Table 4).

The 28-day compressive strength of CKD based CLSM mixes ranged between 1.9 and 4.0 MPa for mixes with cement (Series I) and between 0.7 and 2.8 MPa for mixes without cement (Series II) which satisfied the acceptable range between 0.1 and 8 MPa of CLSM (Table 4). Generally, an increase in CKD content and a decrease in W/B led to an increase in compressive strength (both 7 and 28 days).

Table 4
Fresh and mechanical properties of CLSM mixtures (Phase I)

	Slump flow (mm)	V-funnel flow time (s)	Air content (%)	FC (%)	Unit weight (kg/m^3)	7-day strength (MPa)	28-day strength (MPa)
Mix 1[a]	460	2.0	2.7	95	1991	1.2	1.9
Mix 2	250	Stuck	2.8	0	1935	0.9	2.1
Mix 3[a]	515	1.9	1.9	98	1977	1.3	2.6
Mix 4	480	3.0	1.8	96	1986	1.6	2.8
Mix 5	420	3.5	1.2	83	1972	1.9	3.5
Mix 6	0	5.0	1.2	29	1844	1.9	4.0
Mix 7	500	2.0	2.8	74	1957	0.3	0.7
Mix 8[a]	535	2.1	1.6	90	2028	0.5	1.5
Mix 9	490	2.0	1.5	86	1986	0.7	1.9
Mix 10[a]	535	2.1	1.6	89	1957	1.0	2.7
Mix 11	490	2.0	1.7	87	1929	1.3	2.9
Mix 12	475	2.0	1.5	85	1787	1.1	2.8

[a] Mixes selected for Phase II investigation.

2.5. Phase II – Detailed investigation on CLSM using CKD from various sources

Based on the criteria of satisfying acceptable fresh and strength properties required for a CLSM, four basic mixes of very different proportions were chosen from Phase I for detailed investigation in Phase II. The mixes selected were Mixes 1D and 3D from Series I (containing both cement and CKD) and Mixes 8D and 10D from Series II (without cement).

Fresh, mechanical and durability characteristics of 16 CLSM mixes based on four selected basic mixes (indicated in Table 4) from Phase I were extensively investigated. In addition to tests conducted on fresh properties in Phase I, more tests were conducted to determine slump flow (using slump flow cone with J-ring), bleeding, setting time and settlement of CLSM mixes. The mechanical and durability tests such as compressive strength, CBR, water permeability, drying shrinkage, freeze–thaw and wetting–drying were also conducted.

2.5.1. Results and discussion on fresh properties (Phase II)

2.5.1.1. Slump flow and fresh unit weight. The cone slump flow with J-ring is a good assessment of the passing ability of CLSM through obstructions. Fig. 1 shows a typical slump flow spread of CLSM with J-ring. Reasonable J-ring results were observed – the slump flow ranged between 510 and 780 mm while the differences in heights between the bars were within the prescribed limits of 0–10 mm (Table 5). The fresh unit weight of CLSM mixes ranged between 1957 and 2230 kg/m^3. As the CKD content in the mixes increased (as in Mixes 3, 8 and 10, with CKD contents of 10%, 15% and 30%, respectively), the slump flow decreased (Table 5). CKD-D mix seemed to produce higher slump flow, lower J-ring height difference and lower fresh unit weight compared to those with CKD Types A, B and C.

2.5.1.2. V-funnel flow time, filling capacity and air content. V-funnel flow time of CLSM mixes ranged between 1.9 and 2.4 s which is within the acceptable range of up to 5 s (Table 6). The filling capacities were also within the acceptable range of 85% or greater (Table 6). As the CKD content increased (as in Mixes 3, 8 and 10, with CKD contents of 10%, 15% and 30%, respectively), the filling capacity decreased (Table 6). In general, the CKD type seems to have no influence on flow time and filling capacity although Type D CKD showed comparatively higher filling capacity compared to others. Air content of CLSM mixes ranged between 1.2% and 2.8%. Air content also decreased with the increase of CKD content (Table 6).

