Cement & Concrete Composites 31 (2009) 564–569

Contents lists available at ScienceDirect

Cement & Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

The utilization of recycled concrete aggregate to produce controlled low-strength materials without using Portland cement

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A R T I C L E I N F O

Article history:
Received 30 August 2008
Received in revised form 28 December 2008
Accepted 30 December 2008
Available online 4 January 2009

Keywords:
Recycled concrete aggregate
Slag
Alkalis
Residual paste
Controlled low-strength materials

A B S T R A C T

This paper reports the results of an experimental study that investigated the feasibility of using fine and coarse recycled concrete aggregate (RCA) with slag or fly ash to produce Controlled Low-Strength Materials (CLSM). The main objective was to produce CLSM using only recycled and by-product materials without the need to add Portland cement. In addition to the hydraulic activity of slag and high-calcium fly ash (HCFA), their pozzolanic reaction was activated by the alkalis and calcium hydroxide present in the residual paste of the RCA. Preliminary tests showed mixtures with slag to have 7-day compressive strengths 70% higher than mixtures with fly ash.

Two types of CLSM with slag were investigated in further detail: one with fine and the other with fine/coarse RCA. The results showed that the developed CLSMs are suitable for a wide range of applications particularly those requiring structural support and fast hardening.

1. Introduction

The concept of sustainable development in construction has been gaining increasing attention at the present time [1]. The most immediate and obvious way to achieve more sustainable construction is by conserving new raw materials such as natural aggregates, and reusing construction and industrial wastes. Recycled concrete aggregate (RCA) is an example of a common construction waste that is produced from demolishing concrete structures as they approach the end of their service life. Supplementary cementing materials (SCM) such as fly ash and slag are industrial by-products, which have a long history of use with Portland cement (PC) in concrete. This paper presents the results of a study that investigated the feasibility of using RCA and SCM, without the use of PC, to produce Controlled Low-Strength Materials (CLSM) for different applications.

Generally, concrete accounts for nearly 75% by weight of all construction materials [2]. Construction and demolition waste in Canada amounts to 15–20% of all landfill materials [3]. By finding new applications for waste concrete and creating a market for its use, we can bypass the need to consume virgin natural aggregate and simultaneously conserve landfill space. Until now, RCA has primarily been used as granular base in road works or in conjunction with natural aggregate in concrete applications. In terms of using RCA in structural concrete, research has shown that the use of 30% RCA and 70% natural aggregate in high strength concrete produces concrete of similar strength as that containing only natural aggregates [4]. However, concrete mixtures made with laboratory crushed RCA as the only source of aggregate show a strength reduction of 10% when compared to conventional concrete [5]. For some types of commercially crushed RCA, research has shown negligible variation from concrete made from virgin materials in terms of compressive and tensile strength [6]. However, drying shrinkage is of concern when using RCA in concrete. New concrete made with RCA experiences creep and drying shrinkage that is 10–30% greater than that of concrete made from natural aggregate [2]. The high porosity of RCA increases drying shrinkage [6] and creep especially when fine RCA is used [7,8]. In addition, RCA generally has a lower elastic modulus than natural aggregate, which also contributes to drying shrinkage and creep.

Fine RCA has been found to have limited use in structural concrete as it is angular and coarser than natural aggregate [7] which affects the workability and ease of finishing. In addition, fine RCA was found to reduce the resistance to freezing and thawing [7,9] and sulphate attack when used with PC of 10.1% C_3A [10]. Research showed substantial improvement in the properties of concrete containing RCA when the fine portion was replaced by natural sand [7,11]; other research work suggested limiting the fine RCA content in concrete to 30% [12] or 50% [13] of the fine aggregate content in the mix.

From the sustainability standpoint, and based on the above review, it is important to develop more construction materials that incorporate RCA. This is of special importance for fine RCA and low-quality coarse RCA, which have limited use in structural concrete. Finding more uses of RCA helps reduce its disposal in

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doi:10.1016/j.cemconcomp.2008.12.011

landfills and conserves the consumption of natural aggregates. One of the possible construction materials where RCA can be utilized is CLSM.

