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DEVELOPING RECLAIMED CONCRETE CEMENT FOR STRUCTURAL GRADE SUSTAINABLE CONCRETES

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Abstract: The demand to consider novel sustainable material development within the concrete construction industry is growing. To consider this trend, the overarching goal of this research paper is to support sustainable concrete development with novel ideas. Recognizing that the bulk of research into demolished concrete waste currently pertains to Recycling Concrete Aggregates (RCA) for conventional aggregate substitution, this research paper instead considers this waste stream for the development of Reclaimed Concrete Cement (RCC). Received concrete demolition waste was sieved as predominately fine RCA (less than 4.75 mm by grain size). A procedure was then developed based on thermo-mechanical analysis of the RCA which justified an optimum preparation for this particular RCC. The procedure also reduced deleterious aggregates which were present within the waste stream. Bench-scale concrete cylinders were prepared according to a conventional 50 MPa structural grade concrete mix design. Trial mixes were considered with RCC replacing conventional cement by mass percentage (0, 20, 30, 50, and 100%). Results indicated that RCC substitutions of less than 20% by mass had no negative impact on mechanical strength properties, and a structural grade concrete could be achieved with up to 50% cement substituted RCC by mass. A short application exercise of this RCC mix is described herein as well as suggested applications and future research directions. It must be acknowledged that the thermo-mechanical procedure used in this study for developing RCC is currently challenging to adapt to conventional practice without adjoining novel cement making technologies. Despite this, the research provides a good introduction to the potential use and development of RCC in sustainable concrete mix designs in the future.

1. Introduction and Background

Debate rages in our construction community as to the degree of green-house gas emissions created through the manufacture of concrete - cement and aggregate production in particular. In the last decade many researchers have considered providing detailed attention to end of life of a concrete structure. Particularly to address high embodied CO_2. In that sense there has been a surge to consider the research of coarse Recycled Concrete Aggregates (RCA) to reduce future quarry depletions or creations. That surge has resulted in multiple code complaint structures being built all over the world using this available (yet resourceful) material in construction. Gales et al (2016a)., lists ten buildings globally that use this RCA technology in their construction. That reference also considers a comprehensive literary review of sustainable concretes. The concrete industry is aware of its duty of care to be environmental stewards and reduce emissions from production processes (bearing in mind most material manufacturers likewise take on similar initiatives). There has subsequently been initiatives to reduce emissions and energy consumption through the development of new manufacturing technologies for the production process of cement.

However there has only been limited studies, a sample of some provided below that have seriously considered the development of alternative and environmentally friendly cements themselves.

Some initiatives by industry to consider the creation of new environmentally friendly alternatives to traditional general use cements. One initiative recently adopted in Canada is the adoption of Portland Limestone Cement (substituting approximately 15% cement with crushed and well graded limestone). This technology has shown multiple benefits. In fact in North America all conventional general use cements available are migrating to this blend. Other cementing technologies include Alkali-activated cement materials derived from waste products (Rice husk ash for example) as are itemized within Bernal et al (2016) and the interested reader is encouraged to consult that work for further details. An interesting development, which was later described as non-scalable, was the creation of cements containing magnesium oxide developed by researchers in the United Kingdom. This product was called Novacem. The technology essentially relied on magnesium silicate being heated to 700°C to produce MgO which is then blended with proprietary admixtures. This process would, unlike the traditional cementing process, produce limited amount to no CO_2 in manufacturing. In fact, it is considered that the inclusion of certain types of magnesium carbonate within the proprietary blend would act as atmospheric CO_2 eaters but may also introduce difficulties for passivation of steel (durability against corrosion of steel reinforcement) due to the cement's pH levels (see Gartner et al., 2011 for discussion on the limitations of this cement). That cementing technology was later sold and the research discontinued.

Figure 1: Construction and Demolition waste is a problem. Various quarries are now accepting this waste and marketing it as Recycled Concrete Aggregates as shown in this photo of a stockpile taken at a Quarry in Ottawa, Canada.