2.5.1.3. Bleeding and settlement. For Mix 1 with 4% CKD by mass, the bleeding ranged between 3.1% and 5.8% (Table 6). However, as the CKD content in the mixes increased (as in Mixes 3, 8 and 10, with CKD contents of 10%, 15% and 30%, respectively), the bleeding decreased drastically (Table 6). CKD D produced lower bleeding compared to others. Mix 1 showed an average of 3% settlement, and Mix 3 about 1%. No settlement was noticed for Mixes 8 and 10 (Table 6). Fig. 6 shows the typical settlement of a CLSM Mix in the cylindrical mould. Settlement decreased with the increase of CKD content. This confirms the beneficial effect of CKD in reducing bleeding and settlement as these are the causes of concern because of the high water content of the CLSM mixes. Settlement is associated with the reduction in volume of CLSM as the heavier constituents fall to the bottom and it releases water and entrapped air during settling. In field conditions, the excess water after hydration is generally absorbed by the surrounding soil or released to the surface as bleed water. Most of the settlement occurs during placement and the degree of subsidence is dependent on the presence of excess free water.

Table 5
Fresh and hardened properties of CLSM mixes in Phase II

	Cone slump flow with J-ring (mm)				J-ring flow height diff. (mm)				Fresh unit weight (kg/m^3)				28-day unit weight (kg/m^3)			
	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
Mix 1	650	630	630	670	5	8	7	4	2160	2187	2056	1990	2220	2234	2103	2190
Mix 3	630	610	600	780	2	2	3	1	2230	2173	2102	2000	2219	2241	2223	2232
Mix 8	590	510	630	620	9	10	5	2	2201	2183	2123	2028	2195	2206	2157	2207
Mix 10	610	500	510	600	5	9	8	2	2102	2090	2098	1957	2094	2118	2140	2068

Table 6
Fresh properties of CLSM mixes in Phase II

	Air content (%)				V-funnel flow time (s)				Filling capacity (FC) (%)				Bleeding (%)			
	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
Mix 1	2.6	2.3	2.4	2.8	2.1	2.2	2.1	2.0	91	86	92	95	5.4	3.1	5.0	5.8
Mix 3	2.0	2.2	2.1	2.2	2.0	2.1	2.1	1.9	94	92	93	98	0.9	0.8	0.8	1.0
Mix 8	1.2	1.5	1.3	1.8	2.1	2.3	2.0	2.1	90	84	99	96	0.4	0.2	0.7	0.4
Mix 10	1.2	1.4	1.3	1.5	2.2	2.4	2.3	2.1	87	82	84	97	0.0	0	0	0.2

Mix 1: A–B–C–D: Settlement = <3%; Mix 3: A–B–C–D: Settlement = <1% Mixes 8 and 10: A–B–C–D: Settlement = 0%.

Table 7
Fresh properties of CLSM mixes in Phase II

	Initial setting time (h)				Final setting time (h)				Ball drop setting time (h)			
	A	B	C	D	A	B	C	D	A	B	C	D
Mix 1	13	10	11	17	27	23	19	27	19	15	15	25
Mix 3	25	14	15	31	37	25	25	43	32	18	22	43
Mix 8	80	32	95	77	106	63	153	127	93	52	113	122
Mix 10	43	30	36	74	81	50	68	123	64	48	56	116

Table 8
Strength properties of CLSM (Phase II)

	7-day compressive strength (MPa)				28-day compressive strength (MPa)				CBR at ball drop time of 76 mm indentation (%)			
	A	B	C	D	A	B	C	D	A	B	C	D
Mix 1	1.2	1.5	0.7	1.2	1.6	2.2	1.2	1.9	40	41	30	50
Mix 3	0.8	0.9	0.7	1.3	1.9	2.4	2.2	2.6	[a]	[a]	[a]	[a]
Mix 8	0.4	0.7	0.2	0.5	1.0	1.9	0.7	1.5	21	27	20	38
Mix 10	0.9	1.0	0.8	1.0	2.0	2.7	2.3	2.7	26	33	23	45

[a] Samples damaged.

