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Shrinkage Deformation of Concrete Containing Recycled Coarse Aggregate

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Authors' contributions

This work was carried out in collaboration between all authors. Author MAS designed the experiment, provided the protocol of study and supervised the laboratory works. Author MAS also gave guidelines for drafting of the manuscript. Authors EEI and AOA managed the experiment and analysis of results of the study and writing of the manuscript. Author AOA carried out literature search on the study while author MAS and EEI managed all reviewers' comments and queries. All authors read and approved the final manuscript.

Original Research Article

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ABSTRACT

The long term properties of Concrete containing Recycled Coarse Aggregates (CRCA) were investigated. Initially, series of short term tests were carried out to determine the density, workability, absorption and compressive strength of concrete with and without locally available recycled aggregates from demolition wastes. The water cement ratio of 0.52 was adopted for all the mixes, while the coarse aggregate in concrete was replaced with 0%, 25%, 50% and 100% recycled coarse aggregates.
The test results indicated that the replacement of normal coarse aggregates by recycled aggregates up to 25% had no significant effect on the compressive strength but higher levels of replacement reduced the compressive strength. A replacement level of 100% caused a reduction of about 27% in compressive strength.
The shrinkage deformation characteristics of concrete made with 25% recycled coarse aggregate were compared with those of normal concrete. Eight 10cm x 10cm x 40cm concrete sealed and unsealed short columns made with and without RCA, were under investigation for 120 days. The results of the investigation showed that the basic shrinkage strains of normal concrete is about 1.07 times greater than that of CRCA (with

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25% RCA). The drying and total shrinkage strains of CRCA (with 25% RCA) are respectively 2.56 and 1.26 times greater than that of normal concrete. 25% RCA content in concrete was therefore considered for use in load bearing structural elements.

Keywords: Recycled coarse aggregate concrete; shrinkage deformations; compressive strength; temperature and humidity.

1. INTRODUCTION

Concrete recycling gains importance because it protects natural resources and eliminates the need for disposal by using the readily available used concrete as an aggregate source for new concrete or other applications. The scale of the problem in the production of normal concrete makes it prudent to investigate other sources of raw materials in order to reduce the consumption of energy and available natural resources and to achieve a more 'green' process, free of environmental degradation.

After removal of contaminants through selective demolition, screening and/or air separation and size reduction in a crusher to aggregate sizes, crushed concrete may be used as new aggregate in concrete for pavements, shoulders, median barriers, sidewalks, curbs and gutters and bridge foundations; structural grade concrete; soil-cement pavement bases; lean-concrete and bituminous concrete, Tam et al. [1]

Etxeberria et al. [2] investigated four different mix designs made with 0%, 25%, 50% and 100% recycled coarse aggregate obtained from crushed concrete and concluded that the way of preparing recycled aggregate for concrete mixtures influences the concrete workability. Their results showed that bulk density of fresh concrete is slightly decreased with increasing quantity of recycled aggregate. They opined that the type of coarse aggregate has no influence on the air content in concrete while the concrete compressive strength mainly depends on the quality of recycled aggregate.

Gómez Soberón [3] opined that concrete with more than 50% of recycled coarse aggregate has significantly more shrinkage compared to concrete with natural aggregate. He attributed the increased shrinkage to be as a result of the attached mortar and cement paste in the recycled aggregate grains and also concluded that the bond between recycled aggregate concrete and reinforcement is not significantly influenced by recycled concrete aggregate, because it is realized through new cement paste. His results show that for a fixed mix proportion, there is a considerable variation in the shrinkage strain of the resulting concrete batched with coarse aggregate of different types. He observed that the phenomenon is due very likely to the difference in modulus of elasticity among aggregate of different types.

Aggregate size and shape may also affect the shrinkage of hardened concrete. Rizvi et al. [4] indicated that the total length and the depth of micro cracking caused by shrinkage of concrete will increase with larger aggregate size.

Malešev et al. [5] in their research concluded that the coarse aggregate type didn't influence the concrete compressive strength value.

In their work, Berry et al. [6] tested pervious concrete specimens with 0, 10, 20,30, 50 and 100% RCA replacement. Their results showed that the density of the recycled concrete aggregate is lower than the density of natural aggregate. Also, mix designs with 0 to 50%

RCA replacement were found to have densities within the same general range; however, concrete made with 100% RCA replacement resulted in decreased density.