CLSMs are construction materials that consolidate under their own weight making them ideal substitutes for compacted soil [14]. Unlike soil, CLSMs do not settle once they are hardened. CLSMs can be used in a variety of applications including backfills, structural fills, pavement bases, conduit beddings and void fillings [14]. Materials used in the production of CLSM are usually the same as those used in traditional concrete; however, the mix proportion is different as the strength of CLSM is much less than that of traditional concrete. CLSMs can also incorporate supplementary cementing materials such as high-calcium fly ash (HCFA) [15,16] and co-generated products such as cement kiln dust [17,18]. The strength of CLSMs varies depending on the application. For backfills with possible future excavation such as some utility fills, the 28-day strength should not exceed 2.1 MPa [14]. For road bases and structural fills, such as foundation support above weak or uneven soil, the required compressive strength can reach 8.3 MPa [14]. The flowability of CLSM can be measured using the traditional slump cone test (ASTM C 143) or slump flow test as per ASTM D 6103, as will be described under the Materials and Experimental Work subsection. CLSM is required to have a slump flow of at least 200 mm without segregation using the ASTM D 6103 or a slump value of at least 150 mm using ASTM C 143 [14]. Although CLSM is not usually designed to resist freezing/thawing or wetting/drying, it is recommended to design CLSM to withstand these conditions, if the material is intended for use as road bases [14]. The hardening time of CLSM is measured using the penetration test as per ASTM C 403 [14] or the Ball Drop Test as per ASTM D 6024 [19].

This paper aims at utilizing RCA and SCM's, with emphasis on slag, to produce sustainable CLSM without PC. The sustainability of such materials is achieved by using only recycled and industrial waste materials. An important contributor to the sustainability is that the developed material incorporates RCA that has limited applications in structural concrete such as fine RCA and low-strength coarse RCA. The idea is to make use of the available alkalis and calcium hydroxide from the residual pastes in the RCA to fuel the pozzolanic reaction of the slag and fly ash (HCFA in this study). This pozzolanic reaction coupled with some hydraulic activities of slag and HCFA are believed to help in hardening and strength development of the CLSM. The developed CLSM are designed to have a wide range of applications as follows:

1. CLSM containing fine RCA for use in trench backfilling, and conduit bedding. This is specifically applicable to trenches that are narrow with some congested areas or conduits with small spacing. CLSM with fine RCA is also useful in situations where future excavation is expected, such as utility fills, as the lack of coarse aggregates facilitates the digging operations [14].
2. CLSM containing fine/coarse RCA for use in road bases and structural fills. This material is expected to have higher strength and shorter hardening time compared to CLSM with fine RCA.

2. Materials and experimental work

Two types of RCA were investigated in this study: (a) fine RCA with nominal maximum size of 10 mm and (b) coarse/fine RCA with nominal maximum size of 28 mm. The gradation curves for both types are shown in Fig. 1. The slag used in this study was slag 80 with the chemical composition listed in Table 1. HCFA was tested with fine RCA but only for cube compressive strength to obtain a comparison between slag and HCFA in terms of strength development. The rest of the experimental program was conducted on CLSM containing slag.

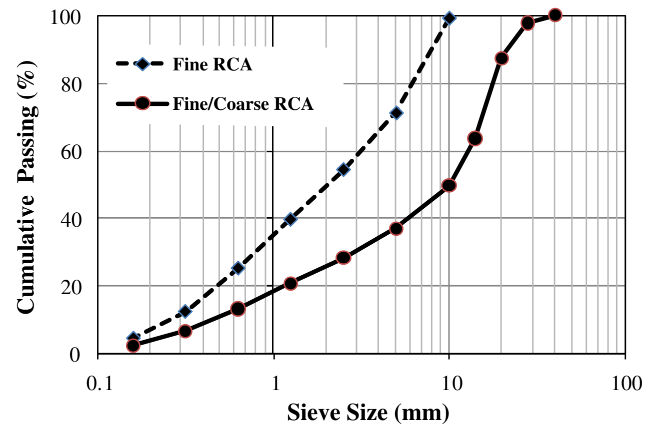

Fig. 1. Grain size distribution of the fine and fine/coarse RCA.

Table 1
Chemical composition of the fly ash and slag.

