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Properties of controlled low-strength materials incorporating cement kiln dust and slag

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ABSTRACT

This research evaluated the potential use of cement kiln dust (CKD) together with slag to replace the use of cement in the production of controlled low-strength material (CLSM). The low strength requirements of CLSM compared to conventional concrete enable the use of industrial by-products for the production of CLSM. In this study, the workability-related fresh properties of CLSM mixtures were observed through slump flow diameter, V-funnel flow time and filling capacity. Setting times, temperature rise, air content and unit weight of CLSM mixtures were also determined as part of fresh properties. The hardened properties that were monitored for 28 days included the unconfined compressive strength. The test results presented herein show that a combination of less than 50 kg/m^3 slag and up to 300 kg/m^3 CKD provides a good mix that satisfies the requirements of a CLSM with similar or better properties to that of CKD-based CLSM mix containing Portland cement. Suitable CLSM mixtures with reasonable fresh and hardened properties could also be developed by using CKD alone. However, reduced strength in such CLSM mixtures may limit their field application. The slag significantly assisted in increasing compressive strength of CKD-based CLSM mixtures. A CLSM mix containing a combination of slag and CKD was shown to have excellent characteristics for flowable backfill and excavatable base material. Therefore, producing CKD/slag based CLSM through the use of co-generated products from the cement and iron manufacturing processes can provide leadership for the construction industry in the transition for sustainable development.

1. Introduction

As described by ACI Committee 229, controlled low-strength material (CLSM) refers to "a self compacting, cementitious material used primarily as a backfill in lieu of compacted fill" [1]. CLSM is, as defined by ASTM, "a mixture of soil, cementitious materials, water, and sometimes admixtures that hardens into material with a higher strength than the soil but less than 8270 kPa" [2]. Maximum strength recommendations ensure that CLSM can be removed with conventional excavating equipment. Typical CLSM mix contains 80–85% fine aggregate (size ranging from 4.45 mm to 0.075 mm) or filler, 10–15% supplementary cementing materials, 5–10% cement by mass, and 250–400 L/m^3 of water – although the actual mix proportion can vary depending on the application [3,4].

CLSMs have proven to be ideal backfill materials for use on street cut/repair and infrastructure rehabilitation projects for a number of reasons. These materials develop high early penetration resistance, have low shrinkage and compressibility characteristics, are economical, not labor intensive, digable at any age, and not adversely affected by varying moisture contents. The first use of CLSM in the US was reported in 1964 for the Canadian River Aqueduct Project in north-western Texas [5], and its use reduced the project cost by about 40% compared to conventional backfill. The estimated US market for all types of CLSM was at approximately 10 million cubic yards in 1997 [6].

In recent years, there have been significant efforts in utilizing various industrial by-products in the production of CLSM, and promising results for the use of various industrial by-products were reported. One of the recently used by-products in CLSMs is cement kiln dust (CKD) that is found to improve flowability and reduce segregation and bleeding. CKD is finely divided, dry particulate material carried out from a cement kiln by exhaust gases, and captured by the kiln's air pollution control system. In general, the compositions of CKDs are similar to that of cement as they contain alumina, silica, calcium oxide, alkalis and sulfates. However, the amounts of alkalis and sulfates are substantially higher in CKDs compared to cement. While significant quantities of CKD are generated every year (worldwide, approximately 30 million tonnes of CKD is produced each year [7]), its utilization in construction has been to this day quite limited. Recently, researchers have started investigating the feasibility of using CKD as one of the component in CLSM. Al-Jabri et al. conducted a preliminary study on the use of one CKD in the production of CLSM [8]. The two mixtures

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tested by these authors (one with 249 kg/m^3 of CKD and 47 kg/m^3 of cement; the other with 296 kg/m^3 of CKD without cement) showed satisfactory strengths at 28 days with 2.74 and 1.04 MPa, respectively. Pierce et al. investigated the combined use of CKD and fly ash at different ratios in the production of CLSM [9]. This study involved the evaluation of both the workability and hardened properties of CLSM, and comparison to the results obtained with fly ash based CLSM. The results showed that high flowability and relatively rapid setting time could be achieved with CKD-CLSM mixtures. Additionally, the 28-day compressive strength was found to increase with CKD-fly ash ratio. More recently, Lachemi et al. compared the properties of CLSM mixtures using different proportions of CKD [10]. The results of this study indicated that CKD-CLSMs were characterized by lower flowability, higher water demand, higher viscosity, lower bleeding, higher shrinkage, higher setting time, lower freeze–thaw resistance and lower wetting–drying resistance. The research suggested suitable CLSM mixtures could be developed using a maximum of 15% by mass of CKD. Overall, it was concluded that CKD with good cementing properties could be used as a partial or full substitute for cement in flowable fill.