Parekh and Modhera [7], in their work, reported that the workability of fresh concrete decreases with increase in incorporation of recycled aggregates. There is also no effect traceable to known or unknown source of aggregate. Water absorption of RCA was 5 to 9 times higher and specific gravity of RCA is 15% to 20% lower than the NCA. Furthermore, RCA had 9 to 11% lower density. They observed a significant reduction in slump of the RCA concrete mixtures in comparison to the natural aggregate concrete mixtures. The RCA used was pre-soaked as this was expected to reduce the slump loss due to coarse aggregate absorption of mixing water during batching. They therefore concluded that the reduced slump values in the RCA concrete mixtures can be attributed to the more angular shape and roughened surface texture of the recycled aggregates that increased the inter-particle friction in the fresh concrete.

Rao et al. [8] opined that strength and modulus of elasticity values tend to be smaller for concrete containing RCA than for natural aggregate concrete. This is attributed to a lower modulus of elasticity of the recycled concrete aggregates themselves.

With respect to drying shrinkage of CRCA only, the results obtained from the past works may be summarized as follows:

(i) The increase in drying shrinkage of CRCA is imputable to the old mortar adhering to the natural aggregate and also due to the content, interconnection and distribution of pore size, Katz [9].
(ii) The values of drying shrinkage may range from 20% to 70% more than the reference concrete, and when 100% of the aggregate is replaced, this increase may exceed 70%, even reaching values of up to 263%, Matsushita et al. [10].
(iii) Attenuation of the increases in drying shrinkage of CRCA may be feasible through suitable use of shrinkage-reduction agents, Yamato et al. [11].

So far much work has been done on the properties of deformation of concrete made with recycled coarse aggregate on the short term. Therefore, the main purpose of this paper is to investigate the shrinkage of concrete made with recycled coarse aggregate on the long term and thus, to provide further information on the current application requirements.

2. EXPERIMENTAL PROCEDURE

All concrete mixes used are made from of Ordinary Portland Cement, natural coarse aggregate (crushed granite), recycled coarse aggregate (RCA), natural fine aggregate (river sand) and water. Ordinary Portland Cement (OPC) was determined to have a bulk specific gravity of 3.05**.** Maximum size of coarse and fine aggregates was 20mm and 4.75mm respectively. The RCA was obtained from rubbles of demolished buildings. The parent concrete was broken up with diesel crusher hammer into aggregates sizes not greater than 20mm. The notable physical characteristics of these RCA include

* Coarse normal aggregate with little or no mortar adhered to surface.
* Coarse aggregate with small to thick layers (3-6mm) of mortar adhered to surface in one or more spots,
* Coarse natural aggregate with a lump of mortar on one side and
* Particles made entirely of mortar.

The RCA was washed and dried before being used in the CRCA. This was done in order to remove impurities and contaminants. The RCA was neither soaked in water nor pre-wetted for use. The percentage of natural aggregate by weight of the total coarse aggregates was varied in steps of 25% from 0% (corresponding to normal concrete) up to a maximum of 100%. The concrete mix adopted was 1:1.7:2.5 with w/c ratio of 0.52 by weight as recommended by Gómez Soberón [3]. In all, forty-eight cubes of concrete (150x150x150mm) were cured and tested for physical and short term strength properties.

Twelve short columns (100x100x400mm) of the same w/c ratio and mix proportion were tested; six samples corresponding to the same aggregate content of either 0% RCA content (normal concrete) or 25% RCA content.

The concrete cylinders were demoulded after 24hrs and three concrete cylinders from each of the concrete mix were sealed by treating with a layer of paraffin wax (3mm thick layer) to prevent seepage of water from the specimen environment while the other set was left uncovered.

The concrete cylinders (twelve of them) were set on measuring rigs for the shrinkage measurement after 48hrs of casting. The measuring rigs were designed and constructed to consist of a simple steel frame with an adjustable height beam to hold the measuring gauge and a base plate on which the concrete specimen is placed. The arrangement of the adjustable height beam with the measuring gauge is then placed centrally on the concrete specimen as shown in Fig. 1. The measuring gauge is calibrated to read to the nearest 0.01mm. Measurements were taken every day in the first three weeks and then three times a week up to 120 days.

Fig. 1. Loading and measuring frame for shrinkage test

Humidity and temperature conditions in the laboratory could not be controlled; therefore, measurements of temperature and relative humidity were taken where the specimens were stored during the test using a hydrometer. The hydrometer measurements were observed whenever shrinkage strain measurements were taken.