Sample	CaO (%)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MgO (%)	SO_3 (%)	K_2O (%)	Na_2O (%)	TiO_2 (%)
Slag	43.20	34.40	7.40	0.94	9.30	0.83	0.58	0.57	0.44
Fly ash	31.81	32.42	16.92	5.80	5.81	2.11	0.57	1.62	1.34

To evaluate the amount of alkalis contributed form RCA to the CLSM mixtures, a sample of RCA particles in the size range between 9.5 and 12.5 mm was soaked in distilled water at a solid-to-water ratio of 1:10. After 28 days, the water was analyzed and the concentrations of alkali cations (Na^+ and K^+) were determined using Induction-Coupled Plasma (ICP). The alkalis released from the RCA to the water were then calculated as a percentage Na_2O_e (equivalent sodium oxide) per dry mass of RCA.

A preliminary study was conducted on slag and HCFA samples to investigate the strength development when each of them was used with fine RCA. Fine RCA passing 5 mm sieve was mixed with slag or HCFA at different levels expressed as % of RCA mass. The water content was adjusted to obtain mixtures of similar workability as determined by visual examination. Table 2 lists the mix proportion as well as the flow obtained for each mix using the flow table as per ASTM C230. The cube samples were tested for compressive strength at the ages of 3 and 7 days as listed in Table 2. In addition, cube samples were also prepared and tested without SCM (only fine RCA and water). These cubes were tested to evaluate the strength resulting from the hydration of unreacted cement in the RCA.

A detailed study was then conducted on CLSM with slag and fine or fine/coarse RCA. The CLSM mixtures containing fine RCA were prepared using slag contents of 5%, 10%, 20% and 30% expressed as a percentage of dry mass of RCA. The levels of slag tested

Table 2
Properties of fine RCA/SCM mortar samples.

Slag					Fly ash				
Slag (%)	w/b	Flow (mm)	Strength (MPa)		Fly ash (%)	w/b	Flow (mm)	Strength (MPa)	
			3-day	7-day				3-day	7-day
5	3.00	118	0.70	0.55	5	2.65	120	0.36	0.20
10	1.63	165	1.44	2.10	10	1.25	119	0.81	0.56
15	1.00	135	3.08	4.98	15	0.83	132	0.93	0.74
20	0.75	152	4.67	5.84	20	0.63	108	1.21	1.54
30	0.54	135	5.21	6.54	30	0.50	141	1.17	1.77

Table 3
Mix proportions of CLSM with fine and fine/coarse RCA and slag.

Fine RCA				Fine/coarse RCA			
Slag (%)	w/b	Slump flow (mm)	Unit weight (kg/m^3)	Slag (%)	w/b	Slump (mm)	Unit weight (kg/m^3)
5	4.00	135	1840	5	1.70	190	
10	1.70	141	1855	10	1.67	190	2062
20	1.23	160	2014	20	1.02	210	2185
30	1.00	137	1986				

with fine/coarse RCA were 10%, 20% and 30%. The amount of added water was expressed as a water-to-binder (w/b) ratio where the binder is the slag. The added water was adjusted to obtain visually workable mixtures. The fresh properties were then assessed using different workability and flowabilty tests as discussed in the following paragraphs.

The workability of CLSM with fine/coarse RCA, was assessed using the slump cone test where a minimum slump of 150 mm was required to satisfy the minimum flowability requirement of CLSMs [14]. The flowability of CLSM can also be evaluated using the slump flow test (ASTM D 6103). The test involves placing the CLSM in a 75 mm × 150 mm cylinder, lifting the cylinder and measuring the diameter of the spread material. For traditional CLSM with coarse/fine aggregates, a minimum flow of 200 mm is specified [14]. The CLSM with fine RCA was evaluated using the slump flow test. Table 3 lists the mixture proportions, slump flow (or slump in case of fine/coarse RCA), and unit weight of the tested samples.

Since CLSM with fine RCA was designed mainly for applications that involve narrow areas such as small trenches, or beddings for conduits with small spacing, the plastic properties of these mixtures are very important. Hence, the fresh properties of these mixtures were assessed using additional fresh property tests. The objective of conducting such tests was to obtain a balance between different aspects of fresh properties, such as the flowability and ability to pass through obstacles, and resistance to subsidence. These additional tests are the filling capacity, J-ring and subsidence.