The objective of the study described herein is to provide engineering properties (flowability, bleeding, unit weight, setting time and unconfined compressive strength) of CLSM incorporating CKD and slag to expand the beneficial use of CKD together with slag for potential applications and to substitute the use of cement in the production of CLSM. The development of environmentally friendly CKD/slag 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. Experimental investigations

2.1. Materials and properties

Canadian Standard Association-General Use (CSA-GU), equivalent to ASTM Type I, Portland cement (PC), Grade 80 ground granulated blast furnace slag and CKD supplied by local sources were used in the production of CLSM mixtures. The physical properties and chemical compositions of PC, slag and CKD are presented in Table 1. A local natural sand with a bulk specific gravity of 2.73 and water absorption of 1.83% was also used. Table 2 presents the particle size distribution as per ASTM C136 as well as the physical properties of sand. Coarse aggregate was not used in the production of CLSM mixtures because of difficulties to excavate CLSM as a backfill material in the presence of coarse aggregate even at low strengths.

Table 1
Chemical compositions and physical properties of cement and CKD.

Chemical compositions	PC	CKD	Slag
Silicon dioxide (SiO_2)	19.4	13.1	40.5
Aluminium oxide (Al_2O_3)	5.3	4.2	8.5
Ferric oxide (Fe_2O_3)	2.3	2.3	0.48
Calcium oxide (CaO)	61.8	58.1	38.7
Magnesium oxide (MgO)	2.3	3.3	11.5
Sodium oxide (Na_2O)	0.2	0.7	0.4
Potassium oxide (K_2O)	1.1	2.8	0.6
Phosphorous oxide (P_2O_5)	0.1	0.2	–
Titanium oxide (TiO_2)	0.3	0.3	–
Sulphur trioxide (SO_3)	3.8	10.6	2.3
Loss on ignition	2.1	3.1	–
Chloride (Cl)	0.1	–	–
Specific gravity	3.1	3.2	2.8
Blain fineness, cm^2/g	3740	4100	4330

Table 2
Particle size distribution and properties of fine aggregate.

Sieve size	% Passing by mass
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
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. Mixing and testing procedures for the CLSM

The mixture proportions are summarized in Table 3. As seen, 12 CLSM mixtures were prepared and investigated. The principal criteria in designing these mixtures was to select a wide range of possible CLSM mixtures whilst trying to keep the slump flow within the acceptable range (more than 200 mm without segregation and bleeding) and the density in the range of 1600–2200 kg/m^3 [1,10–12]. As shown in Table 3, Mix-1 and Mix-8 were used as control mixtures. These two mixtures were manufactured with CKD and/or cement without including slag. The mix designs for the control mixtures were selected based on the outcomes of previous research studies conducted by Lachemi et al. [10,12]. Water requirement of the mixtures was arranged by the desired flowability requirement and ranged from 341 to 361 kg/m^3. The quantity of fine aggregate (sand) in the mixtures ranged from 1230 to 1470 kg/m^3 (Table 3).

CLSM ingredients, mixing, placing technique and handling are similar to those of conventional concrete. The mixing procedure included placement of fine aggregate, cement (if used), CKD and slag 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 1½ min. During the next 1½ 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. After the mixing procedure was completed, tests were conducted on the fresh CLSM to determine slump flow diameter, V-funnel flow time, filling capacity, final bleeding, temperature rise and setting times.