3. RESULTS AND DISCUSSIONS

3.1 Particle Size Distribution of the Recycled Coarse Aggregate and the Natural Aggregate.

After the crushing of the parent concrete, the particles were sieved through the 25mm sieve size and any particle retained on the sieve was discarded. The resulting aggregate particles were again passed through the 4.75mm sieve size and any particle passing was also discarded. Thereafter, the particle size distribution was done using sieve analysis. Fig. 2 shows the graph of the particle size distribution of the recycled coarse aggregate and the natural aggregate.

From the obtained result, most of the natural coarse aggregate and recycled coarse aggregate passed through 25mm sieve size but less than 1% of the natural coarse aggregate passed through 4.75mm sieve size and about 2% of the recycled coarse aggregate passed the 4.75mm sieve size.

The results show that both the recycled coarse aggregate and the natural coarse aggregate are well graded. They can hardly be differentiated in terms of the particle size distribution.

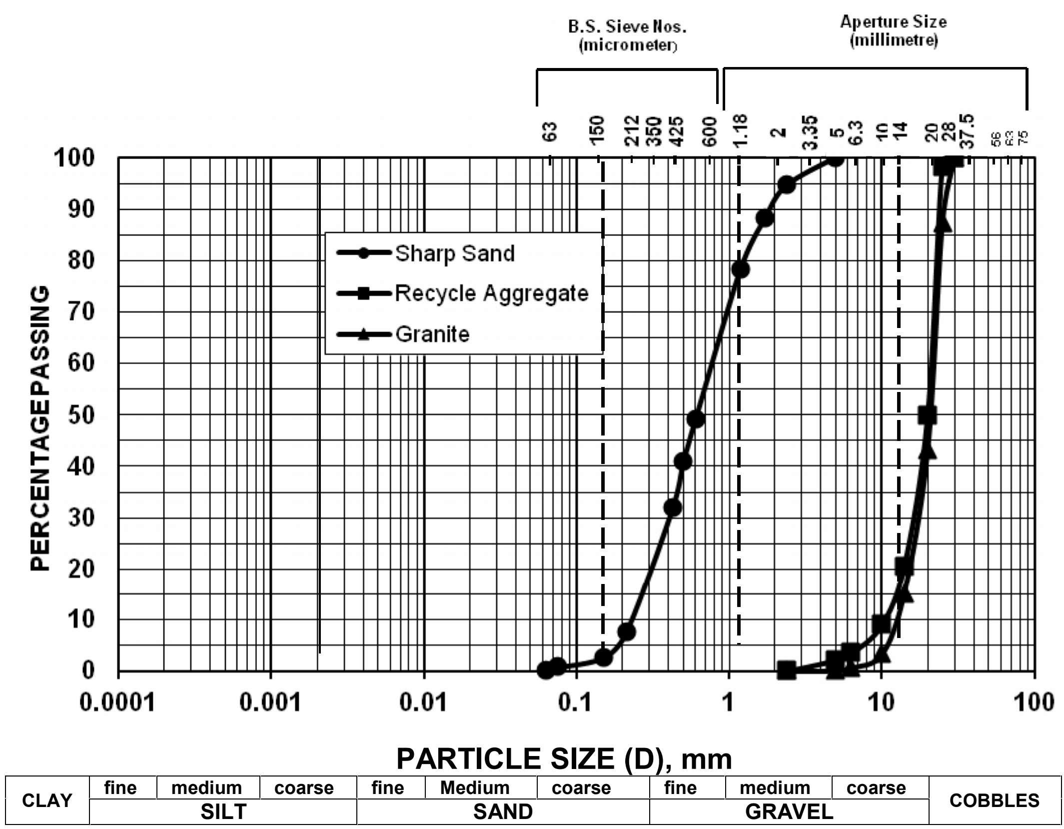

Fig. 2. Particle size distribution of the fine and coarse aggregates

3.2 Density and Water Absorption of Coarse Aggregates

The results of density of the recycled coarse aggregate in Table 1 showed that it is lower than that of natural coarse aggregate. The average particle density of the natural coarse aggregate is 2895 kg/m^3 and 2935 kg/m^3 for dry condition and saturated surface dry condition respectively while the average particle density of recycled aggregate is only 2311 kg/m^3 and 2446 kg/m^3 for dry condition and saturated surface dry condition respectively.

Table 1. Results of density and water absorption of all coarse aggregates

Types and size of aggregate	Dry density, kg/m^3	Saturated surface dry density, (SSD), kg/m^3	Water absorption, (%)
25mm natural aggregate	2884	2920	1.24
10mm natural aggregate	2894	2933	1.32
6.3mm natural aggregate	2905	2951	1.56
25mm recycled aggregate	2342	2472	5.54
14mm recycled aggregate	2281	2421	6.16

This means recycled coarse aggregate is lighter than natural coarse aggregate; this will not be unconnected with the fact that RCA also consists of low density cement paste. When the particle size of recycle aggregate is increased, the volume percentage of residual mortar increases too; this invariably reduces the specific gravity and the density of the aggregate particles.