While industry has been considering the reduction of waste materials from concrete structures through avocation of RCA (crushed and fine, see Figure 1), researchers have given limited attention to using this construction waste stream to harvest sustainable cements. This would serve to address concrete's end of life issues and requirements of new quarries for limestone.

The overarching goal of this research paper is to support sustainable concrete development with novel ideas. Recognizing that the bulk of research into demolished concrete waste currently pertains to coarse RCA for conventional aggregate substitution, this research paper instead considers this waste stream for the development of Reclaimed Concrete Cement (RCC) with a secondary focus on conventional fines substitution with fine RCA. Theoretically, a concrete can be produced using only waste materials (Fine and coarse RCA, and RCC), and by that definition could be considered truly sustainable. Of course that requires very significant research, and this study mainly serves to begin deeper discussions into this topic.

The research programme discussed herein is consisted of two phases, optimal preparation of the RCC material and structural grade mechanical testing of both blended concretes with fine RCA and/or RCC. Durability testing was beyond the initial scope of this study but is currently underway by the authors.

2. Motivation

Inspiration for developing RCC in the context of this study came from the Fire Safety Engineering field. Gales et al., (2016b) considered concrete that upon cooling from a fire, began to swell and expand. The conclusion is that heated concrete begins to absorb moisture from the air which surrounds it, undergoing a (slight) re-hydration action. In that sense knowing that the dissociation of Calcium Carbonate is said to occur around 700ºC, as while as de-hydration of bonded water - it should theoretically be possible to control the heating of RCA to reverse the hydration of the cement particulates and make them reactive with water again. The idea is not necessarily a new one, but is novel in the sense to develop the technology as a partial replacement to cement if it can be shown to be environmentally friendly and structurally sound.

This is the primary motivator for developing a RCC technology herein. It should be known that the dissociation process will release CO_2 again as well as other inorganic vapours from the waste products which are incinerated – making the proper acceptance of waste materials for RCA even more critical (i.e., they should not have any plastics etc.) and future work will have to consider these emissions as well as other chemical compositions (use of TGA for example).

The green foot-print so to be of RCC should be lower than traditional manufacture of cement, less energy intensive as smaller temperatures will be used, however a true investigation of its sustainability will require a more extensive environmental study which is beyond the scope of this pilot research.

Depending on the source of the concrete, results will differ as the waste streams for RCA are often highly variable. Therefore any investigation will require a very extensive characterization of a waste stream and the results herein are only generally applicable to the specific RCA waste stream utilised which is currently being assessed by the authors and briefly discussed herein.

3. Materials

The demolition materials that were delivered to Carleton University were prepared as RCA cement materials. The project began by sieving the RCA into two maximum sizes of materials that would be utilized in the initial pilot study. The maximum sieved sizes were 4.75 mm and less than 2.38 mm (the larger grain sizes were kept and reserved for a second project where coarse aggregate substitution could also be studied for this waste stream). The choice of sieve size was used for simplicity in study, it should be acknowledged that conventional cement is very fine, and the fine sizes utilized would not have the same particle surface area as the cement. It would be recommended that (more) ‘finer’ samples be studied to assess if results improve, and these are briefly considered in the application section of this paper.

Characterization began with moisture evaluation. A moisture content test (by mass) was conducted on six representative samples of each sieved size of material. The samples were placed in a furnace chamber housed at Carleton University at 105°C for 24 hours. The average moisture content of the < 2.38 mm material was 1.44%, and of the < 4.75 mm material was 1.43%. Characterization followed with an attempt to define the amount of organic content (wood debris for example etc.) of the material within the fine RCA. At this temperature, the moisture content samples of each sieved material were then transferred into two larger containers. These samples were placed in a convection furnace at 300°C for 5 hours. The estimated content of the < 2.38 mm material was 1.12%, and of the < 4.75mm material was 1.02% (after subtraction of the losses from moisture). Small pieces of material were seen to be black, as if partially charred. These are hypothesized to be plastics found in the construction and demolition waste possibly from wiring being intermixed. Considering that this heating may not have completely burned off all of the organic material, the actual organic and volatile content may be higher, and is of course subject to variability in material composition.