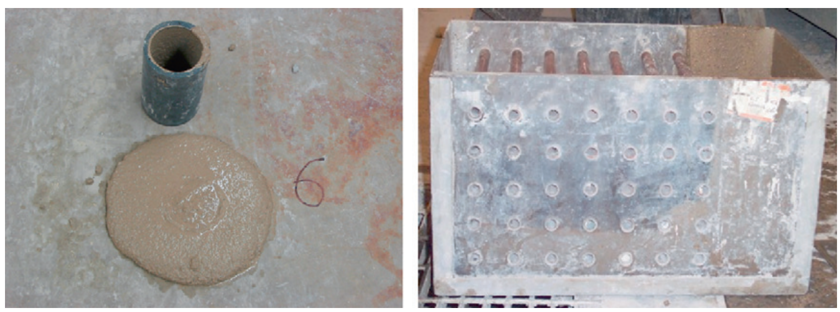
Flowability is the most important attribute of flowable fill which allows the material to be placed without compaction. Flowability of CLSM was measured by cylinder slump flow as per ASTM D6103, in which a 75 $\times$ 150-mm plastic cylinder mould with open ends is placed on a levelled non-absorptive plate. Fresh CLSM mixture is filled to the top of the plastic cylinder and the cylinder is quickly lifted, allowing the material to spread freely on the plate. The diameter of the formed "pancake" is measured as the flow of fresh CLSM (Fig. 1). A CLSM with good flowability should show a horizontal spread (slump flow) of at least 200 mm in diameter without noticeable segregation and bleeding. However, stiff CLSM mixtures can have a slump flow of less than 150 mm; whilst a fluid CLSM can have as high as 300 mm or greater.

The V-funnel test was used to measure the viscosity and deformability of CLSM [13]. In this test, a V-funnel was filled completely with CLSM and the bottom outlet was opened, allowing the CLSM

Table 3
Mix proportions for CLSM mixtures.

Mix. ID.	Cement (kg/m^3)	Slag (kg/m^3)	CKD (kg/m^3)	Water (kg/m^3)	W/B[a]	Fine aggregate (kg/m^3)
Mix-1	40	–	200	341	1.42	1470
Mix-2	–	40	200	341	1.42	1450
Mix-3	–	50	200	341	1.36	1450
Mix-4	–	65	200	341	1.29	1435
Mix-5	–	100	200	341	1.14	1407
Mix-6	–	200	200	341	0.85	1320
Mix-7	–	300	200	341	0.68	1230
Mix-8	–	–	300	361	1.20	1410
Mix-9	–	20	300	361	1.13	1350
Mix-10	–	25	300	361	1.11	1340
Mix-11	–	30	300	361	1.09	1330
Mix-12	–	45	300	361	1.05	1305

[a] B = binder (PC + CKD + slag).



Cylinder slump flow **Box apparatus**

Fig. 1. Workability tests on CLSM mixtures.

to flow out. The time of flow from the opening of outlet to the seizure of flow was recorded. High flow time can be associated with a low deformability due to high CLSM viscosity, high inter particle friction or blockage of flow. For CLSM, the flow time should be less than 10 s for the materials to be self-consolidating [10,12].

The filling capacity (FC) of CLSM was determined by 300 × 500 × 300-mm transparent box apparatus [13,14]. The box had two chambers: one with closely-spaced, smooth, horizontal, 20-mm diameter copper tubes as obstacles and the other without obstacle (Fig. 1). A CLSM mix 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 C940. 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. Sedimentation and bleeding were also visually checked during the slump flow test. Based on visual observation evaluation, all the grouts were cohesive, homogeneous and flowed as a heavy liquid without any segregation and bleeding (Fig. 1).

Hardening of CLSM mixtures was measured in terms of initial and final setting times as per ASTM C 403 procedure based on penetration resistance. The air content and unit weight of CLSM mixtures were determined as per ASTM D6023. The unconfined compressive strength of CLSM mixtures was also determined at 7 and 28 days as per ASTM D4832 using 150 × 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. The compressive strength was computed as an average of at least three specimens at each age.

3. Results and discussion

Table 4 summarizes the testing results of the fresh CLSM mixtures. Compressive strength and unit weight of CLSM mixtures are presented in Table 5.

3.1. Cylinder slump flow

Fig. 2 shows the influence of slag addition on the slump flow characteristics of CKD-based CLSM mixtures without cement. The slump flow of all the CLSM mixtures was within the acceptable range of 205–245 mm. Initially, the slump flow increased with an increase in slag content until the slag mass was approximately equal to 100 kg/m^3. The slump flow then decreased when the slag quantity surpassed the quantity of 100 kg/m^3. This behavior confirms the slag's affinity for water (as expected) and its slump flow reducing characteristics.