The obtained average water absorption rates of recycled and natural coarse aggregate are 5.85% and 1.40% respectively. This shows that water absorption of recycled coarse aggregate is more than 4 times of natural coarse aggregate. This result shows that more water is needed when using 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 Shayan et al. [12]. They reported that the total water absorption of concrete made with recycled aggregate was about 6.9-7.6%, greater than absorption of the reference concrete of about 3.8-3.9%. Definitely, source of recycle aggregate is a major factor on its absorption capacity.

3.3 Workability of Recycled Coarse Aggregate Concrete

Workability is the ease at which concrete can be worked in terms of batching, mixing, transporting and placing it. Workability is a very important property of fresh concrete; in that it determines the quality of the concrete produced. Slump test is used to determine how workable a concrete is. The results of the slump tests carried out on the recycled coarse aggregate concrete are shown on Table 2.

Table 2. Slump test result with w/c = 0.52, mix ratio = 1:1.7:2.5

Percent RCA (w/c = 0.52)	Slump height (mm)	Comments
0%	90	True slump (wet mix)
25%	82	True slump (wet mix)
50%	72	True slump (stiff)
100%	68	True slump (quite stiff)

The height of the slump reduces with increase in percentage of recycled coarse aggregate; the highest slump obtained was 90mm for normal aggregate concrete and the lowest slump was 68mm for 100% RCA concrete. Therefore, target slump had been achieved; where the range is from 50mm to 120mm (BS 1881 Part 208) [13]. The workability was good and can be satisfactorily handled for 0% recycled aggregate to 50% recycled aggregate. The slump of 100% RCA was 68mm, this mix was not as workable as the others but it still falls within the target slump range. Workability decreases with increasing percent replacement of natural coarse aggregate with RCA. This is due to the rate of absorption of water by the recycled coarse aggregate, because of the mortar that adhered to the RCA. This means that concrete made with RCA is less workable than conventional concrete if the same water-cement ratio is applied.

In addition to this, many authors have noted that the presence of adhered mortar on the surface of recycled aggregates leads to a significant increase in water absorption [14-16] and therefore reduces the amount of water available to hydrate the cement. This has given way to a number of methods to correct this effect; these are: working with dry aggregates while increasing the amount of water incorporated into the mixer [17] or pre-wetting or pre-soaking the aggregates before using them [18-24].

In this work, the pre-washed and dried RCA was not pre-wetted before use in making concrete. This was done deliberately in order to measure the effect that absorption rate of RCA can have on concrete quality; both in the fresh and hard state. Comparing the results from previous research (Parekh and Modhera [7]), there has not been a large difference in absorption rate of RCA and workability of concrete containing RCA for RCA that was soaked before use and RCA that was used dryly. Also, from previous research, pre-wetting of RCA has not been found to be the major cause of reduction in workability of concrete containing RCA, Parekh and Modhera [7].

It can therefore be concluded that the reduced slump values in the RCA concrete mixtures can be attributed to the more angular shape and roughened surface texture of the recycled aggregates that increased the inter-particle friction in the fresh concrete, Poon [25]. The shape and texture of aggregates also play a role in the workability of concrete. A higher water-cement ratio will be needed for the same normal concrete mix ratio, if recycled coarse aggregate is used.

3.4 Density and Compressive Strength of Concrete with Recycled Aggregate

Table 3 shows the density and compressive strength of concrete with recycled coarse aggregate.

It was observed that the density of the concrete cubes for all the mix proportions (i.e 0%, 25%, 50% and 100% RCA replacement) increased as the curing period increased. At the 28^{th} day, the normal concrete has the highest density value and the density reduced as the percentage replacement of RCA increased.

Compressive strength-time curve with varying percentage of recycled coarse aggregate is shown in Fig. 3. The compressive strength of all the mix proportions increased as the curing period increased. The compressive strength value decreases as the percentage replacement of RCA increases. The 100% RCA has the lowest compressive strength value of 16.4N/mm^2 at the 28th day. CRCA is weak in its early stages but can rapidly gain strength with hydration of the old mortar, Yang et al. [26]. Strength of CRCA concrete is governed by the weaker interface between natural aggregate and adhered mortar and between the adhered mortar and the new mortar. Less adhered mortar on recycled aggregates improves the strength of the concrete because the old mortar of the recycled aggregates is lower in strength than that of the new mortar.