The filling capacity test was performed as per EFNARC 2005 for self-consolidating concrete [20]. In this test, a 300 mm × 500 mm × 300 mm transparent box consisting of two adjacent chambers is used. One of the chambers contains closely spaced 20 mm copper tubes acting as obstacles while the other chamber is obstacle-free. These two chambers are connected by a gate.

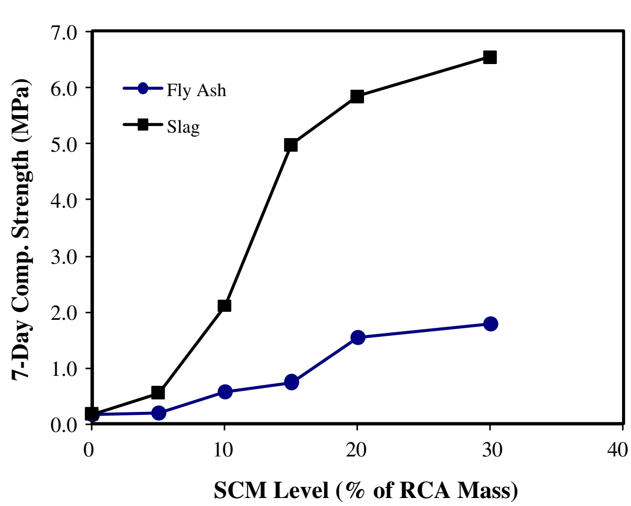

Fig. 2. Compressive strength of mortars containing fine RCA and slag or fly ash.

The CLSM is placed in the obstacle-free chamber and once the chamber is full (300 mm in height), the gate is opened so that the CLSM can flow through the chamber with the obstacles (tubes). Once the flow of the CLSM is complete the height of the materials at both ends of the box is measured. The filling capacity is the ratio of the height at the end of the chamber with the obstacles to the height at the obstacle-free chamber. A higher ratio is a measure of high flowability through obstacles.

The CLSM with fine RCA was also tested for flowability using the J-ring test described in EFNARC [20]. In this test, a stranded slump cone is placed inside a J-ring which consists of a 300 mm-diameter ring with vertical bars of 125 mm height. The CLSM is poured in the cone; after lifting the cone, the diameter of the CLSM spread is measured and reported as the total flow. In addition, the difference in the height of the CLSM spread just before and after the J-ring is measured at four locations and the average is reported as the difference in height or step height. Larger total flow and smaller step height indicates higher workability. The mixtures were also tested for subsidence by measuring the percentage reduction in height of the CLSM placed in 150 × 300 mm standard cylinders at different time intervals until no further subsidence.

The hardened properties of both types of CLSM (with fine and fine/coarse RCA) were evaluated using the same suite of tests. This includes the time required to load application (time-to-loading) or hardening time using the Ball Drop Test (ASTM D 6024), compressive strength using 150 × 300 mm cylinders (ASTM D 4832), resistance to freezing and thawing (ASTM D 560) and resistance to cycles of wetting and drying (ASTM D 559). In the Ball Drop Test, a 14-kg cylinder with hemispherical shaped bottom is dropped onto the surface of a 400 × 400 × 200 mm slab of freshly placed CLSM. The CLSM is considered ready for load application when the ball causes an indentation of a diameter ⩽76 mm in the slab. In the freezing/thawing and wetting/drying tests, 100 mm × 200 mm cylinders are cured for 7 days at 100% relative humidity. At the age of 7 days, the samples are weighed for initial mass and then exposed to 12 cycles of freezing and thawing or wetting and drying as per applicable ASTM standards. After each cycle, the cylinders are subjected to 20 strokes of a standard wire brush on the sides and four on the ends. The total mass loss after the 12 cycles is divided by the original mass of the cylinder and reported as the percent mass loss.