Table 3 also shows that the water demand of CLSM mixtures for similar flow values increased with the increase of CKD content to achieve a flowable mix. The amount of water needed for a constant flow of the fresh mix was in the range of 341–361 kg/m^3 (Table 3) in accordance with CKD content. Therefore, the amount of water

Table 4
Fresh properties of CLSM mixtures.

Mix. ID.	Slump flow (mm)	V-funnel flow time (s)	Air content (%)	Filling capacity (%)	Final bleeding (%)	Initial setting time (h)	Final setting time (h)	Temp. (°C)
Mix-1	225	2.0	1.9	92	1.02	21	43	26
Mix-2	210	2.3	2.5	90	3.50	37	72	19
Mix-3	215	2.4	2.1	92	3.25	35	65	20
Mix-4	230	3.0	2.2	94	2.45	34	62	21
Mix-5	245	3.2	2.0	96	2.10	32	63	22
Mix-6	240	2.6	1.9	93	1.90	30	68	23
Mix-7	230	2.5	2.3	92	1.10	28	65	23
Mix-8	205	2.1	1.7	89	0.40	28	52	29
Mix-9	210	2.1	1.5	91	0.90	27	51	28
Mix-10	215	2.1	1.6	93	0.95	28	55	28
Mix-11	225	2.2	1.4	91	0.85	25	57	29
Mix-12	240	2.1	1.5	90	0.90	26	51	28

Table 5
Unit weight and compressive strength of CLSM mixtures.

Mix. ID.	Unit weight (kg/m^3)	7-Day strength (MPa)	28-Day strength (MPa)
Mix-1	1977	1.30	2.60
Mix-2	2012	0.52	1.93
Mix-3	2015	0.60	2.99
Mix-4	2013	0.65	3.45
Mix-5	2020	0.76	4.85
Mix-6	2030	0.79	6.14
Mix-7	2010	0.92	8.11
Mix-8	2028	0.50	1.50
Mix-9	2010	0.50	1.72
Mix-10	2035	0.53	1.82
Mix-11	2040	0.58	1.90
Mix-12	2010	0.64	2.11

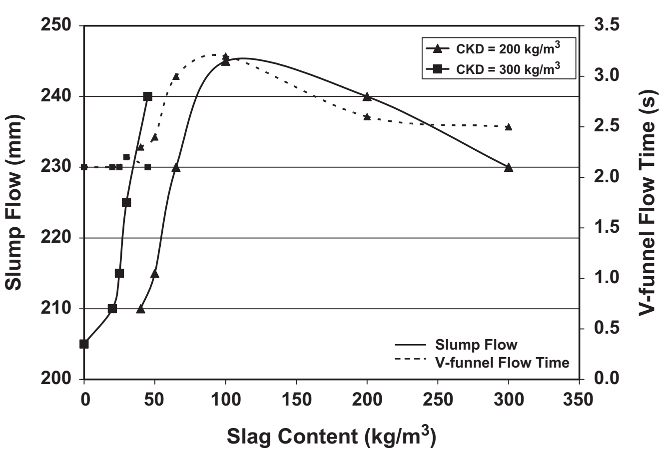


Fig. 2. Influence of CKD and slag content on the slump flow and V-funnel flow time of CLSM mixtures.

depends on the amount of CKD in the mix. Mixtures 1–7, for example, contain the same amount of CKD but different amount of slag. The water needed for the Mixtures 1–7 was the same (341 kg/m^3). Increasing the CKD content from 200 to 300 kg/m^3 increased the water required for a similar flow from 341 to 361 kg/m^3 (Table 3). On the other hand, increasing the slag content from 20 to 300 kg/m^3 was accompanied by an equivalent reduction in the content of the sand. As a result, the total content of fines was increased, however the replacement of the sand with slag did not lead to an increase in the water demand.

3.2. V-funnel flow time and filling capacity

V-funnel flow times of CKD-based CLSM mixtures with slag were also within the acceptable range of 2–4 s (less than 10 s), and all of the mixtures exhibited excellent viscosity properties showing a V-funnel flow time of about 2.5 s (Table 4). For the mixtures with 200 kg/m^3 CKD content, as in the slump flow test, the V-funnel flow time slightly increased with an increase in slag content until the slag mass was approximately equal to 100 kg/m^3. The flow time then decreased when the slag quantity exceeded the quantity of 100 kg/m^3 as observed in the slump flow test (Fig. 2). Overall, the increase in the amount of CKD content has not significantly influenced the V-funnel flow time of CLSM mixtures.

