

Effects of Elevated Temperature on Concrete with Recycled Coarse Aggregates

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Abstract. This paper discusses the effects of heating temperatures of 200°C, 400°C and 600°C each for 2 hours at a heating rate of 2.5°C/min on concrete with the content of Natural Coarse Aggregates (NCA) partially replaced with Recycled Coarse Aggregates (RCA), obtained from demolished building in the ratio of 0%, 15% and 30%. There was an initial drop in strength from 100°C to 200°C which is suspected to be due to the relatively weak interfacial bond between the RCA and the hardened paste within the concrete matrix; a gradual increase in strength continued from 200°C to 450°C and steady drop occurred again as it approached 600°C. With replacement proportion of 0%, 15% and 30% of NCA and exposure to peak temperature of 600°C, a relative concrete strength of 23.6MPa, 25.3MPa and 22.2MPa respectively can be achieved for 28 days curing age. Furthermore, RAC with 15% NCA replacement when exposed to optimum temperature of 450°C yielded high compressive strength comparable to that of control specimen (normal concrete). In addition, for all concrete samples only slight surface hairline cracks were noticed as the temperature approached 400°C. Thus, the RAC demonstrated behavior just like normal concrete and may be considered fit for structural use.

1. Introduction

Heavy Construction Industries such as manufacturing of foundries, furnaces, gas turbines are at the forefront of development in developing countries, like Nigeria, as they produce resources that are necessary for driving the economy. At the moment, only natural aggregates are used in construction for the needs of these industries, in spite of the fact that using recycled concrete aggregates reduces the need for virgin aggregates. Use of recycled aggregates reduces the environmental impact of the aggregate extraction process as well as enhances the greenhouse effect by absorption of large amount of carbon dioxide from the surrounding environment. The primary challenge with using recycled aggregates such as partial or total substitutes for coarse aggregates in concrete, as observed by Fady [1] is that their usability is a function of many uncontrollable factors such as the amount of impurities

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e.g. glass, wood, brick etc., water content of the parent concrete and the quantity of natural aggregates to be replaced in the concrete matrix.

Katz [2] concluded that the concrete with recycled coarse aggregate in concrete are said to exhibit similar behaviour to that of Natural Aggregate Concrete (NAC) when exposed to temperatures, ranging between 25°C and 800°C if the replacement level is limited to between 0% and 40%, and done with hydrated old concrete. Salau et al [3] used Cassava Peel Ash (CPA) as partial replacement for cement in concrete which is exposed to relatively high temperature. It was shown that with 15% CPA replacement for Cement, the concrete can withstand up to 200°C without any negative effect on compressive strength. Salau and Oseafiana [4] focused on the thermal technique of activating pozzolanic activity of calcined kaolinitic clay in the form of metakaolin. The results showed the optimum heating temperature for the kaolin to be 750°C and the proportion of metakaolin in concrete to be 10% of the cement weight, while the strengths of concrete were 99% and 97% of normal concrete strength at 28 and 90 days respectively.

Maya et al [5] investigated the residual mechanical performance (compressive and splitting tensile strengths and elasticity modulus) of concrete made with recycled coarse aggregates after exposure to high temperatures. Specimens from all types of concrete, besides being tested at ambient temperature (about 20°C), were subjected to the following three temperatures for a period of 1h: 400°C, 600°C and 800°C at age 49 days and, after cooling down to ambient temperature, 4 days later they were finally subjected to mechanical testing. The results showed that in spite of higher porosity and the different thermal properties of the matrix-aggregate interface of recycled concrete coarse aggregate when compared to reference concrete, the incorporation of recycled aggregates does not influence the thermal response of the material. Accordingly, in terms of post-fire residual mechanical properties there are no limitations to the structural use of recycled aggregate concrete when compared with conventional concrete. These findings negate that of Katz [2] who proposed that the presence of the recycled aggregates influences fire resistance, hence, the residual strength.

The present strength work aims to highlight the differences in the behaviour of concrete with recycled coarse aggregates, subjected to ambient temperature.