3. Results and analysis

The 7-day compressive strength of the cube samples containing fine RCA and slag or HCFA are shown in Fig. 2. The compressive strength value corresponding to 0% SCM (0.17 MPa) is the value for the cubes containing only fine RCA and water. This strength is mainly due to the hydration of unreacted cementing materials in the RCA. It is clear that the addition of slag or HCFA contribute significantly to the strength development. It is also clear from the graph that both slag and fly ash can develop strength when mixed with RCA without the need to add PC. This strength development is attributable to the hydraulic and pozzolanic activities of both slag and HCFA. It is believed that the pozzolanic activity was activated by the alkalis and, to some extent, the $Ca(OH)_2$, contributed from RCA. Indeed, the simple leaching test conducted in this study showed that the RCA releases alkalis when soaked in water. The amount of Na_2O_e contributed from RCA during 28 days of soaking was 0.08% of RCA mass.

Fig. 2 also shows that fly ash produces lower strengths when compared to slag. This demonstrates that CLSM with a wide range of strengths can be produced using RCA and SCM. However, the detailed investigation conducted in this paper covers CLSMs containing slag.

The fresh properties of CLSM with fine RCA are listed in Table 4. These include subsidence values after 6 h, workability as measured by the slump flow test, filling capacity box and J-ring. As the Table shows, the subsidence decreases with increased quantities of slag. This is attributable to the enhanced cohesiveness of the mixtures when a larger amount of fines (slag) is used. It has been reported that a typical CLSM has a subsidence up to 2% [14,17]; all CLSMs containing fine RCA met this level of subsidence except the mix with 5% slag.

The slump flow of CLSM should be higher than 200 mm [14]. The filling capacity and J-ring tests are normally used to evaluate self-consolidating concrete. However, they are used in this study as additional tests to better evaluate the plastic properties of CLSM with fine RCA. For self-consolidating concrete a filling capacity of at least 80% is recommended. In terms of the J-ring, a minimum diameter (total flow) and maximum difference in height (step height) of 400 and 10 mm, respectively, are recommended [20]. Table 4 shows that the developed CLSM did not meet any of the requirements for slump flow, J-Ring or filling capacity. However, higher workability can be achieved by increasing the water content for the mixes with slag contents of 20% and 30% as the subsidence values of these mixtures are very low and a reasonable increase in the water content is unlikely to cause considerable increase in subsidence. Raising the water content for CLSM with fine RCA and 5% or 10% slag is not recommended as these mixtures already have high level of subsidence (2% and 4%, for 10% and 5% slag, respectively).

Table 4
Fresh properties of the CLSM containing fine RCA and slag.

Slag (%)	Slump flow (mm)	Filling capacity (%)	J-ring		Subsidence (%)
			Total flow (mm)	Step height (mm)	
5	135	78	381	25	4.0
10	141	63	403	43	2.0
20	160	69	367	29	0.3
30	137	75	330	19	0.3

The compressive strengths of CLSM containing fine RCA and fine/coarse RCA are illustrated in Fig. 3a and b, respectively. Each point on the graphs represents the average of two specimens. The coefficient of variation ranged from 0% to 11% for fine RCA and 0% to 9% for fine/coarse RCA. The 28-day strength result of the CLSM with fine/coarse RCA at 5% slag was not available as the two cylinders broke during demoulding. The graphs show that changing the amount of slag and the maximum size of RCA can produce CLSMs of different compressive strength. The strength of fine RCA with 5% or 10% slag was <2.1 MPa which is the recommended strength for applications that require future excavation [14]. The other mixtures showed higher strengths which makes them suitable for applications such as permanent structural fills and road bases. Fig. 3a also shows that for CLSM with fine RCA, there is no increase in strength when more than 20% slag is used. In fact the 28-day strength for the sample with 30% slag was lower than that of the sample with 20%. It is also noted that the unit weight of the mixture with 30% slag is lower than that of the mixture with 20%. This low density could be a result of the high cohesiveness of the mixture (due to high fines content) which produced less densification of the cylinder sample; and hence, lower strength.