The filling capacities of CKD-based CLSM mixtures with slag were within the acceptable range of 85% or greater (Table 4). The V-funnel flow time and filling capacity test results illustrate that it is possible to obtain CKD-based CLSM mixtures with slag having more or less similar flow times by varying the proportions of ingredients.

3.3. Air content and unit weight

The air content of all CLSM mixtures decreased with the increase of CKD content from about 2.2% to 1.5% (Table 4). This can be attributed to the increased fineness of CKD as well as its affinity for water. On the other hand, no correlation was observed between the air content and the amount of slag used in the mixture.

The unit weight of all the mixtures was about 2000 kg/m^3 regardless of the amount of CKD and slag content. A similar range in unit weight is reported by Lachemi et al. [10]. The values of mass density of all mixtures lie well within the normal density of CLSM, which ranges from 1840 to 2320 kg/m^3 [1].

3.4. Final bleeding

Bleeding is a high concern because of the high water content of the CLSM mixtures. 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.

The results of final bleeding test results are summarized in Table 4. The bleeding values of CLSM mixtures used in this study (except Mixtures 2–5) are within the specified limit of 2% [15]. For Mix 2 with 200 kg/m^3 CKD by mass, the final bleeding was around 3.5% (Table 4). However, as the slag content in the mixtures increased from 40 to 300 kg/m^3 at constant CKD content, the bleeding decreased (Fig. 3). The CLSM mixtures with 300 kg/m^3 of CKD content had higher water demands than the control mixtures with similar flow values, but had significantly lower final bleeding. All CLSM mixtures with 300 kg/m^3 of CKD showed final bleeding values less than 1% and the addition of slag in CLSM mixtures with 300 kg/m^3 of CKD did not influence the final bleeding

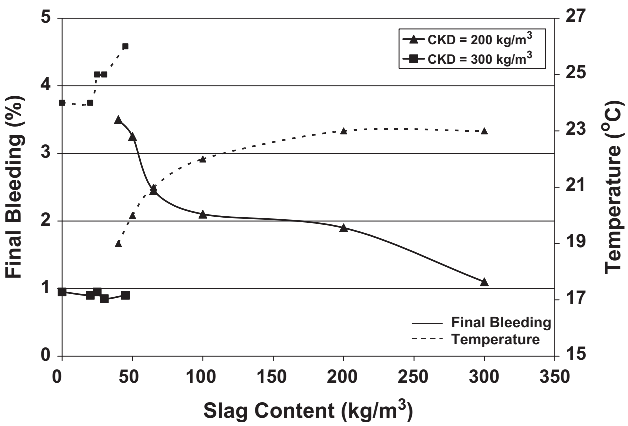


Fig. 3. Influence of CKD and slag content on the final bleeding and temperature of CLSM mixtures.

values. Therefore, it is possible that the cementing capacity of the CKD enhances the thickening of the mix at an early age, helping to reduce the bleeding in these mixtures. The low bleeding values of CKD-CLSM mixtures might be helpful in avoiding ponding of water on the CLSM surface, which in turn can contribute to the formation of a weak surface layer and can also delay the setting time [15].

3.5. Setting time and temperature

The setting times of the CLSM mixtures were measured based on ASTM C 403-99. Setting time is critical for any CLSM mix from its practical application point of view and will dictate the types of project for which it can be used. To use CLSM as sub-base of road or in footpath construction, it is important to allow traffic after 24 h of pouring [16]. So, CLSM mixtures that can set and achieve the level of strength required to sustain loading within 24 h or less are of particular importance.

Table 4 summarizes the initial and final setting times calculated as per the standard, which for the mixtures investigated varied between 21 and 37 h. The control CKD-CLSM mixture with cement (Mix-1, 200 kg/m^3 CKD) had initial and final setting times of about 21 h and 43 h, respectively, and the control CLSM mixture without cement (Mix-8, 300 kg/m^3 CKD) had initial and final setting times of 28 h and 52 h, respectively. This slight increase in setting time is mainly attributed to the lack of cement in Mix-8 compared to Mix-1, even though Mix-8 has more than 100 kg/m^3 CKD content. Setting times also significantly shortened with the increase of CKD content (Fig. 4). Therefore, CKD-CLSM without cement content can also take a shorter time to set and hence these mixtures can be feasible to use in situations where construction work has to be started immediately. According to Gassman et al. [16], setting times of 24 h are usually acceptable.

