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HIGH TEMPERATURE PERFORMANCE OF SUSTAINABLE CONCRETE WITH RECYCLED CONCRETE AGGREGATES

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Abstract. *The substitution of conventional aggregates in concrete with recycled concrete aggregates (RCA) can act to lower environmental impact. Applications of concrete with RCA are limited because of a lack of research providing clear design guidance. Specifically, the performance in fire must be considered. To address this need, three different concrete mixes were assessed for performance at high temperature with the only variable being the proportion of coarse aggregate substituted with RCA. For each mix, ambient and high temperature compression tests were performed using novel digital image correlation measurement. Small-scale concrete slabs were heated to evaluate thermal and deformation behaviours of these mixes. Results indicated that strength reductions at high temperature were more pronounced with increasing RCA content. However, even with 100% RCA content, the strength reductions at high temperature were within the range suggested by Eurocode provisions.*

1 INTRODUCTION

The impact of human activity on the natural environment is more important today than it has ever been. The reliance on conventional structural concrete to satisfy society's infrastructure needs is producing considerable greenhouse gas emissions, depleting quarries, and consuming large amounts of energy. Thus, sustainable measures of construction with low environmental impact are urgently needed. One sustainable construction measure gaining interest is substituting conventional coarse aggregate with recycled concrete aggregates (RCA) in concrete. RCA can come from concrete demolition waste that is crushed and graded. Incorporating RCA into structural concrete has been limited by the lack of sufficient research and clear guidelines on use, especially in regard to the fire performance of this material. To date, only the post-heated behaviour has been considered by researchers [1]. The more critical aspect of behaviour at high temperature has been neglected. To protect the public, all structural materials must demonstrate reliability, integrity, and resistance in fire before use in design. With the global importance of climate change, research into the fire performance of such sustainable materials is more essential than ever. Therefore concrete with RCA merits consideration in fire and elevated temperatures before its implementation as a suitable construction material. Prior to performing expensive full-scale standard fire tests or recommending new design guidance, it is first necessary to understand the effect that substituting

coarse aggregate with RCA will have on the high temperature performance of concrete. The effect of this substitution is the central theme discussed herein.

2 METHODOLOGY

To investigate the effect of adding coarse RCA to concrete at high temperature, three different concrete batches were cast during May 2013 at the University of Edinburgh for comparison. Each concrete batch used the same mix design amounts: ordinary Portland cement content; water; fine aggregate; and 10 mm max graded coarse aggregate (limestone by default). The only difference between each batch was the mass proportion of a coarse aggregate substituted with coarse RCA (at 0, 30 and 100%). The coarse RCA was sourced and graded from a decommissioned flooring system with known and therefore controlled structural properties (Grade 40/50). The coarse RCA was sourced from undamaged locations of these flooring systems. This was exactly the same flooring system as reported by Gales et al. [2][3]. The testing programme described in this paper considers four cubes (100×100×100 mm) and two unreinforced small-scale concrete slabs (500×200×50 mm) for each concrete mix. The limited number of specimens was controlled by the volume of the onsite concrete mixer.

The cubes were tested in compression under ambient and high temperature at Queen's University, Canada to comparatively characterize mechanical properties of the respective concrete mixes. The cubes were not cast with thermocouples because this would have complicated international shipping.

The small-scale slabs were tested in a steel restraining frame with high radiant heat at the University of Edinburgh to assess thermal properties and deformation behaviour of each concrete mix. All slabs were cast with two K-type thermocouples to measure exposed soffit temperatures (placed to a precision of ±2 mm). The thermocouples were placed at the centremost location of the soffit.

All testing occurred at a minimum of six months after casting. Selected concrete mix details are tabulated in Table 1. Testing procedures are detailed below.

Table 1. Concrete mix properties.