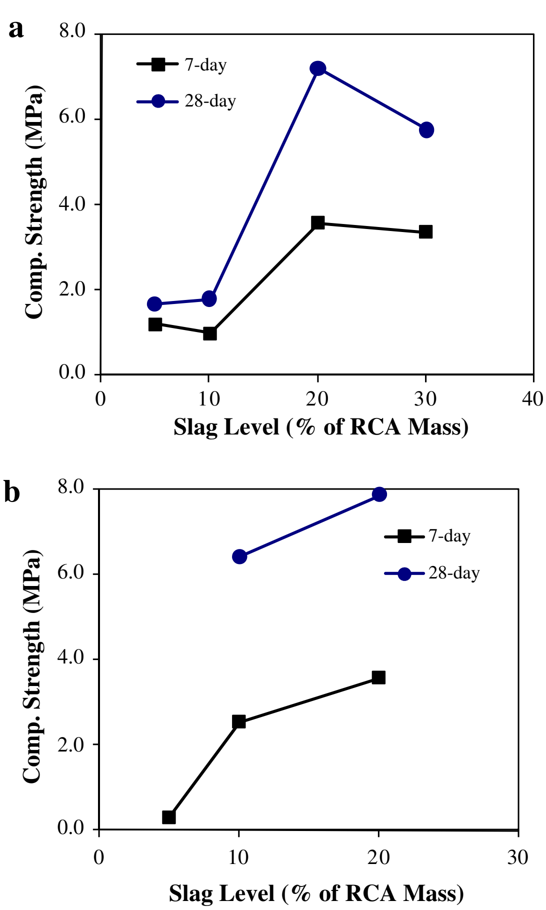

Fig. 3. Compressive strength of CLSM: (a) with fine RCA and (b) with fine/coarse RCA.

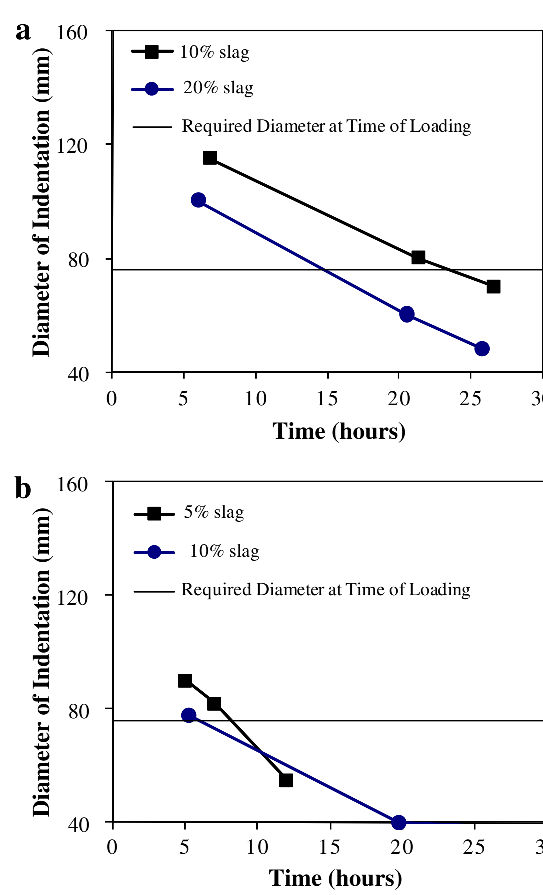

Fig. 4. Ball drop results for CLSM with: (a) fine RCA and (b) fine/coarse RCA.

Table 5
Resistance to freezing/thawing and wetting/drying of the tested CLSM.

Freezing and thawing				Wetting and drying			
Slag (%)	Mass loss (%)		Average	Slag (%)	Mass loss (%)		Average
	Sample I	Sample II			Sample I	Sample II	
CLSM with fine RCA							
5	12.05	12.56	12.30	5	16.23	14.58	15.41
10	17.19	16.89	17.04	10	15.25	15.84	15.55
20	3.39	4.07	3.73	20	5.52	5.70	5.61
30	3.48	3.31	3.39	30	6.40	6.09	6.24
CLSM with fine/coarse RCA							
10	9.88	9.71	9.79	10.00	4.26	3.85	4.05
20	10.67	10.12	10.40	20.00	4.29	3.79	4.04

The hardening time or time-to-loading for both types of CLSM was measured using the Ball Drop Test as per ASTM D 6024. The results are illustrated in Fig. 4 in which the horizontal line at a diameter of indentation = 76 mm represents the time when the CLSM is ready for load application. CLSM containing fine/coarse RCA with 5% and 10% slag were ready for load application after 8 and 5 h, respectively. The CLSM with fine RCA required a longer time to reach the strength required for loading. At slag contents of 10% and 20%, the time required until load application for CLSM with fine RCA were 24 and 15 h, respectively. The shorter hardening time obtained for CLSM with fine/coarse RCA could be attributable to better packing of aggregates which was reflected in the high unit weight obtained for this material (Table 3). The better aggregate packing, or higher unit weight, also resulted in higher compressive strength as shown in Fig. 3.