Even though CKD is generally assumed as an inert material in terms of strength giving property, the reason of the reduction in the setting time of CLSM mixtures with the further addition of CKD may be attributed to the high absorption capacity of CKD particles, which lead to continuous adsorption of free water in mixtures. Accordingly, shorter setting time values recorded for CLSM mixtures with 300 kg/m^3 CKD are probably due to the reduction in consistency of the mixtures rather than faster setting of the blended system. This kind of behavior, reduction in setting time, was already reported for natural pozzolan blended systems by others [17,18].

In addition to CKD, the addition of slag also shortened the set of the CLSM mixtures (especially initial setting time) at constant CKD content, as seen in Fig. 4. This is primarily an effect of hydration. When ground to very fine particles, the slag has both pozzolanic and weak hydraulic properties [19]. For the pozzolanic reactions, it requires the presence of calcium hydroxide to form cementitious compounds. Because the calcium hydroxide is a by-product of the hydration of Portland cement, the pozzolan always lags behind the Portland cement reaction. Moreover, slag also exhibits some hydraulic reactions when it contacts with water, and this property can shorten the setting time of CKD mixtures. However, to obtain reasonable setting times, it should be used together with Portland cement or higher CKD content.

Fig. 5 shows the influence of CKD content on initial temperature of various CLSM mixtures as per ASTM C1064. 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. At low CKD contents (200 kg/m^3), an average initial temperature of 21 °C was recorded. The average initial CLSM temperature was increased from 21 to 28 °C when CKD content was increased from 200 to 300 kg/m^3. On the other hand, the effect of the slag on raising the temperature was not as significant as that of the CKD.

3.6. Compressive strength

A unique requirement typically encountered for CLSM is the need to limit the maximum compressive strength. The load-carrying ability of CLSM is measured by its unconfined compressive strength. Therefore, typical CLSMs have compressive strengths of 8 MPa or less, whilst the excavatable CLSMs have a maximum strength of 2.1 MPa [1]. The development of strength at higher ages may cause problems in accessing equipment buried in the CLSM

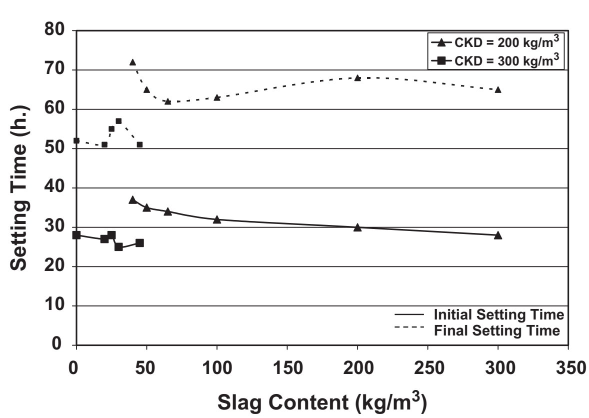


Fig. 4. Influence of CKD and slag content on the setting times of CLSM mixtures.

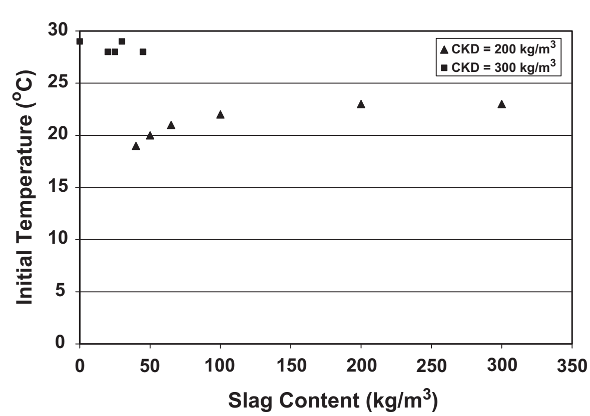


Fig. 5. Influence of CKD and slag content on the initial temperature development of CLSM mixtures.

(pipes, tanks, *etc.*). This requirement to maintain strengths at a low-level (less than 2.1 MPa) is necessary in cases where future excavation may be required for maintenance, repair and replacement of embedded utilities. Some mixtures with acceptable early strength may continue to gain strength with time, hindering future excavation.