2. Materials and experimental methodology

Cement used was Ordinary Portland Cement, with the corresponding properties. The aggregates were selected based on the limitation of BS 882. The fine aggregate used was river sand. Two different types of coarse aggregate were used in this study. One was natural coarse aggregate (crushed granite), collected from the quarry and the other was recycled aggregates, obtained from demolished concrete members at the site of the Pan Atlantic University building site, at IbejuLekki, Lagos. It consists of crushed concrete pavements, rejected structural precast elements and abandoned laboratory crushed concrete cubes. Prior to the mix design, the recycled coarse aggregate had to be sieved and graded to ensure quality concrete matrix. Previous work of Tam et al [6] suggests that the gradation of RCA be the same as that of the virgin aggregate. In order to reduce the RCA's water demand, all particles less than 4.75mm [No 4 sieve] were not used.

The coarse aggregates were soaked in water for 48 hours and then the excess water was drained off before they were mixed with the other ingredients in the production of the concrete. The water used for this work is clean, clear and fit for drinking (portable water) which satisfies the BS 5328 standard for water requirements for mixing concrete. The mix ratio was 1:1.7:2.5 (cement: sand: aggregate recycled/virgin granite) with water cement ratio of 0.50. The granite normal concrete was substituted with 15% and 30% recycled aggregates. After the crushing of the parent concrete, the particles were

sieved through the 25mm sieve size and any particle passing the sieve was discarded. The resulting aggregate particles were again passed through the 4.75mm sieve size and any particle passing was also discarded. A gradation test was performed on the sharp sand, natural and recycled coarse aggregate used and results are given in particle size curves. Various fresh trial concrete mixes were made to determine the ideal moisture content required for the experiment. As recommended by Matsushita et al [7], it is expected that concrete with RCA must have a minimum slump of 75mm. The test was carried out using a 300mm high concrete cone. The slump cone with the base plate below it was filled in three layers, and each layer tapped using a tapping rod to about 25 blows. The slump or reduction in height of the cone was taken to be the measure of workability.

The cube samples with 0%, 15% and 25% RCA were heated in an electric furnace (carbolite GPC 12/65) at temperatures of 200°C, 400°C and 600°C each for 2 hours at a heating rate of 2.5°C/min. The sample was left to cool for a few minutes before taking readings for strain and finally conducting the strength tests. The tests were also carried out on each sample at room temperature (i.e. about 24°C), as a basis for comparison.

3. Results and discussion

3.1. Particle size distribution of the coarse aggregates

The size distribution curves for sand, natural and recycled coarse aggregates are shown in figure 1. The obtained fineness modulus for the fine aggregate (sand) was 2.83 while the coefficient of uniformity (Cu) and coefficient of curvature (Cc) were 2.83 and 1.41 respectively. The fineness modulus for fine aggregates should be in the range of 2.3 to 3.1. The fineness modulus is a measure of the fine aggregates' gradation, and is used primarily for Portland cement concrete mix design. It can also be used as a check in the production of concrete. The value of Cu is less than 6 for the fine aggregate which according to the Unified Soil Classification System infers a poorly graded soil.

For natural coarse aggregate (granite), the coefficient of uniformity (Cu) is 1.5 while that of recycled coarse aggregates is 2.2. Coefficient of curvature of both the RCA and NCA were similar with an average value of 5.5. Hence, according to the Unified Soil Classification System, both types of coarse aggregate (RCA) and (NCA) cannot be classified as well graded but similarity of the curves (figure 1) makes them suitable substitutes for each other. The results of the distribution curves show that they can hardly be differentiated in terms of the particle size.

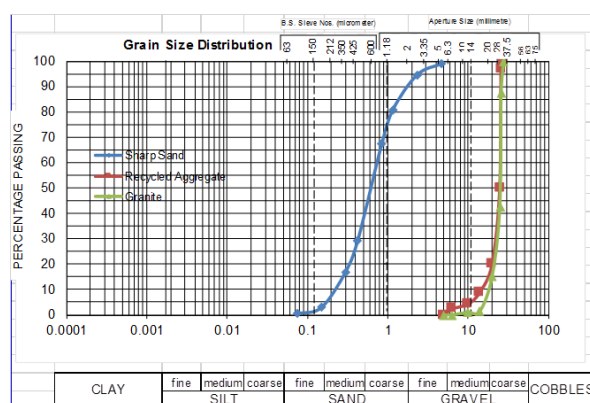


Figure 1. Particle size distribution curves of aggregates.