% of coarse RCA	Slump mix (mm)	Moisture content by mass at slab testing (%)	Density (kg/m ³)
0	50	1.4	2120 (+/-70)
30	55	1.9	2160 (+/-30)
100	65	2.4	2140 (+/-40)

2.1 Compression tests

The concrete cubes were tested in compression using an Instron 600LX servo-hydraulic materials testing frame equipped with a furnace and a viewing window. The furnace was capable of heating samples safely up to a temperature of 585°C. Therefore, all cubes had to be tested below this temperature. Two specific soak temperatures were considered for comparison; ambient and the 500°C isotherm temperature [4]. Because concrete is known to be variable, at least two samples were considered at each temperature. Repeatability and testing at two temperatures was considered by the authors to be of more importance than testing one cube at four different temperatures.

The concrete cubes were heated without any applied stress at a furnace control rate of 2 °C/min to the target temperature and held for two hours. During the soak time, considerable thermal expansion of the concrete was observed within the first 15 minutes but then reduced considerably suggesting that the concrete was approaching uniform temperature. After two hours of soaking, the change in extension was negligible with time. After soaking at the target temperature for two hours, the specimens were loaded to failure. All compressive tests (ambient and high temperature) were loaded using stroke control at approximately 0.5 mm/min. Under ambient temperature this loading rate is expected to induce a

minimum loading rate in compliance with North American testing standards. The choice of stroke control allowed the authors to stop the tests after peak stress in a safe and controlled manner. Had load rate control been used there was a substantial risk of damaging the furnace's viewing window at specimen failure. The strain was calculated using a novel and non-contact Digital Image Correlation (DIC) technique (detailed below) to allow the approximate relative stiffness loss (by calculating the 40% f'_c secant modulus). Other measurable variables such as thermal expansion and transverse strain (the Poisson effect) are beyond the scope of this current paper. For every test, the ultimate strength of the cube was also recorded for direct comparison.

The accurate derivation of high temperature material properties is challenging using conventional instrumentation (due concrete's brittle failure) and therefore as described above, a non contact DIC technique was employed. DIC is capable of measuring deformation by comparing a sequence of high resolution digital photographs using an image processing (pixel tracking) algorithm. At high temperature, DIC has been shown to accurately describe the deformation behaviour of various structural materials and assemblies ([5][6]). For this study, DIC was performed using a digital single lens reflex (SLR) Canon EOS 5D mark III camera acquiring images at a predefined rate of 1 Hz. The GeoPIV8 image processing algorithm [7] was used to translate pixel movement into deformation measurement. Figure 1a illustrates the experimental set up and the default strain measurement location for each compressive test. Before using the DIC technique to describe the concrete compressive deformation in ambient and high temperature, a brief confirmation exercise was performed to confirm the technique's applicability. Unlike previous studies that have used DIC for high temperature deformation measurement (i.e. steel) concrete is brittle and has much lower strain at failure. In order for the DIC measurement procedure to be as accurate as possible, a virtual gauge length of 1500Px (75 mm) was used [5]. Figure 1a defines the location of the 'virtual' strain gauge for every test. The expected scatter in measurement with this gauge length would be less than 0.004% strain [5]. The confirmation exercise was a compressive test of a conventional concrete cube at ambient temperature. Measurement from a strain gauge was compared to the measured DIC strain. The maximum deviation between these values was less than 0.05% strain. The strain gauge stopped functioning just prior to failure below 1% strain. The dilation of the concrete towards the camera was assumed to be negligible since the digital image correlation measurement matched satisfactorily to the strain gauge reading. A second confirmation exercise, was performed at both ambient and high temperature by comparing the difference between the theoretical extension rate of the cross head (0.5 mm/min) and the DIC as measured extension rate. The differences in loading rate measured by DIC was found to be at maximum 4% different than the theoretical extension rate of the cross head.

Without thermocouples in the concrete cubes, some uncertainty exists regarding the uniformity of the temperature of the specimens during heating. However, in separate testing by one of this paper's co-authors, using the same experimental set up but using slightly larger concrete specimens with K-type thermocouples installed at the centremost portions of the specimen, it was found that a soak time of two hours was satisfactory to ensure uniform specimen heating at a furnace control near 500°C [8].