4. Optimum Preparation of RCC

To re-hydrate the cement particles, the RCA was treated in principle with a similar manner in which it was created using elevated temperatures – though at bench scale. Though it must be acknowledged that such a procedure may not be feasible in practice outside of a cement manufacturing plant which would have access to a kiln, it nevertheless provides a good starting point for the RCA’s potential for re-hydration until a more environmental solution using either chemical or mechanical means is studied (suggested future studies).

The heating process will induce a re-hydration process. This process has been previously shown to help RCA bonding by numerous other studies in the peer reviewed domain but has seen limited application for producing RCC. An initial mix was made with material that was heated at 500°C for 5 hours. The mix consisted of 3 parts sand, 1 part RCC, and approximately 0.4 parts water (typical grout formulation). After several days of anticipated curing, this mix did not set nor harden at all. This mix design was based on the assumption that the RCC was 100% cement. Such a consideration is an over- simplification and allows the effect as a cement substitute to be studied. It was decided afterwards that the test mixes would simply consist of prepared RCC and water. A water to RCC ratio of 0.3 was used in all trails. The rehydration was tested at various temperatures, for a heating duration of 5 hours. The mix was then cast into 50mm cubes, and tested in mechanical compression after 3 days of curing.

The heating started at a temperature of 500°C. Additional heating tests were conducted at 50°C increments. Tests were performed in duplicate. The results of all compressive cube tests are illustrated in Figure 2.

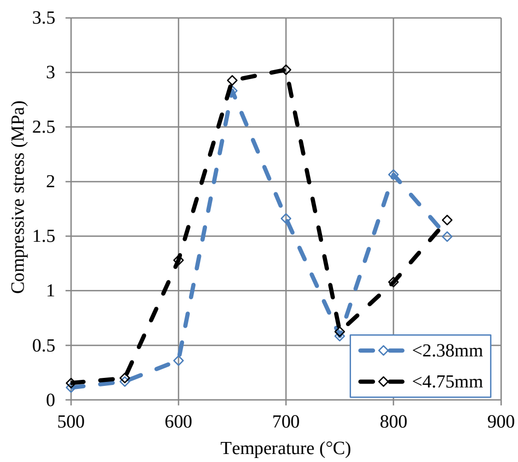

Figure 2: Peak load at increasing temperature for two sieve sizes of RCC

Up until 650°C, the 3-day peak load increased, with a more drastic increase between 600 and 650°C. At 700°C, the < 2.38 mm peak load decreased, and the < 4.75 mm peak load increased only slightly. Material was then heated at 750°C to test the observation that the < 2.38 mm peak load was decreasing, and the < 4.75 mm peak load was plateauing. The 750°C 3-day peak loads for both sizes dropped significantly. The heating was increased to 800°C to confirm this drop in strength, however the 3-day peak loads of the materials increased. The last test conducted was at 850°C, where it was seen that the < 2.38 mm material again decreased in strength, and the < 4.75 mm material increased in strength. Further testing past 850°C was not conducted at this time. The energy demand associated with heating at this temperature is currently not validated by the strengths seen at lower temperatures but would be interesting to confirm as existing cement plant technologies could be explored. The mixes were also becoming less workable at temperatures above 850°C. It was desired to keep the water contents of the mixes relatively equal to maintain a level of comparability between the mixes. The mixes at higher temperatures were thus less workable, since the addition of water at these temperatures was not affecting the consistency in the same way. There also appears to be a difference between the duration of heating and the peak loads achieved. From this the heating rate was adjusted by changing the duration of heating. It also noteworthy that without any heat applied both sizes of RCC did not set, so some method of treatment appears necessary for those sample sizes. A 3-day test was performed on cubes of conventional cement and water, yielding peak loads of over 100 kN. This is over a tenfold increase, and suggests that using the RCC as a cement substitute may require more consideration. This is relatively expected, since the RCC is not 100% cement. It is thus difficult to conclude the effectiveness of the rehydration process on the actual cement material, since the strength of the cubes is affected by all of the material in the mix. At the moment, a total substitution of RCC does not seem feasible; the difference in strength between the RCC and conventional cubes was more than expected, and does not currently support a total substitution. It was determined that the optimal heating time was approximately 3 hours in accordance with Figure 3.