2.5.1.4. Setting time. Table 7 presents setting times of CLSM mixes from the penetration resistance. Mix 1 had initial and final setting times of 10–17 h and 19–27 h, respectively whereas Mix 3 had longer initial and final setting times of 15–31 h and 25–43 h, respectively. This significant increase in setting time is mainly attributed to the decrease in cement content in Mix 3 compared to Mix 1. Mix 8 had initial and final setting times of 32–95 h and 63–127 h, respectively, compared with 30–74 h and 50–123 h, respectively, of Mix 10.

The ball drop times required to reach an indentation of about 76 mm diameter also showed a similar trend to setting times for the mixes as observed in the case of penetration resistance method (Table 7). The ball drop at 76 mm indentation corresponds to a penetration resistance of about 8.5 MPa in the setting time test as per ASTM C 403. According to ASTM D 6024, the ball drop test determines the readiness of the CLSM to accept loads prior to adding a temporary or permanent wearing surface.

It is noted that the CKD based CLSM mixes with cement (Mixes 1 and 3) had a lower setting time than CLSM mixes without cement (Mixes 8 and 10). Setting times extended with the increase of CKD and the decrease of cement content in the mixes. Setting times either by penetration resistance or ball drop (at 76 mm indentation) are affected by the type of CKD, and CKD B produced lower setting times compared with those of the others (which can be attributed to its comparatively higher free CaO content and fineness).

Setting time is critical for any CLSM mix from its practical application and will dictate the types of project it can be used. For the use of CLSM as sub-base of road or in footpath construction, it is important to allow traffic after 24 h of pouring. So, CLSM mixes with 24 h of ball drop setting time (or less) are of particular importance. Mix 1 (A–B–C–D) and Mix 3 (B–C) will be suitable for such applications.

2.5.2. Results and discussion on mechanical properties (Phase II)

2.5.2.1. Compressive strength and 28-day unit weight. The 28-day unit weight of CLSM mixes ranged between 2068 and 2241 kg/m^3 (Table 5). The 7-day compressive strength ranged between 0.2 and 1.5 MPa. The 28-day compressive strength ranged between 0.7 and 2.6 MPa which satisfied the acceptable range between 0.1 and 8 MPa of CLSM (Table 8). CKDs B and D produced higher compressive strength compared to A and C. The load-carrying ability of CLSM is measured by its unconfined compressive strength. An excavatable CLSM should have a maximum strength of 2.1 MPa. Fig. 4 shows strength gain of CLSM mixes showing 7-day strength (S_7) as % of 28-day strength (S_{28}). Mix 1 showed higher compressive strength gain (between 62% and 72%) between 7 and 28 days compared with other mixes. This can be attributed to the presence of cement (4%) in this mix. Type C CKD shows lower strength gain compared with other CKD types.

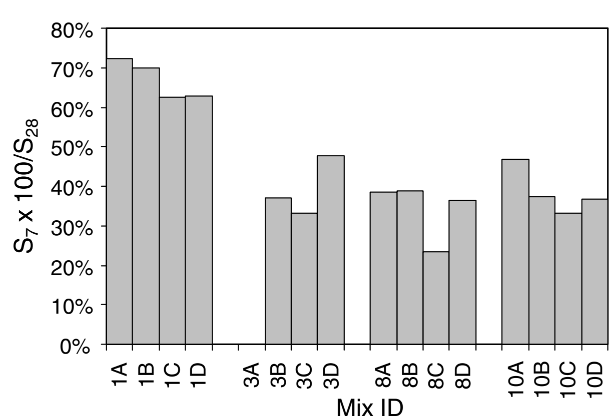

Fig. 4. Influence of type of CKD and mix design on compressive strength gain.

It is important to maintain strength at a low level especially where excavation of CLSM is required later. Some mixtures with acceptable early strength may continue to gain strength with time, hindering future excavation. The limits for excavatability are dependent on the CLSM mixture – CLSM with high quantities of coarse aggregates can be difficult to remove even at low strengths. Thus, it is important to do long-term strength tests beyond the conventional 28 days. The long-term strength gain of CLSM can be controlled or prevented by limiting the cementitious content as well as by air entrainment. The mixes with 28-day strength of less than 2.1 MPa can be classified as excavatable fill (Table 8). Bearing capacity of a well-compacted soil ranges between 0.3 and 0.7 MPa [32]. Hence, CKD based CLSM developed in this research can be used as an alternative to the compacted soil in practical applications.