The resistance of both types of CLSM to cycles of freezing/thawing and wetting/drying were determined using ASTM D 560 and ASTM D 559, respectively. These tests are used to evaluate durability of soil–cement mixtures compacted at the optimum moisture content. For such mixtures, the Portland Cement Association (PCA) recommends a maximum mass loss of 14% after 12 cycles of freezing and thawing or wetting and drying [21]. The mass losses for different samples are listed in Table 5. Although the 14% limit is applicable to compacted soil–cement, it is used here as a rough measure of the CLSM's resistance to cycles of freezing/thawing and wetting/drying. As listed in Table 5, CLSM with fine RCA showed excellent resistance to degradation at slag contents of 20% and 30%. At lower slag levels, however, the resistance to freezing/thawing or wetting/drying was much lower. The tested CLSMs containing fine/coarse RCA and 10% or 20% slag showed high resistance to degradation as the mass loss values were way below the 14% limit. In general, the results show that the resistance to freezing/thawing and wetting/drying is related to the compressive strength, the higher the strength the lower the mass loss. For instance, a large difference in mass loss was found between CLSM with fine RCA at 10% and 20% slag as the strength of the sample with 20% slag was much higher. On the contrary, the mass loss was the same at 20% and 30% slag as the difference in strength was not significant, as shown in Fig. 2.

4. Summary and discussion

The results presented in this paper confirmed that CLSM can be produced using only recycled concrete aggregates and industrial by-products (SCM). The development of such material without the need to add PC supports the growing sustainable development movement in the construction industry. The alkalis contributed from the residual paste of RCA, which was found to be 0.08% of RCA mass, are believed to help activate the pozzolanic reaction of SCM. Knowing that the average mass of RCA in m^3 of the developed CLSMs is 1600 kg, the alkali contribution from the RCA within the first 28 days would be 1.28 kg/m^3. This is higher than the alkali contributed from PC in a traditional CLSM with PC and SCM. For instance, a CLSM with natural aggregates, SCM and 50 kg PC of 1.0% Na_2O_e would produce a Na_2O_e content of 0.5 kg/m^3 of CLSM. Hence, it is likely that the relatively high alkali content in CLSM with RCA would provide a better environment for the pozzolanic reaction and strength development of SCM, or slag in this study. It should also be noted that the hydraulic activity of slag has a role in the hardening and strength development of CLSMs. The trend of strength development of mortar samples in this study demonstrates that the use of slag produces higher strength compared to HCFA. This is probably attributable to the higher calcium content of the slag which increases its reactivity.

The developed CLSM was produced using only recycled materials which make it an excellent example of a sustainable construction material. An additional benefit in terms of sustainability is that the developed materials made a good use of fine RCA. This has the following advantages: (1) reduces the use of natural resources (sand), (2) creates a use for fine RCA which is not recommended for use in structural concrete due to its negative impacts on concrete properties as mentioned earlier. Fine RCA has another advantage when used in the development of CLSM's; its relatively high surface area, compared to that of coarse RCA, may help accelerate the release of alkalis. The alkalis released from RCA are important for activating the pozzolanic reaction of slag or other SCM's.