Table 3. Density and compressive strength test results

% RCA content	Age of concrete cubes (days)	Average Mass (kg)	Average density (Kg/m^3)	Average cube strength (N/mm^2)
0	7	7.97	2361	15.1
	14	8.08	2394	18.8
	21	8.12	2405	21.5
	28	8.24	2441	22.4
25	7	7.79	2308	14.7
	14	7.88	2334	16.9
	21	8.01	2373	18.2
	28	8.07	2391	21.4
50	7	7.48	2216	15.3
	14	7.50	2222	16.0
	21	7.55	2237	17.8
	28	7.62	2258	19.8
100	7	7.20	2133	14.0
	14	7.32	2169	14.6
	21	7.35	2178	15.8
	28	7.37	2184	16.4

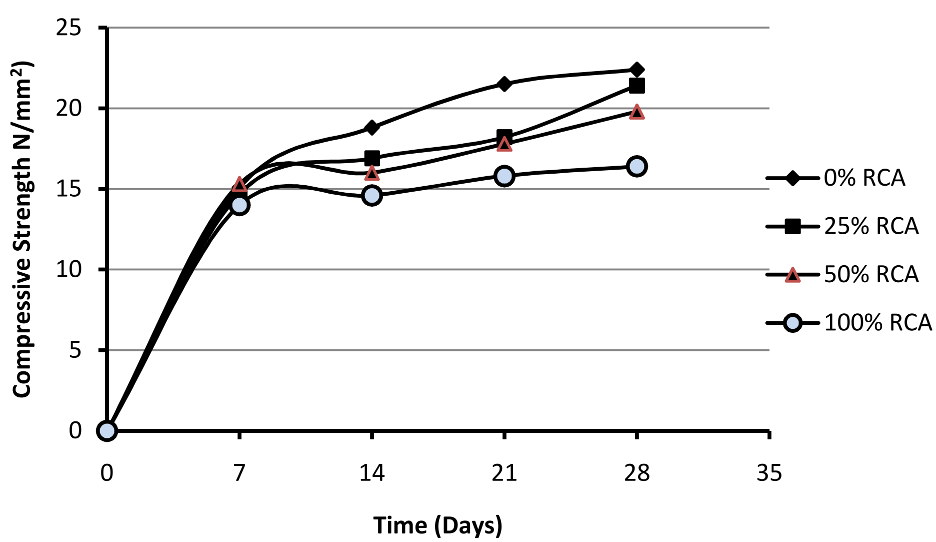

Fig. 3. Compressive strength-time characteristics of concrete with different % of RCA

The compressive strengths of all concrete made with RCA are less than that of the control concretes but the compressive strength of the 25% RCA concrete compare favorably with that of the control concrete of 22.4 kN/m^2. Reduction in 28-day compressive strengths for RAC compared to natural aggregate concrete was 5%, 12% and 27% for 25%, 50% and 100% RCA replacement in concrete respectively. The variation in percentage decrease depends on the percentage of replacement of natural coarse aggregate with RCA but not proportional.

3.5 Effect of Temperature and Humidity

The temperature during the experiment varied between 27ºC and 32ºC while the humidity varied between 85% and 96%. The variation of the temperature values was due to the raining season. Fig. 4 shows the variation of temperature and humidity with time.