2.5.2.2. Bearing strength (CBR). CBR values at 5.08 mm were found to be higher than those at 2.54 mm and hence CBR values at 5.08 mm are reported (Table 8). In general, CBR values increased with the increase of cement and CKD contents in the CLSM. CBR for the mixes at ball drop setting time ranged between 20% and 50%. Similar to compressive strength, CKDs B and D produced higher CBR values compared to A and C. Based on CBR values, the CLSM mixes reached a capacity equivalent to that of 'sand/gravelly sand' (20–50%) or 'silty sand' (20–40%) [33].

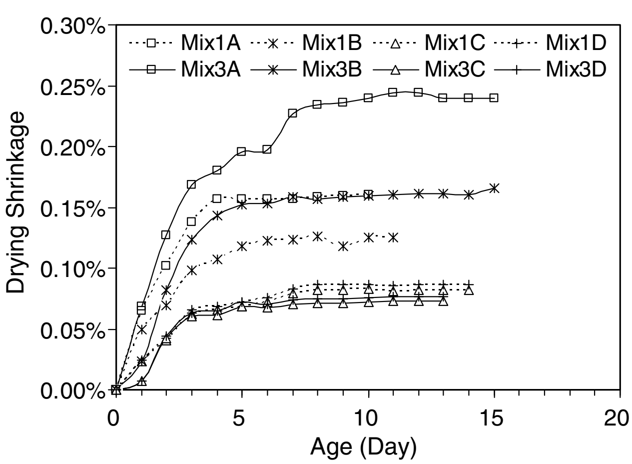

Fig. 5. Development of drying shrinkage in CLSM.

2.5.3. Results and discussion on durability characteristics (Phase II)

2.5.3.1. Drying shrinkage. Fig. 5 compares the development of drying shrinkage in Mix 1 and Mix 3 (with a combination of CKD and cement) with age after demoulding. The drying shrinkage is affected by the type of CKD used. Type A CKD showed the highest shrinkage followed by B, C and D. Ultimate shrinkage is reached when no more shrinkage was noticed with time which was about 8 days after demoulding. The ultimate drying shrinkage was about 0.25% for Mix 3A (0.15% for Mix 1A) and 0.15% for Mix 3B (0.12% for Mix 1B) compared to 0.08% of Mix 1C and Mix 1D (0.07% of Mixes 3C and 3D). The drying shrinkage of Mixes 1C, 1D, 3C and 3D is within the acceptable range of a typical ultimate drying shrinkage of 0.10% for concrete. However, the ultimate shrinkage of CLSM reported in previous research studies is typically in the range of 0.02–0.05% [12]. The presence of CKD increases the drying shrinkage of CLSM.

On the other hand, Mixes 8 and 10 (with CKD and no cement) showed considerable shrinkage – they cracked within the mould and the monitoring of shrinkage after demoulding was not possible. The cracks within the moulds were over 2 mm, and Fig. 6 shows the typical shrinkage cracks developed in such a specimen.

The development of such shrinkage cracks may be attributed partly to the increased heat of hydration generated due to the presence of higher quantity of fine CKD in the mixes. This phenomenon was tested by measuring the development of initial temperature in CLSM mixes as per ASTM C 1064. Temperature readings were recorded after about 2 min when the temperature stabilized. An increase in CKD content clearly increases the initial temperature of the mix. The initial CLSM temperature was increased from the minimum value of 20 °C to the maximum value of 46 °C when CKD content was increased from 4 (Mix 1) to 30% (Mix 10). The comparatively higher temperature development in Types A (40 °C) and B (46 °C) CKD compared to Types C (25 °C) and D (33 °C) (as shown in Table 9) justifies the development of higher drying shrinkage in CLSM with A and B CKDs.