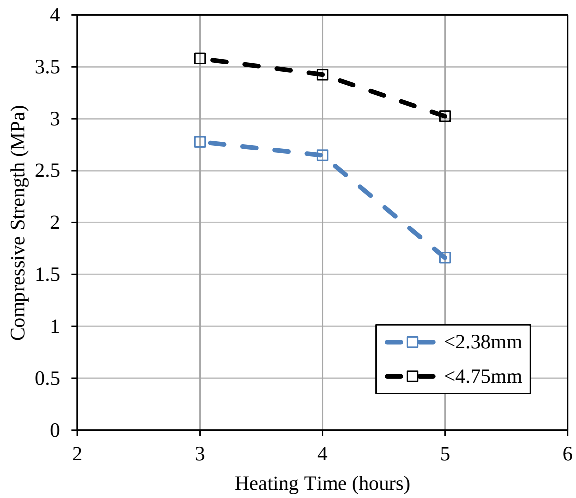

Figure 3: Peak compressive stress with increasing heating time for two sieve sizes of RCC for 650°C

It should also be noted that there was in increase in pH of the concrete from 9 before heating to 12 after heating to 650°C confirming a more alkaline material. This would be satisfactory to ensure passivation of reinforcing steel.

5. Mechanical Strength Testing of Cylinders with and without RCC

Following the identified heating temperature and duration, a fixed quantity of RCC was prepared at a candidate temperature of only 650°C. For simplicity a sieved size of <4.75mm was used to prepare RCC. The samples were heated for at least 3 hours to allow uniform heating and allowed to naturally cool. After preparation the RCC was stored indoors. Later the samples were cast in eight different trial mixes illustrated below in Table 1 with both fine RCA and RCC substitutions by percent. Cylindrical specimens were cast (100mm diameter by 200mm in length) in triplicate to be tested in compression. Cubes should not be prepared as they do not represent the appropriate mechanics that a cylinder can illustrate. Table 1 is prepared in such a way that a practitioner can easily determine the mixture composition by ‘parts’ assume one part may be one kg for example.

Table 1: Cylindrical Trial Mixes

Mix Number	Water to Cement (by parts)	Fines substituted with Fine RCA (%)	Ordinary Cement substituted with RCC (%)	Fine to Coarse Aggregate (by parts)	Water to Fine Aggregate (by parts)	Resulting Colour of Cylinder
1	0.35	0	0	1	0.35	Grey
2	0.35	20	0	1	0.35	Grey
3	0.35	50	0	1	0.35	Grey
4	0.35	100	0	1	0.35	Grey
5	0.35	0	20	1	0.35	Grey
6	0.35	0	30	1	0.35	Grey
7	0.35	0	50	1	0.35	Grey
8	0.35	0	100	1	0.35	Pink

It should be noted that mix number 8, while it did ‘set’, had numerous fines easily breaking off the surface just by touch. All samples hardened after 3 days of curing. After 28 days of curing in a relative humidity of

75% the samples were tested in compression in a loading actuator under a deformation stroke rate control of 0.5 mm/min.

Figure 4 illustrates the strength reduction with respect to substituting with only fines with Fine RCA, whereas Figure 5 illustrates the strength reduction with respect to substituted RCC. Figure 6 represents the idealized reduction curves in strength for the values observed. It can be remarked that there is a rapid strength loss after 20% cement substitution with RCC. By 100% cement substitution it can be observed that less than one 1 MPa strength as a result. In fact demolding was nearly impossible. A representative time lapse is illustrated in Figure 7. Figure 8 illustrates failure planes for all specimens with increasing RCC content. Note that the black paint on the specimens is applied to measure stains which can inform the determination of modulus of elasticity through digital image correlation. That measurement study is currently beyond this paper's scope. The baseline substitutions with fine RCA indicate a short strength gain at 20%. But there was a steady decline as the percentage of fine RCA aggregate increases as it is substituted. It would be proposed that a sustainable mix containing 20% Fine RCA and 20% RCC substitutions be considered as this may be hypothesized to have the same strength as conventional concrete.