2.2 Small-scale slab tests

The small-scale concrete slabs were tested at high temperature in a custom frame and radiant heater assembly without mechanically applied stress. Heating was via four propane fuelled radiant heaters (each of dimensions 200 × 143 mm) placed in a 2 × 2 grid. The heaters, as supplied from *FiberTech Company*, would induce higher temperature exposure than was possible in the compression tests. During testing, both temperature and (when possible) deflection were recorded. Figure 1b illustrates the experimental configuration for the tests reported herein. Every slab test used a calibrated and constant incident radiant heat flux of 65 kW/m² for one hour. For every concrete mix, at least two slabs were tested for repeatability. Details on the construction, calibration, and control of this heating system and restraining frame are provided by Elliot et al. [9].

Two tests for each concrete mix were conducted with the bespoke loading frame and radiant heaters. Exposed soffit temperatures were calculated based on the average of the two K-type thermocouples. The maximum deviation between thermocouples was within the manufacturer's allowable error ($\pm 0.0075T$, where T was the maximum recorded temperature). The unexposed surface of concrete was measured with one attached K-type thermocouple in an assembled pad. This assembled pad was constructed out of 100 mm² aluminium tape placed directly on to the concrete surface, a 100 mm² ceramic fibre insulating ceramic wool that encompassed the thermocouple, and a covering of 120 mm² aluminium tape to adhere to both the concrete surface and the insulating ceramic wool.

Deflection near the centremost point of the unexposed surface was measured using linear potentiometers (LP). In many cases, this measurement was aborted because of a risk of damaging the instrument from the elevated temperature.

The thermal exposure of constant incident radiant heat flux was chosen because: 1) for these slab dimensions it represented an exposure capable of inducing temperatures through the concrete surface similar to what would be observed in a ASTM E119 standard fire for a target time of one hour [10]; 2) future numerical modelling efforts could be simplified with such a straightforward input thermal boundary; and 3) each test would yield a simple yet comparable thermal gradient that would allow the absorbed heat to be rationally compared.

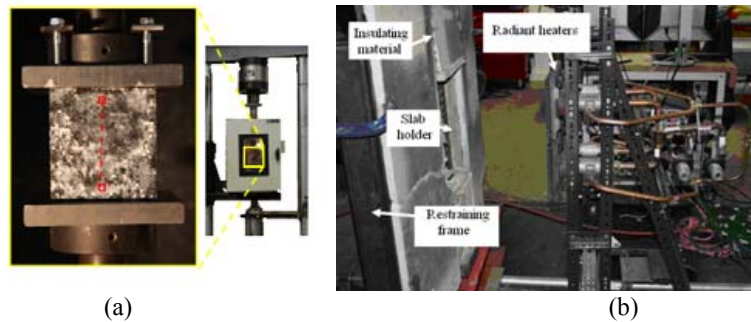


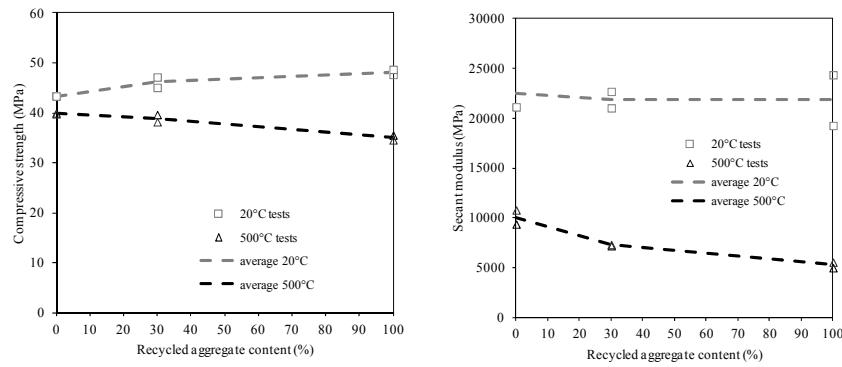
Figure 1. (a) Compression test experimental set up using DIC with virtual strain patch shown in red
(b) Radiant heaters and loading frame

3 COMPRESSION TEST RESULTS

At ambient temperature, compressive tests showed a strength increase with increase in proportion of RCA coarse aggregate (Figure 2a). This behaviour may have been influenced by the raw RCA coarse aggregate strength being 20% greater than that of the concrete in the new mix design. These tests showed considerable variability between measured ultimate strain and elastic secant modulus (Figure 2b). Less variability was observed in ultimate strength (less than 1.5 MPa).