2.5.3.2. Freeze–thaw and wetting–drying. The freeze–thaw test was done for 12 cycles to effectively understand how CLSM would behave under severe repeated freezing and thawing cycles. Fig. 7 shows the deterioration of CLSM

Fig. 6. Drying shrinkage cracks within the moulds.

Table 9
Durability properties of CLSM (Phase II)

	Freeze–thaw (%)				Wetting–drying loss (%)				Initial temperature (°C)			
	A	B	C	D	A	B	C	D	A	B	C	D
Mix 1	18.3	29.7	22.2	11.8	22.9	32.4	4-cy	19.8	22.0	24.8	20.0	23.3
Mix 3	17.8	12.8	18.5	18.5	6.8	27.1	17.0	24.2	26.8	29.2	22.5	25.9
Mix 8	28.0	15.3	14.8	14.1	5-cy	9-cy	30.3	20.0	27.7	34.3	28.5	29.3
Mix 10	22.7	20.1	23.0	18.0	15.8	12.3	14.2	17.7	39.8	46.0	33.0	24.6

cy: cycles.

Fig. 7. Freeze–thaw specimens before and after testing.

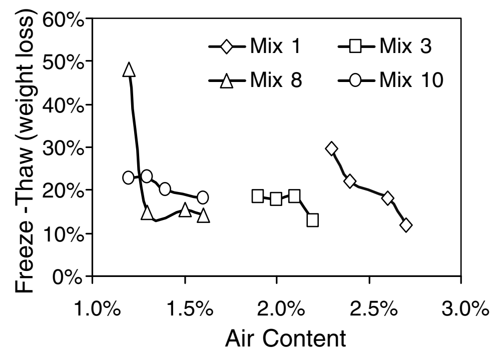

Fig. 8. Relation between freeze–thaw weight loss and air content.

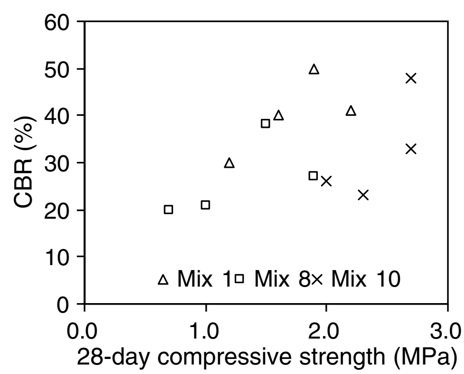

Fig. 9. Relation between compressive strength and CBR.

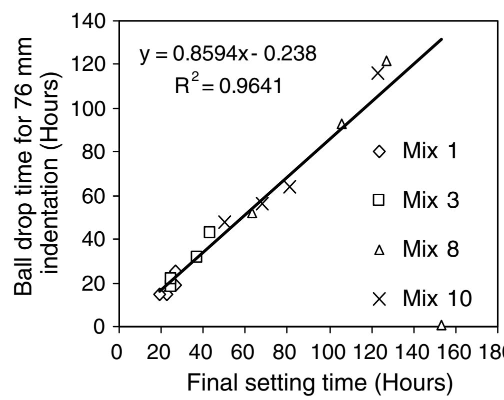

Fig. 10. Relation between setting times.

specimens after freeze–thaw test. Overall weight loss ranges between 12% and 30% for the mixes (Table 6). In terms of wetting and drying, all the mixes did not last (Mix 1C – after 4 cycles; Mix 8A – after 5 cycles; Mix 8B – after 9 cycles) for the entire duration of the test (Table 9). The weight loss ranges between 18% and 32% for all the tested samples. No definite conclusions can be drawn regarding the influence of types of CKD on freeze–thaw and wetting–drying resistances of CLSM.

2.5.3.3. Permeability. CLSM mixes provided an approximate hydraulic conductivity (k) value of 2.38×10^{-5} cm/s which is less than 1.0×10^{-4} cm/s (dividing line between well and poorly drained soils). This indicates that CKD based CLSMs are in the category of soils with very low permeability [34]. One application in which permeability of CLSM has the importance is the case of gas utility trenches, where increased permeability allows for the upward flow of any leaking gas. Most excavatable CLSMs have coefficient of water permeability values ranging from 10^{-4} to 10^{-5} cm/s, which is similar to compacted granular fills. Higher strength CLSMs have coefficient of water permeability values as low as 10^{-7} cm/s [35].