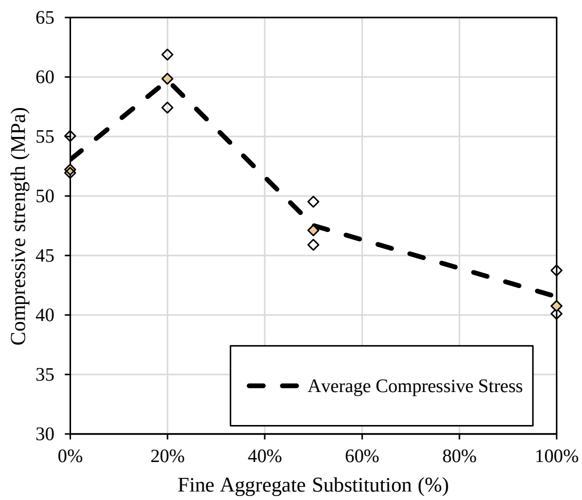

Figure 4: Cylinder compressive strength with fine aggregate substitution

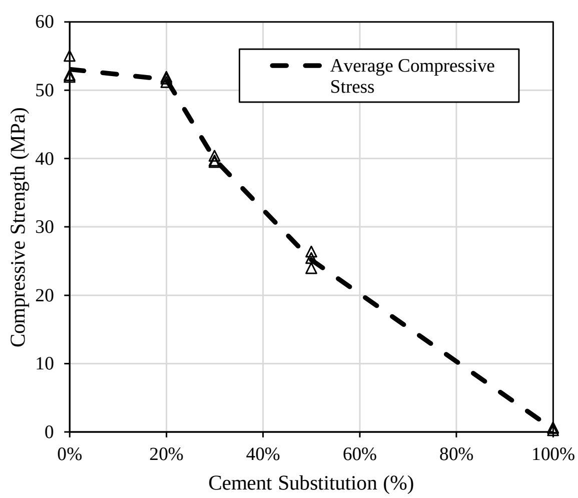

Figure 5: Cylinder compressive strength with recycled cement substitution

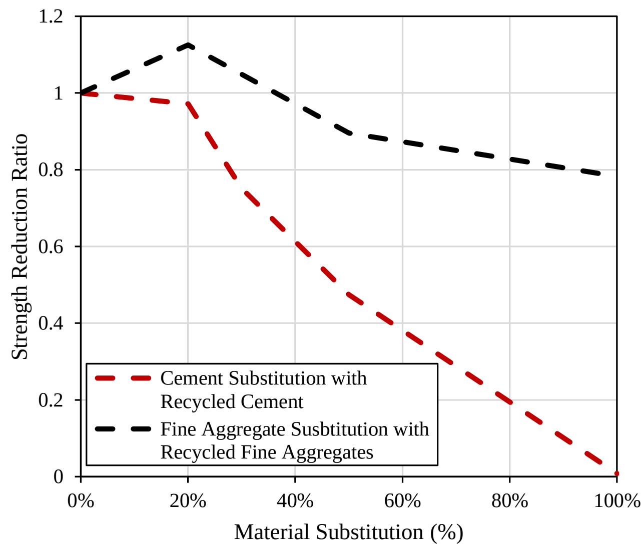

Figure 6: Proposed strength reduction factors

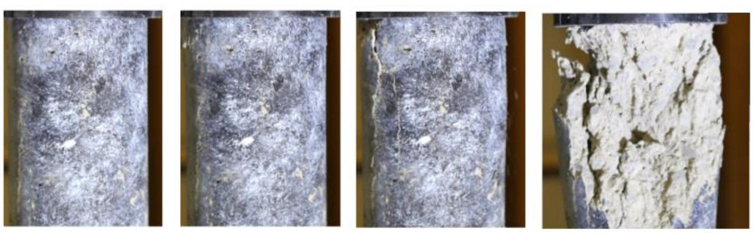

Figure 7: Failure progression time lapsed of 100% recycled cement substitution

Figure 8: Failure planes with various recycled cement substitution

6. Applications with RCC and future research

There are many potential applications both immediate and long term that can be explored for RCC. Primarily for use in structural applications where loading will be continuous it is essential that further studies be performed. In the short term, after scale up technologies can be developed and specific environmental requirements met, RCC may find specific use as cement paste backfills for mineage or in various transportation structures where loading may be small. As this study considered one waste stream it will be needed to investigate other RCA stocks for similar behaviors by other companies if the results are to be generally applied.