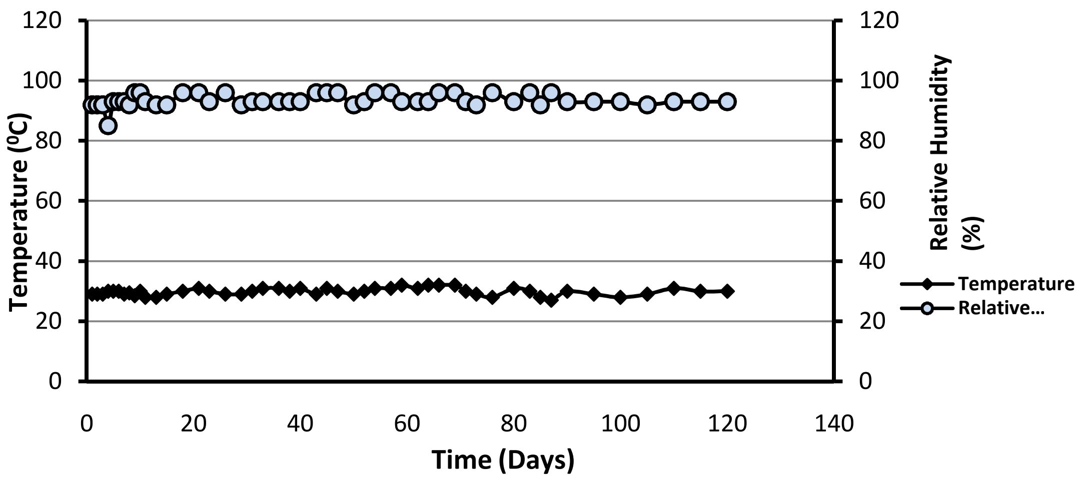

Fig. 4. Change of temperature and relative humidity with time during the experiment

3.6 Shrinkage Deformation Results

The results of the shrinkage deformation with time of normal and concrete containing recycled aggregate (25% RCA) are as shown in Table 4. From the results, the unsealed concrete prisms, irrespective of RCA content, showed higher deformation than the sealed concrete prisms. This could have happened as a result of internal drying (moisture loss due to hydration) as well as external drying (effect of temperature and humidity) while the specimen under the sealed condition shrunk only because of internal drying. Both natural and recycled coarse aggregates display similar rates of shrinkage development, mostly at the early age. However, with age, the shrinkage deformation is higher in the recycled coarse aggregate concrete.

3.6.1 Basic shrinkage deformation

Basic shrinkage is a measure of the strain on a concrete specimen in which moisture loss from the capillary of the concrete is caused by internal drying only. In other words, basic shrinkage occurs as the hydration process in the concrete uses up the moisture content in the concrete. Basic shrinkage is therefore, the shrinkage deformation of a concrete that has been shielded from external factors (such as temperature and relative humidity) that may affect and aid shrinkage deformation in the concrete. The shield of concrete from this external factors is achieved by covering the concrete surface (except the topmost face where the measuring gauge is applied) with paraffin wax and foil paper to extinguish the effect of temperature and humidity on the specimen.

Table 4. Basic, total and drying shrinkage deformation of normal and recycled aggregate concrete

Time after loading (Days)	Normal concrete			25% RCA concrete		
	Basic shrinkage (mm/m)	Drying shrinkage (mm/m)	Total shrinkage (mm/m)	Basic shrinkage (mm/m)	Drying shrinkage (mm/m)	Total shrinkage (mm/m)
1	0.0075	0.0050	0.0125	0.0000	0.0125	0.0125
2	0.0200	0.0000	0.0200	0.0075	0.0050	0.0125
3	0.0300	0.0150	0.0450	0.0375	0.0200	0.0575
4	0.0525	0.0175	0.0700	0.0575	0.0375	0.0950
5	0.1075	0.0000	0.1075	0.0625	0.0625	0.1250
6	0.1200	0.0050	0.1250	0.0750	0.0750	0.1500
7	0.1450	0.0000	0.1450	0.0875	0.0875	0.1750
8	0.1575	0.0000	0.1575	0.0950	0.1050	0.2000
9	0.1700	0.0250	0.1950	0.1075	0.1175	0.2250
10	0.1825	0.0300	0.2125	0.1075	0.1300	0.2375
11	0.2000	0.0375	0.2375	0.1200	0.1425	0.2625
13	0.2075	0.0500	0.2575	0.1375	0.1625	0.3000
15	0.2450	0.0250	0.2700	0.1450	0.1750	0.3200
18	0.2855	0.0270	0.3125	0.1750	0.2000	0.3750
21	0.3075	0.0300	0.3375	0.1950	0.2125	0.4075
23	0.3325	0.0175	0.3500	0.2075	0.2250	0.4325
26	0.3500	0.0200	0.3700	0.2200	0.2375	0.4575
29	0.3625	0.0250	0.3875	0.2500	0.2250	0.4750
31	0.3825	0.0175	0.4000	0.2625	0.2250	0.4875
33	0.4000	0.0125	0.4125	0.2825	0.2175	0.5000
36	0.4000	0.0450	0.4450	0.3125	0.2200	0.5325
38	0.4000	0.0500	0.4500	0.3375	0.2075	0.5450
40	0.4125	0.0500	0.4625	0.3625	0.1875	0.5500
43	0.4125	0.0575	0.4700	0.3750	0.1875	0.5625
45	0.4250	0.0500	0.4750	0.3750	0.1950	0.5700
47	0.4250	0.0625	0.4875	0.3875	0.1950	0.5825
50	0.4450	0.0625	0.5075	0.4075	0.2000	0.6075
52	0.4500	0.0575	0.5075	0.4075	0.2000	0.6075
54	0.4575	0.0550	0.5125	0.4250	0.1825	0.6075
57	0.4575	0.0550	0.5125	0.4325	0.1750	0.6075
59	0.4625	0.0500	0.5125	0.4325	0.1800	0.6125
62	0.4500	0.0575	0.5075	0.4125	0.2075	0.6200
64	0.4450	0.0625	0.5075	0.3875	0.2325	0.6200
66	0.4125	0.0950	0.5075	0.3825	0.2425	0.6250
71	0.3875	0.1125	0.5000	0.3625	0.2550	0.6325
76	0.3875	0.1000	0.4875	0.3625	0.2750	0.6375
80	0.3750	0.1000	0.4750	0.3575	0.2875	0.6450
85	0.3750	0.1075	0.4825	0.3375	0.2925	0.6375
90	0.3750	0.1000	0.4750	0.3450	0.2925	0.6375
95	0.3700	0.1050	0.4750	0.3450	0.2925	0.6375
100	0.3700	0.1000	0.4700	0.3400	0.2900	0.6300
105	0.3650	0.1050	0.4700	0.3400	0.2900	0.6300
110	0.3650	0.1050	0.4700	0.3350	0.2950	0.6300
115	0.3650	0.1000	0.4650	0.3350	0.2900	0.6250
120	0.3650	0.1000	0.4650	0.3350	0.2900	0.6250