3. Correlation between different properties

Freeze–thaw (weight loss) decreases with the increase of air content (Fig. 8) for all CLSM mixes, as expected. An increase in air content from 1.2% to 2.8%, decreases the weight loss from 50% to 15%. This demonstrates the beneficial effect of air entrainment in enhancing durability of CLSM mixes and potential use of air entraining admixtures.

Correlations also exist between CBR and 28-day compressive strength (Fig. 9) as well as between setting times by ball drop and penetration resistance (Fig. 10). CBR values increase with the increase of compressive strength. A linear correlation showing an increase in ball drop setting time with the increase of final setting time by penetration resistance is shown in Fig. 10. This equation may be used to predict the readiness of a CLSM based on the setting time by penetration resistance in the laboratory to take load in field condition.

4. Conclusions

Cement kiln dust (CKD) from four different sources/manufacturers having varying chemical compositions was used in combination with Portland cement and sand to develop controlled low strength material (CLSM). The fresh properties of CLSM were assessed by slump flow, V-funnel flow time, air content, bleeding, settlement and setting times while mechanical properties were assessed by unit weight, compressive strength and California bearing ratio (CBR). The durability of CLSM mixes was also assessed by drying shrinkage, falling head permeability, freeze–thaw and wetting–drying. The following conclusions are drawn from the study:

1. An increase in CKD content increases the water demand of a CLSM mix to achieve a specific flowability. The flowability and filling capacity of a CLSM mix decrease and as a consequence V-funnel flow time increases with the increase of CKD. An increase in CKD content has the beneficial effect of lowering the bleeding of a CLSM mix.
2. Setting times generally extended with the increase of CKD and the decrease of cement content in the CLSM mixes. The compressive strength and CBR of CLSM increases with the increase of CKD and cement. However, the compressive strength of CLSM derived from a combination of cement and CKD was higher compared to those derived from CKD only.
3. The drying shrinkage of CLSM mixes increased with the increase of CKD content and significant shrinkage was observed when CKD content was greater than 15%. The freeze–thaw resistance of CLSM appeared to decrease with an increase in CKD content.
4. A water permeability of about 2.38×10^{-5} cm/s was found for the CLSM mixes which shows that they are less permeable than the well-drained soil. Based on CBR values at initial setting time, the CLSM mixes can be classified as 'sand/gravelly sand' or 'silty sand'.
5. Type of CKD (as classified by their sources as A, B, C and D) influenced fresh, hardened and durability characteristics of CLSM. This can be attributed to the variation in their chemical compositions. Type of CKD influenced fresh properties as flow time and filling capacity of CLSM with Type D CKD were comparatively higher compared with the others. Setting times either by penetration resistance or ball drop were affected by the type of CKD and CKD B produced lower setting times compared with the others. CKDs B and D produced higher compressive strength and CBR compared to A and C. Type C CKD showed lower strength gain compared with the other CKD types. Lower setting times and higher compressive strength with CKDs B and D can be attributed to their higher free CaO content and lower loss on ignition (parameters that control the reactivity of CKDs). Although no definite conclusions can be drawn regarding the influence on freeze–thaw and wetting–drying resistances, the drying shrinkage of CLSM is affected by the types of CKD with Type A showing the highest shrinkage followed by B, C and D.
6. The study confirms that CLSMs with acceptable properties can be developed with CKD alone or in combination with cement. However, source/types of CKD should be considered as an important mix design parameter. CLSM mixes with a ball drop setting time of less than 24 h can be used in road or footpath construction allowing traffic after 24 h of pouring. CLSM mixes with more than 24 h of setting time can be used in other projects based on their suitability.

Proposed mix designs can be used as guidelines for the development of CLSM incorporating CKD with variable chemical compositions. Development of non-expensive and environmentally friendly CKD based CLSM with acceptable properties (as illustrated in this study) can be helpful for the sustainable development.

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