For the purposes of this study a brief application was performed in a student experiential learning initiative led by this paper's co-author. Following the identified heating temperature, a fixed quantity of RCC was prepared at a candidate temperature of only 650°C for an initial application of RCC. For simplicity, this RCC was further refined to roughly around the size of regular Portland cement. The material was then used in the concrete designed for the annual engineering competition, the Great Northern Concrete Toboggan

Race (GNCTR) in Canada. The idea of the competition is to build a toboggan fitting five persons, complete with steering and braking. One of the requirements of the competition is that the running surface, i.e. the surface touching the ground, must be made of concrete. Another official rule is that the concrete design must contain a minimum of 30% Portland (ordinary) cement. Since the production of Portland cement requires a lot of energy, it can be considered desirable to find more sustainable production methods. RCC was considered as a possible replacement to make the concrete more environmentally friendly in this competition. In the final design of the concrete, the sieved RCC was used to replace 20% of Portland Cement that was used. A 20% substitution was used because it was the highest amount replacement without reducing too much of the overall strength as demonstrated earlier in this paper, however; testing of how the RCC would interact with different concrete materials was conducted. Different percentages were substituted throughout the testing period to analyze the compressive strength of the concrete mixes. Subsequently there were no significant changes to the strength of the concrete with the new added materials hence it was concluded that a 20% substitution was adequate for this design (7 day and 14 day strength tests were 31 and 39 MPa respectively). Table 2 illustrates the final composition utilized. The use of the RCC made the design more sustainable and environmentally friendly. Because RCC is still in fact Portland cement, the competition rule of minimum 30% Portland cement was still achieved even with other substitutions made in the mix design.

Figure 9. In an experiential learning exercise students utilized the RCC replacing 20% of the ordinary cement to meet green and sustainability objectives in the concrete toboggan competition in Canada.

Table 2: Mix Design

Components	Percent Ratio by weight (%)
Coarse Aggregates	34.67
Fine Aggregates *(includes non- reactive proprietary blends)*	23.80
Portland Cement	25.40
Recycled Concrete Cement	6.35
Fly Ash	2.50
Silica Fume	0.42
Water	7.23
Superplasticizer	0.25

7. Preliminary Conclusions and Future Work

The 2.38 mm RCC size is being considered as the better alternative for a cement substitute due to its smaller particle size which approaches the size of the cement aggregate. The < 4.75 mm material does produce higher strengths though which is obviously the result of larger particles in this mix. The < 4.75 mm material could be favored if this higher fine aggregate content is considered when making the concrete mixes. The < 4.75 mm material though would be more conventionally easier to prepare and this was studied herein and may have further applications in developing regions with limited access to technologies. Various percentages of RCC (after heat treatment) substitution were explored, in order to determine if the conventional mix can be altered to include RCC while maintaining adequate strengths. These showed favorable results below a 20% substitution. These should be followed by mechanical and chemical attempts to re-hydrate the RCA. When dealing with RCA and RCC, compositional variability is something that should always be considered. There is no certainty regarding what is contained in the mix, and so individual results may be outliers from any actual trends. The drops and fluctuations in strengths must be analyzed while keeping in mind that compositional variability may be the cause for these results. In the temperature trials at 650°C; the 3-day peak load began to drop and fluctuate, and residues appeared. From these observations, 650°C may be the optimal heating temperature; some of the highest strengths are achieved, and no potentially damaging residues appear. The heating time is a more difficult factor to make conclusions on. It is dependent on the individual set up. Heating time is known to affect the strength of aggregates. A heating rate of at least 3 hours of uniform heating is required (to ensure the center of the RCA reaches the prescribed temperature). At this stage additional research should be conducted to investigate additional parameters to ensure that the proposed RCC meets durability requirements depending upon its use.

8. Acknowledgements

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