The basic shrinkage of normal concrete is more than the basic shrinkage of concrete containing RCA. The recycled coarse aggregate has a high porosity and specific surface area, together with the possibility of contributing non-hydrated cement particles, which may allow the hydration to be prolonged for more time and thus achieve a better hydration process. Additional restraint is provided by the unhydrated cement grains and the stable micro-crystalline products of hydration.

Both normal and recycled coarse aggregates display similar rates of basic shrinkage development, mostly at the early age. The basic shrinkage of concrete with RCA was less than that of concrete with natural aggregate, though both curves followed quite similar pattern (Fig. 5).

The basic shrinkage curves of both the normal concrete and concrete containing RCA as shown in Fig. 5 rose quite rapidly at the beginning. The basic shrinkage curve for the normal concrete continued to rise until it reached a maximum value of 0.4625mm/m at 59 days. It then started to fall quite steeply until it reached a constant value of 0.3650mm/m at the age of 120 days.

The basic shrinkage curve of the CRCA variable is similar to the normal concrete curve, as shown in Fig. 5. It also rose rapidly at the first 40 days of the test and then continued to rise just gradually for 20 more days before it started to decline quite rapidly at first and then gradually in the last 40 days of the test.

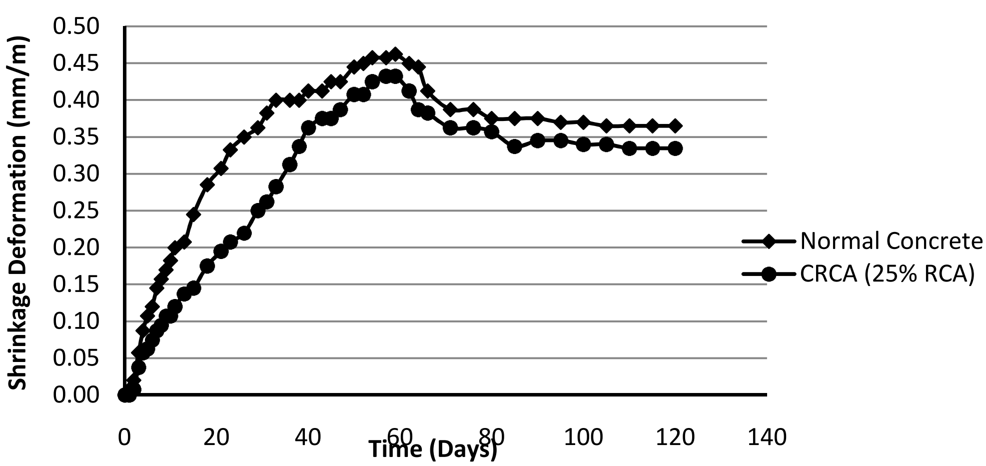

Fig. 5. Basic shrinkage of normal concrete and CRCA (25%RCA)

The maximum basic shrinkage of normal concrete is 0.4625mm/m at 59days while the maximum basic shrinkage for 25% CRCA is 0.4325mm/m at 57 days. The basic shrinkage of normal concrete is 1.07 times more than the basic shrinkage of CRCA (with 25% replacement). The stability of the basic shrinkage deformation is around the same age for normal concrete and 25% CRCA.