At elevated temperature, compressive tests showed a strength decrease with increasing RCA content (Figure 2a). However, at the 500°C critical isotherm, the 100% RCA was shown to meet the strength reduction guidance of the current Eurocode with less than 25% strength reduction [4]. The 100% RCA concrete mix had comparable strain at ultimate load as specified by the Eurocode guidelines (1.4% strain compared to 1.5% strain as reported by the Eurocode [4]). The high temperature specimens had a lower modulus of elasticity (Figure 2b) than their ambient counterparts. As the RCA content increased this behaviour was more pronounced. However, like their ambient counterparts, the high temperature tests showed variability between both measured ultimate strain, and elastic secant modulus. Little variability was observed in ultimate strength (less than 1.1 MPa).

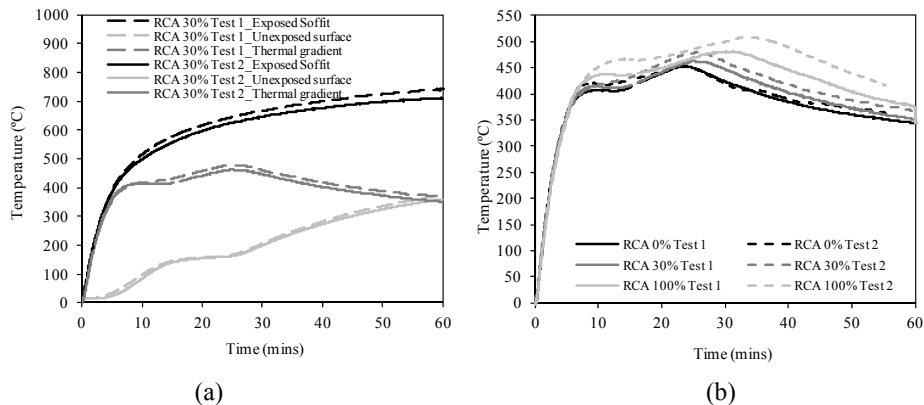
The reduced performance of sustainable concrete in high temperature with RCA is hypothesised to be due to: (1) a weak interface between the old cement on the RCA and the new cement, (2) and/or micro-cracking in the RCA possibly induced during sourcing. These hypotheses are considered in greater detail in Section 5.



(a) (b)
Figure 2. (a) Compressive strength at ambient and high temperature
(b) Secant modulus at ambient and high temperature

4 SMALL-SCALE SLAB TEST RESULTS

The measured temperatures of the two tests performed with 30% coarse RCA are illustrated in Figure 3a. All test series for each concrete mix showed very similar exposed soffit temperature measurements indicating satisfactory repeatability in heating. The maximum deviation between tests of the same series was 30°C. Discrete thermal cracking was present in the 30% coarse RCA mix tests. These cracks ran longitudinally along the exposed surface at approximately 1 mm in width to outside the heating zone. An investigation into the tensile properties of RCA concrete may help explain these cracks. Discrete (10 mm in diameter) ‘pop-corn’ spalling was observed in each of the 0% and 30% mix coarse RCA mixes. The 100% RCA concrete slabs did not show any evidence of spalling. Figure 3b illustrates the measured thermal gradient (the difference taken directly between the exposed and unexposed surface temperature) for each test. As RCA content increases it can be seen that the thermal gradient becomes larger (and thus also the expected deformation due to slab bowing increases). These small differences in thermal gradient can be due to a multitude of factors such as RCA aggregate type, thermal conductivity (functions of specific heat, density and diffusivity), moisture content, porosity etc. However, the thermal gradient between all tests differed at most by 68°C indicating that a direct substitution of coarse RCA with conventional coarse aggregate, as has been done herein, appears to have minimal impact on the thermal properties of the slab. Figure 3b also suggests that, at some point in all tests, the thermal gradient in each slab began to decrease. Throughout the duration of testing, the deflection increased continuously (reaching a maximum of less than 5 mm). This increase in deflection could have been caused by either increased thermal stresses which cracked the slab, non uniformity in heating, errors in surface temperature measurement, or high temperature exposure to the LPs compromising the readings. Future modelling may help interpret these measurements.