3.2. Density and water absorption of all coarse aggregates

Table 1 shows the results of density and water absorption of the coarse aggregates. The average particle densities of the natural coarse aggregate are 2895 kg/m^3 and 2935 kg/m^3 for dry condition and saturated surface dry condition respectively, while the average particle densities of recycled aggregate are 2311 kg/m^3 and 2446 kg/m^3 for dry condition and saturated surface dry condition respectively. This means recycled coarse aggregate is lighter than natural coarse aggregate, and this can be a result of RCA also consisting of low density cement paste. When the particle size of recycle aggregate is increased, the volume percentage of residual mortar will increase; this invariably reduces the specific gravity and the density of the aggregate particles.

The average water absorption rate of the recycled coarse aggregate is 5.85%, while that of the natural coarse aggregate is only 1.4% that is, about 4 times. The results shown in table 1 indicate that more water was needed to be added when using the recycled aggregate in the concrete mixing to get an acceptable workability. This may be attributed to the fine aggregate and cement that have adhered to the recycled aggregate during its production. This result is in consonance with the results reported by Katz [2], that the total water absorption of concrete made with recycled aggregate was about 6.9-7.6%, and greater than absorption of the reference concrete of about 3.8-3.9%. The sources of recycled aggregates will determine its water absorption capacity.

Table 1. Density and water absorption capacity of recycled natural aggregates.

Types and Size of Aggregate	Particle Density (Dry), kg/m^3	Saturated Density (SSD)*, kg/m^3	Water Absorption, %
25mm natural aggregate	2885	2921	1.24
10mm natural aggregate	2895	2933	1.32
6.3mm natural aggregate	2906	2952	1.56
25mm recycled aggregate	2342	2473	5.54
14mm recycled aggregate	2281	2421	6.16

SSD*: Saturated surface dry condition

3.3. Effect of temperature on the density and residual strength of RCA concrete

The results of densities of concrete containing recycled aggregates and granite (virgin aggregates) with temperature increase are shown in table 2. The density of the concrete cubes for all the mix proportions increased as the curing period increased, irrespective of percentage replacement of the virgin coarse aggregate (granite) with the recycled ones. However, on the 28th day, the normal concrete has the highest density and the density reduced as the percentage replacement of RCA increased. Density values, which tend to be smaller for concrete containing recycled aggregate than for natural aggregate concrete, can be attributed to a lower density and specific gravity of the recycled aggregates themselves and a weaker interface between old mortar and new mortar. The average density of all mix proportions reduced on heating by an average of 7% in each instance. With thermal treatment there was a reduction in the density of the cubes with the increase in the temperature. However, the residual

density is more than 95% of the initial density at 600°C heating. The obtained results of the residual compressive strength of thermally treated concrete cube samples 150mm x 150mm x 150mm at different temperatures after cooling are shown in table 3. In both 7 and 28 days, there was a notable increase in residual strength between 300°C and 400°C. The increase in the compressive strength may be due to the acceleration of the hydration of cement gel due to the increased rate of evaporation of free water. However, there is a general reduction in compressive strength of concrete with increasing replacement of natural coarse aggregates with the recycled coarse aggregates. The behaviour of the recycled aggregates concrete can be classified into three regimes with exposure to temperature as follows.

Table 2. Effects of temperature on the density of recycled aggregate concrete.

% RCA	Temp (°C)	Initial Initial W(kg)	Final Final W(kg)	Initial Density kg/m ³	Final Density kg/m ³
0%	25	8.25	8.25	2398	2398
	200	9.13	8.99	2654	2613
	400	8.19	7.68	2381	2232
	600	8.15	7.56	2369	2197
15%	25	8.16	8.16	2372	2372
	200	8.71	8.56	2532	2488
	400	8.13	7.59	2363	2206
	600	8.39	7.75	2439	2253
30%	25	8.15	8.15	2369	2369
	200	7.91	7.74	2299	2250
	400	8.85	8.17	2572	2375
	600	8.13	7.52	2363	2186