The CLSMs presented in this paper are suitable for a variety of applications as summarized below:

1. Applications for CLSM with fine/coarse RCA:
   a. Permanent structural fill: the CLSMs with 10% and 20% slag have 28-day strength of 6.4 and 7.8 MPa, respectively. This makes the materials suitable for permanent structural fill where relatively high strength is required [14]. The selection of the slag level (10% or 20%) would depend on the required strength.
   b. Road bases: since the mixtures with 10% and 20% slag met the PCA's recommendations for resistance of soil–cement to freezing/thawing and wetting/drying cycles [21], both mixtures are suitable for road bases where high durability against freezing and wetting is required [14].
   c. Repairs of road sections: it is often required to complete road repairs within a short period of time to minimize the impact on traffic. In such situations, fast hardening time is often required. Mixtures with 10% and 20% slag were found to be ready for load applications, as determined by ASTM D6024, after 8 and 5 h, respectively. This makes the mixtures suitable for such repair works where the CLSM serves as a road base or a temporary road surface.
2. Applications for CLSM with fine RCA:
   a. Permanent structural fill and road bases: the CLSMs with 20% and 30% slag are suitable for such applications. However, the results of the fresh and hardened properties conducted in this study showed that increasing the slag content from 20% to 30% did not produce improved results. Hence, it is economically preferable to consider the mixture with 20% slag. The mixture has a 28-day compressive strength of 7.2 MPa which is suitable for permanent structural fills. In addition, this mixture met the PCA's recommendations for resistance of soil–cement against freezing/thawing and wetting/drying which makes it suitable as road base material. However, the mixture may not be suitable for works that requires short hardening time as the time required for load application is relatively long (15 h).

b. Beddings for conduits with small spacing: CLSM with 20% slag is suitable for such applications. The lack of coarse aggregates enhances the ability of such mixture to move in narrow spaces and between obstacles. Also, the mixture had a very small subsidence (0.3%) which is an indication of good cohesiveness. More water can be added to such a mixture to achieve more flowability without causing undesirable subsidence or segregation.

The CLSM's with fine RCA and 5% or 10% slag are the only two mixtures that had the strength required for utility fills and other applications that require future excavation (<2.1 MPa). However, these mixtures did not meet the slump flow requirement and had high subsidence values. Adding water to increase workability would increase subsidence and, most likely, segregation. To produce the right CLSM's for applications that require further excavations, it is recommended to use more fines that enhance the cohesiveness of the mixture without increasing the strength. One approach would be adding inert fines such as limestone dust to the mixtures; another approach would be using high levels of HCFA, instead of slag, as the HCFA was found in this study to produce lower strengths. These approaches are currently under investigation at Ryerson University.

5. Conclusions

For the range of materials investigated in this study, the following conclusions were drawn:

1. Mixtures of RCA and slag or HCFA were produced and found to gain strength without the need to add Portland cement. The compressive strength of the slag/RCA mixtures was higher than that of HCFA/RCA mixtures. For both types of SCM, the strength of mortar cubes increased with increasing SCM content in the mixtures.
2. Both slag and HCFA produced strength due to their hydraulic and pozzolanic reactions. The latter is believed to be promoted by the alkalis released from the residual paste in RCA. The strength development resulting from the hydration of unreacted PC particles in the RCA was evaluated and found to have minor effect on strength development.
3. Two types of CLSMs were developed in this study: one type with fine RCA for use in narrow and restricted locations, and another type with fine/corarse RCA for use as permanent structural fills and road bases where relatively high strength (up to 8.3 MPa), high resistance to freezing/thawing and wetting/drying and short hardening times are required.
4. For CLSM with fine RCA, a slag content of 20%, expressed as percentage mass of RCA, was found to produce cohesive mixtures with low subsidence and high resistance to cycles of freezing/thawing and wetting/drying. However, the strength was relatively high which renders the mixture not suitable for applications that require future excavation. At the lower slag contents (5% and 10%), the strength met the range required for future excavation (<2.1 MPa), but the mixtures had high subsidence. More work is currently underway to enhance the cohesiveness and reduce the subsidence of these mixtures.
5. CLSM with fine/coarse RCA and slag contents of 10% and 20% showed high resistance to freezing/thawing and wetting/drying cycles and a quick hardening time or time required until load can be applied as determined by the Ball Drop Test (ASTM D 6024). The strength of these mixtures was above that required for CLSM with possible future excavations but within the strength range required for structural fills and road bases. The main difference between mixtures with 10% and 20% slag was the hardening time which was 8 and 5 h for each mixture, respectively.

Acknowledgements

Funding of this research work was provided by a Grant from the Natural Sciences and Engineering Research Council (NSERC) of Canada. The authors acknowledge the financial support of this organization.

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