The unconfined compressive strength data of cylindrical CLSM specimens tested at 7 and 28 days are presented in Table 5. The strength provided is the average compressive strength of at least three specimens tested. Fig. 6 shows the influence of slag and CKD contents on 7- and 28-day compressive strength of CLSM mixtures. The 28-day compressive strengths were 2.6 and 1.5 MPa for control CKD-CLSM mixtures without slag (Mix-1 and Mix-8, respectively) and between 1.72 and 8.11 MPa for mixtures with different proportions of slag which satisfied the acceptable range of 0.1–8 MPa of CLSM (Table 4) [20]. However, the mixtures with 28-day strength of less than 2.1 MPa can be classified as excavatable fill. The CKD-CLSM mixture containing Portland cement (Mix-1) had compressive strength that exceeded the upper limit of 2.1 MPa. An increase in CKD content from 200 to 300 kg/m^3 did not lead to an increase in compressive strength (both 7 and 28-day) of CLSM mixtures (Fig. 6). All of the mixtures containing 300 kg/m^3 of CKD with up to 45 kg/m^3 of slag maintained a compressive strength below the upper excavatable limit (2.1 MPa), and a relatively lower strength (1.50 MPa) is measured for Mix-8 manufactured only with 300 kg/m^3 CKD without slag/cement. In the case of the CKD-CLSM mixtures without slag, no further strength gain beyond 28 days is expected because of the very low reactivity of CKD.

The 28-day strength of the CKD-CLSM specimens containing slag falls in a wide range from 1.72 to 8.11 MPa depending on the amount of slag used in the mixtures. For a constant CKD content, the strength increased with the increase of slag addition. The increase in strength was significant when the slag content was especially more than 50 kg/m^3. For that reason, during the production of CLSM mixtures containing 300 kg/m^3 CKD, a maximum 45 kg/m^3 slag content was selected. As expected, slag mixtures show significant strength gain (227–781%) between 7 and 28 days, and it is expected that further strength gain would be observed in time due to pozzolanic reactions (note that this is likely why the high volume slag mix is not recommended for situations where future excavation is needed).

4. General discussion

A CLSM should exhibit satisfactory fresh and mechanical properties: cylinder slump flow within the range of 200–300 mm, little or no segregation, filling capacity of greater than 85%, final bleeding of less than 2%, compressive strength greater than 0.1 MPa and less than 8 MPa (less than 2.1 MPa for excavatable fill). An initial setting time of less than 24 h can be advantageous for some CLSM's applications in road and footpath constructions.

The properties of the fresh mix are found to be governed by the amount of CKD. Large amount of CKD slightly increased the water demand for maintaining a constant flow, but the addition of slag did not significantly influence the workability and the water demand. Using CKD that contains large amounts of fines increases the water demand on the one hand and reduces the bleeding on the other hand. The shrinkage at an early age will be reduced in the mixtures with high bleeding that provides enough water for evaporation, rather than evaporation of water from within the fresh mix. For a complete understanding of the effect of CKD on the shrinkage at en early age, it will be necessary to conduct further research to investigate shrinkage properties.

Mix-1 with combination of Portland cement (40 kg/m^3) and CKD (200 kg/m^3) met almost all CLSM requirements. Mix-8 with CKD (300 kg/m^3 and no cement) met CLSM requirements based on fresh and hardened properties but increased setting time may limit their field application if CLSM mixture is used in road and footpath applications. The setting time of CLSM mixtures can be improved by using more CKD, slag and decreasing the total water content. The high strength may be a problem in mixtures that are expected to be excavated at later ages, and this should be considered. The engineering properties, such as strength at early and late ages, workability, bleeding were satisfactory despite the small amount of slag (less than 50 kg/m^3) and the large amount of CKD (300 kg/m^3). High compressive strength, up to 8 MPa, was obtained at 28 days when the slag content was about 300 kg/m^3 which may have pozzolanic or cementing properties. Low compressive strengths, less than 2.1 MPa, were obtained when the amount of slag content was less than 50 kg/m^3. Therefore, the strength properties of CLSM made with CKD (inert waste) can be improved by the addition of another waste/by-product that has pozzolanic/cementing properties.