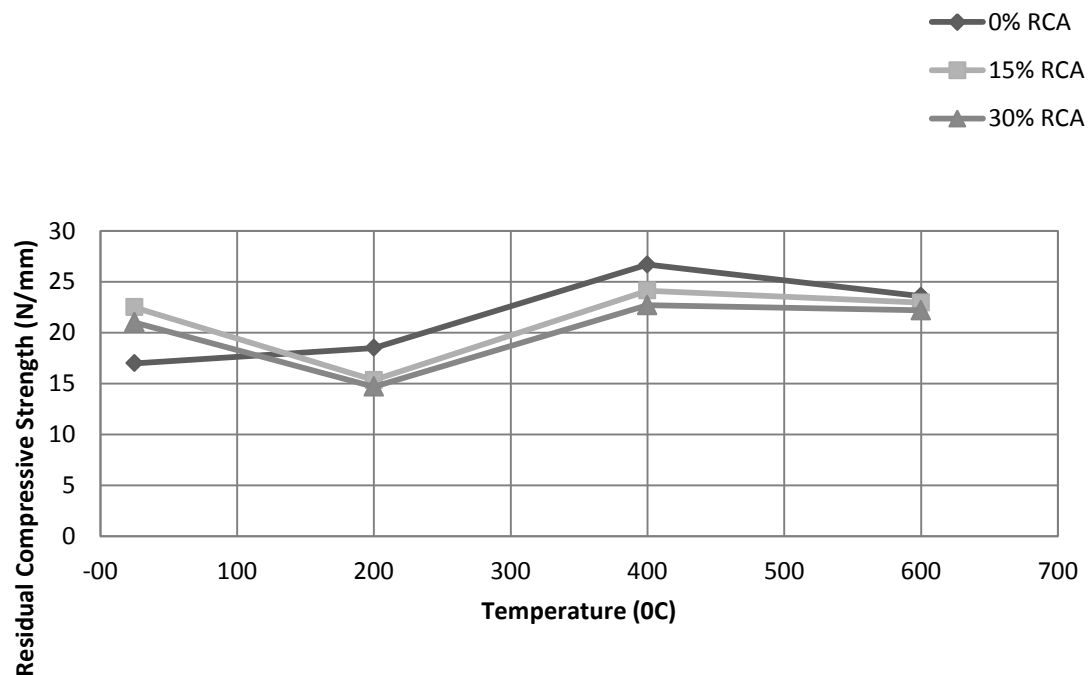
Regime I: Temperature between 25°C and 200°C: It was characterized with distinct pattern of strength loss. Control samples increased steadily up to about 8% (17.00N/mm² to 18.50N/mm²), but samples with 15% RCA replacements displayed 8% (22.50N/mm² to 15.35N/mm²) and 30% loss (21.03N/mm² to 14.70N/mm²) and respectively reduction in strength. There was an initial drop in strength from 25°C through 100°C and 200°C which is suspected to be due to the relative weak interfacial bond between RCA and hardened paste within the concrete matrix

Regime II: Temperature between 200°C and 400°C: In this regime, there was continuous gain in strength. A gradual increase in strength continued from 200°C to 400°C. Control samples increased steadily up to about 30% (18.5N/mm² to 26.70N/mm²), but samples with 15% and 30% RCA replacements respectively displayed 36% (15.35N/mm² to 24.13N/mm²) and 35% (14.70N/mm² to 22.70N/mm²) increase in strength. It is suspected that there was thermal expansion and dehydration of concrete in this regime.

Regime III: Temperature between 400°C and 600°C: There was a subsequent loss of concrete cube strength in this regime and steady drop occurred again as it approached 600°C. Control samples reduced steadily with about 13% (26.70N/mm² to 23.60N/mm²), but samples with 15% and 30% RCA replacements displayed 5% (24.13N/mm² to 22.95N/mm²) and 2% (22.70N/mm² to 22.20N/mm²) reduction in strength. Surface cracks were observed in the cubes.

Table 3. Recycled aggregate concrete residual strength at different temperature and ages.