(a) (b)
Figure 3.(a) Thermal behaviour of 30% RCA concrete slab (b) Temperature gradient in each slab test

5 POST HEATING EVALUATION

Scanning electronic microscopy (SEM) imaging analysis was conducted on samples from virgin (un-cast) coarse RCA (10 mm), heated and unheated failed concrete cubes ($20 \times 20 \times 20$ mm) and samples from heated and unstressed small-scale slabs ($20 \times 20 \times 20$ mm). These samples were used to evaluate the micro-mechanical changes of the concrete containing coarse RCA with high temperatures in an effort to help explain the behaviour observed in Sections 3 and 4. Imaging was done using a MLA 650 FEG Environmental Scanning Electron Microscope (ESEM) housed within the Queen's University Facility for Isotope Research. Images for each sample were taken at regions of interest (aggregate interfaces, spalling, pores, and cracking) at varied resolutions.

Imaging of high temperature exposed failed cubes showed numerous micro-cracks at the interfaces between the old to new cement (see Figure 4a for an example) whereas imaging of samples that had been exposed only to ambient temperature showed no identifiable cracking at the same interfaces. Both samples showed dispersed cracking within the RCA. Virgin coarse RCA also showed dispersed micro-cracking (Figure 4b) throughout. Therefore, it was difficult to confirm whether the reduced RCA performance at high temperature was dependent on micro-cracking at the interfaces between the old and new cement during heating, or on micro-cracking within the coarse RCA before it was even cast.

Imaging of the 100% RCA concrete small-scale slab specimens showed identifiable micro-cracking at old to new cement interfaces (Figure 5a), but no identifiable cracking in the 0% RCA slab counterpart at the aggregate-cement interface. Imaging of 100% RCA samples indicated significant amounts of visible pores (see Figure 5b).

The ESEM was also used to perform an elemental chemical analysis to identify exposed aggregates found in the spalling region of the slabs. The aggregate was confirmed to be limestone for both the 0 and 30% RCA concrete slab samples.

The SEM observations support the hypothesis that the sustainable concrete mixes with RCA are weakest at the old to new cement region at high temperature and that porosity could be the contributing factor for thermal heating behaviour for the higher RCA mixes considered in this paper.

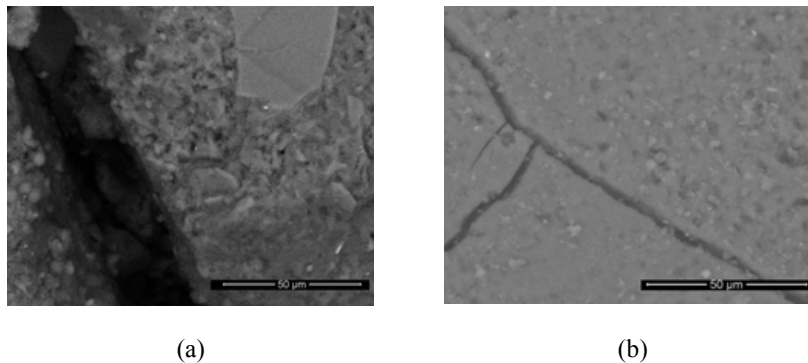


Figure 4. (a) Old to new cement interface of 100% RCA tested cube after testing with applied stress
(b) micro-cracking in virgin RCA before casting ($< 3 \mu\text{m}$ crack)