It should be noted that although a range of different constituent materials were used in this investigation; the findings presented in this paper are case specific, and should not be generalized to reflect specific material types as a whole. There are many potential sources for each of the material types used in this study, including CKD, slag, aggregates, and cements, which may have different chemical and physical characteristics. Thus, caution should be taken in interpreting the behavior of specific materials in this study to the behavior of broad classes or types of materials.

5. Conclusions

This paper discussed the viability of using CKD together with slag in the production of CLSM. The main focus of this research

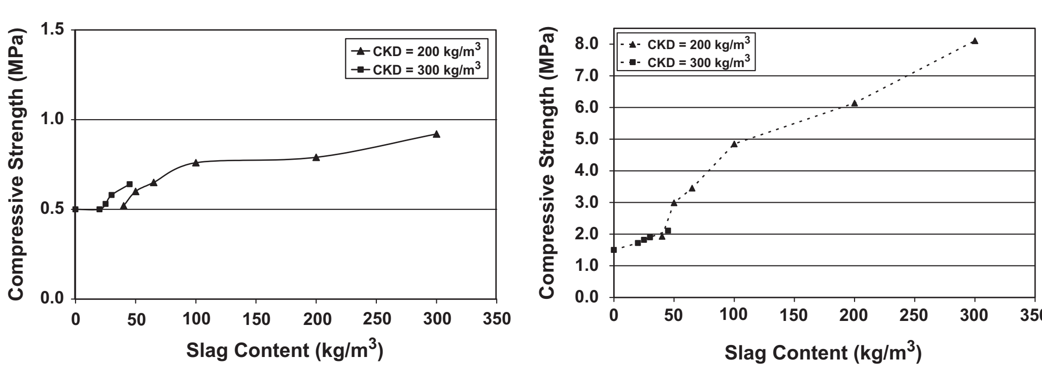


Fig. 6. Influence of CKD and slag content on the compressive strength of CLSM mixtures.

was to develop a CLSM mix while maximizing by-product material utilization and satisfying workability and performance requirements. The following conclusions can be drawn from this study:

- All the CKD-based mixtures displayed excellent flow properties. An increase in CKD content increases the water demand of a CLSM mix to achieve a constant flow of the fresh mix. Therefore, the flowability and filling capacity of a CLSM mix decrease with the increase of CKD content at constant water content.
- Increasing both the CKD and slag contents have the beneficial effect of lowering the rate of bleeding of a CLSM mix. An increase in the CKD content from 200 to 300 kg/m^3, can reduce the bleeding from 3.5% to almost zero. At constant CKD and water contents, an increase in the slag content can also reduce the final bleeding of CLSM mixtures.
- Setting times shortened with the increase of CKD amount, and the elimination of cement in the production of CKD-CLSM mixtures prolonged the setting times. On the other hand, the effect of the slag on the setting time was not as significant as that of the CKD. CLSM mixtures with 24 h of initial setting (or less) are of particular importance. These mixtures may be used in road or footpath construction allowing traffic after 24 h of pouring. However, CLSM mixtures with more than 24 h of initial setting time can be used in other applications based on their suitability.
- The compressive strength of CLSM is not influenced by the increase of CKD content. CKD-CLSMs are easily excavatable and are likely to exhibit limited gain in strength with time. On the other hand, CKD-CLSM mixtures in combination with slag have higher strength compared to those without slag and the strength is proportional to the amount of slag used. For a constant CKD content (200 kg/m^3), a strength gain from 1.93 to 8.11 MPa was observed as the slag content increased from 40 to 300 kg/m^3. To keep the compressive strength lower than the excavatability limit (2.1 MPa), slag content should be less than 50 kg/m^3.
- The study confirms that CLSMs with acceptable properties can be developed with high volumes of CKD alone or in combination with slag. The CKD assists in keeping the strength and setting from exceeding the upper compressive strength and setting time limits, and slag assists in increasing the strength.
- Mix designs proposed in this paper for CLSM are applicable for CKD and slag having similar chemical composition. However, proposed mix designs can be used as guidelines for the development of CLSM incorporating CKD and slag from different sources with variable chemical compositions. The development of economic and environmentally friendly CKD-based CLSM with acceptable properties (as illustrated in this study) is helpful in the transition for sustainable development.
- The field application of CKD-based CLSM needs feasibility study on the potential of ready mix production, pumpability and diggability (in case of temporary use) of CLSM. Investigations are in progress to address these issues as well as on the performance of developed CLSM mixtures in actual field conditions.

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