Temperature (°C)	Temperature of Thermal Treatment							
	25°C (Room Temp)		200°C		400°C		600°C	
% Recycled Aggregate	7 days	28 days	7 days	28 days	7 days	28 days	7 days	28 days
0	19.55	17.00	21.19	18.50	20.60	26.7	19.50	23.6
15	16.4	22.50	11.6	15.35	10.2	24.13	18.7	22.95
30	19.6	21.03	14.7	14.7	16.0	22.7	24.4	22.2

**Figure 2.** Effect of temperature on the residual strength of concrete (at 28 days) with different percentage of recycled aggregates.

3.4. Crack formation

The process leading to cracking is believed to be essentially the same as leading to spalling. Thermal expansion and dehydration of the concrete due to heating may lead to the formation of fissures in concrete in addition to spalling. Crack depths were not measured, but severities of the cracks were noticed as the temperatures approached 600°C. Figure 3 shows the cracks on 15% recycled aggregate cube on 28 days after heating for 2 hours at 400°C. Similar cracks were observed in the other cubes. However, the severity depends on the exposure to the thermal heating, especially after 400°C.



Figure 3. Arrows pointing to crack lines formed on 15% recycled concrete after tempering for 2 hours at 400°C.

4. Conclusions and recommendations

The most prominent physical feature of RAC that determines its behaviour just before it is subjected to high temperature is its porosity and density. This attribute has been seen to be due to mortar and cement pastes adhering to the aggregates. The density reduces with the increase in the percentage of recycled aggregate in concrete, while there is an increase in porosity with the increase in the recycled aggregates.

On heating the concrete samples, no noticeable changes took place until temperature was considerably above 100°C. There was an initial drop in strength from 100°C to 200°C which is suspected to be due to the relative weak interfacial bond between the RCA and hardened paste within the concrete matrix; a gradual increase in strength continued from 200°C to 450°C and steady drop occurred again after that up to 600°C. Also, with temperatures higher than 400°C the cubes showed further loss in weight and increased visibility and higher density of cracks.

Beyond 600°C, deterioration was relatively more severe and the mechanical properties of concrete (such as compressive strength) were largely affected by the temperature. In the case of a real fire, where temperatures may exceed 1000°C, the residual compressive strength values were feeble for the 2 hour exposure time with all mixes of recycled aggregate concrete; concrete structures need special attention in the repairing case if not totally demolished. For applications of concrete in places where temperatures shall not exceed 400°C concrete with the recycled aggregate with up to about 25% RCA content, in a mix proportion of 1:1.7:2.5 by weight and water-cement ratio of 0.50, can be recommended for use. It is recommended that further research should be conducted to find out the influence of longer durations of exposure such as 8 hours with various RCA content at lower temperature ranges (less than 400°C), which are more likely to be encountered in conditions like bakeries and large ovens. Further, cyclic heating and cooling of concrete made from various RCA content at lower temperature ranges less than 400°C could also be considered.

5. References

- [1] Fady M A 2002 *Using of Recycled Aggregate in producing Concrete Elements – A Thesis submitted in partial fulfillment of the requirement of Masters of Science in Civil Engineering-Design and rehabilitation of structures* (The Islamic University Gaza) p 1-5
- [2] Katz A 2002 Properties of concrete made with recycled aggregate from partially hydrated old concrete *Cement and Concrete Research* **33** (5) 703 – 711
- [3] Salau M A, Ikpowonsa E E and Olonode K A 2013 Effect of elevated temperature on Cassava peel ash concrete *American J. of Science* **3** (5) 142–148
- [4] Salau M A and Oseafiana O J 2015 Effects of Temperature on the pozzolanic characteristics of metakaolin-concrete *Physical Science Int. J.* 1–13
- [5] Maya T M, Nivin Philip and Job Thomas 2015 Review on Concrete Subjected to Elevated Temperature *Int. J. of Engin., Business and Enterprise Applications* 9163–69
- [6] Tam V W Y and Tam C M 2006 Crushed aggregate production from centralized combined and individual waste sources in Hong Kong *Construction and Building Materials* **21** 1–8
- [7] Matsushita H H, Tsuruta and Takao Chikada 2000 Experimental Studies on Compressive Strength and Drying Shrinkage of Recycled Aggregate Concrete *Int. Seminar on Recycled Concrete* Sponsored by Niigata University and Japan Concrete Institute, JCI69–78