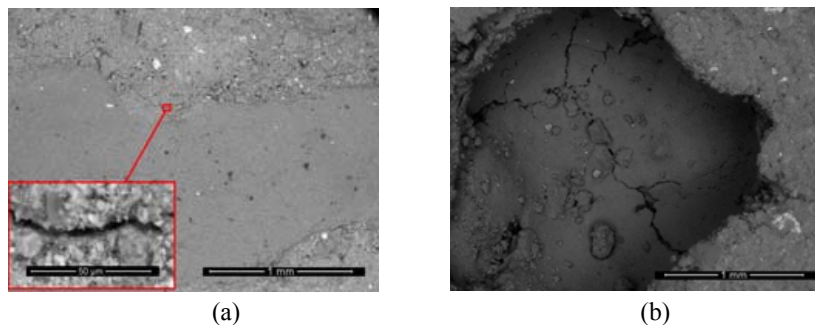


Figure 5. (a) Old - new cement interface of 100% RCA tested slab after testing under no applied stress ($< 4 \mu\text{m}$ crack)
(b) Visible pore of 100% RCA tested slab after testing under no applied stress

6 FUTURE WORK

The testing herein should not be interpreted as a recommendation for new design guidance. This paper only presents an investigation at ambient and high temperature into the effect of adding coarse RCA to concrete. Initial test observations indicate that, by using coarse RCA in sustainable concretes, a reduction in fire performance should be expected. However, limited testing also indicated that, even with a concrete mix of 100% coarse RCA, the resulting concrete may meet current Eurocode strength reduction design recommendations for performance at high temperature [4]. If sustainable concrete with coarse RCA is to be used as a suitable construction material, the following is a brief list of future research that should be considered to complement the work presented herein:

- **Improvements in testing equipment** – Concrete mechanical behaviour at high temperatures has a time and load dependency factor (creep and load induced thermal straining). The compression tests were controlled using one non-constant loading rate. A more systematic testing procedure capable of minimizing equipment damage will be essential for providing accurate material design recommendations.
- **Investigate effects of substituting commercially available coarse RCA in high temperature** – In reality when commercial RCA is prepared there is uncertainty regarding the quality of the aggregates (strength, impurities, damage from fabrication etc). To an extent, this uncertainty was eliminated in the specimens tested herein; however, this may not be so with commercially available coarse RCA. These uncertainties could have consequence for the high temperature performance of sustainable concretes. Therefore, the behaviour of commercially available coarse RCA in sustainable concretes should be evaluated. In the event that the commercially obtained coarse RCA mixes show poor fire performance, suitable investigation should be undertaken to explore various additives that may improve the performance of sustainable concrete.
- **More compressive testing** – Two compressive tests at each temperature are not representative to recommend new design guidance. Such a limited number of tests will not capture the variability that can be found in concrete. While testing was primarily done at 500°C, a temperature widely considered as a critical limiting isotherm [3], the behaviour of the concrete mixes may show increased complexity across the whole temperature spectrum. Additional tests in both quantity and other temperatures should be considered in the future.
- **Tensile testing needed** – No tests were conducted for tensile behaviour in high temperature, but unstressed coarse RCA small-scale slab tests showed significant cracking along their exposed soffits. The tensile behaviour of sustainable concretes containing coarse RCA should be studied at high temperatures.
- **Further analysis of digital image data** – Digital images from the compressive tests allow for additional investigation into the thermal expansion, thermal dilation, and transverse strain behaviour of sustainable concretes with RCA. These properties should be also investigated with the data already obtained.
- **Further slab testing** – Additional small-scale slab tests can be conducted under load to investigate the behaviour of these concrete mixes while concrete is submitted to stresses and high temperatures as would be seen in a fire. These tests should be conducted.
- **Full scale testing** – Once a suitable sustainable concrete mix can be defined, full-scale testing is required to demonstrate reliability, integrity and resistance in fire. This will facilitate applications of sustainable concrete mixes in design.

5 CONCLUSIONS

Despite the large strength reduction of the 100% coarse RCA mix at elevated temperatures, it was shown that the strength reduction guidance of the current Eurocode for the critical isotherm of 500°C could be met by using controlled RCA sources in sustainable concretes. The small-scale slab tests

suggested that the addition of adding coarse RCA to a concrete mix had negligible effects on the slab's thermal behaviour. Various future research needs are identified herein which would help improve the understanding of sustainable concrete mixes with coarse RCA and allow its use in structural design.

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