3.6.2 Total shrinkage deformation

Total shrinkage is the shrinkage deformation of a concrete subjected to all factors that may cause shrinkage. These factors may be categorized into internal factors, such as moisture loss due to hydration and external factors such as temperature and humidity. In order to measure total shrinkage, the concrete prisms are left unshielded, to be affected by only real climatic conditions.

The total drying shrinkage of normal and CRCA (with 25% RCA) is shown in Fig. 6. The total shrinkage of concrete with RCA was more than that of concrete with natural aggregate but both curves, shown in Fig. 6 have similar patterns.

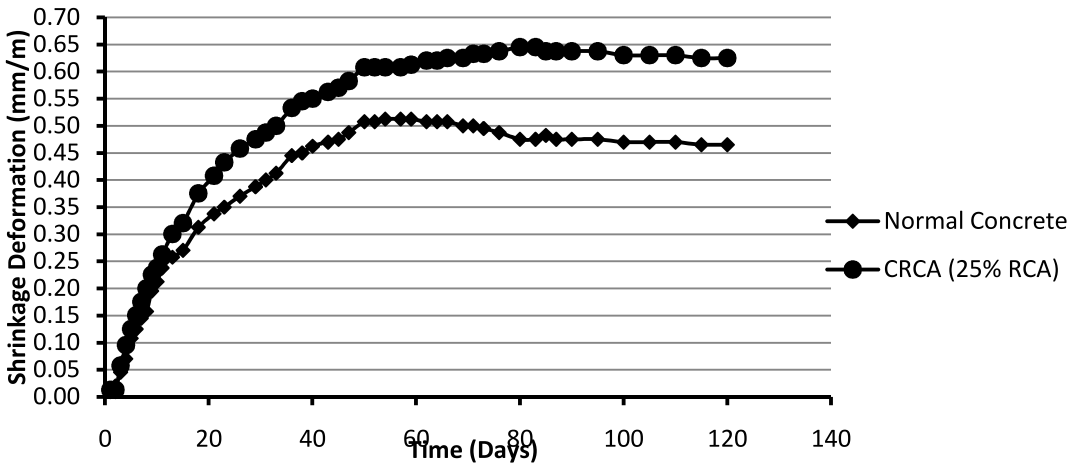

Fig. 6. Total shrinkage of normal concrete and CRCA (25% RCA)

With respect to the normal concrete variable, the total shrinkage curve rises rapidly at the beginning. It continues to rise very steeply until it reaches a final total shrinkage value of only 0.5125 mm/m at 51days before it started to decline. Considering the concrete containing recycled aggregate variable, the total shrinkage curve rises rapidly at the beginning and then continued to rise gradually to a maximum value of 0.6450mm/m at 80days before it declined a little. Therefore, the total shrinkage of CRCA (with 25% replacement) is 1.26 times more than that of normal concrete while the normal concrete attained maximum shrinkage value 29days before the CRCA.

The increased shrinkage obtained in the concrete containing RCA can be attributed to the compressibility or stiffness of the coarse aggregate which directly influences the shrinkage of the concrete. Stiffer coarse aggregates better restrain shrinkage, Ajdukiewicz [27]. The RCA with its attached mortar content are not as stiff as the natural aggregates and can therefore provide less restrain to shrinkage than the natural aggregate. Bisschop [28] supports these findings that coarse aggregates of higher quality (larger elastic modulus) will better restrain shrinkage of the mortar and the concrete specimen as a whole compared to aggregates with low modulus of elasticity. The quality of the aggregates ultimately determines the concrete specimen's potential for strength and resistance to shrinkage. It was noted that the RCA itself shrinks, depending on how much mortar is attached to it before it was used and the elastic modulus of the RCA. The amount by which the RCA shrinks affects the shrinkage deformation of its concrete.

The purity of the employed RCA should be taken into account as a factor for the increase in shrinkage reported in the concrete containing RCA. The type and amount of contaminants that might be present in these aggregates have been reported by Padmini et al. [29] as one of the causes for the differences in the shrinkage behavior of the concrete containing RCA. In order to reduce the effect of contaminants in the RCA, it was washed and dried before being used in the CRCA.

3.6.3 Drying shrinkage deformation

Drying shrinkage is defined as the difference between the length of a prism of matured concrete after immersion in water and its length after subsequent drying, under specified conditions. Just as the hydration of cement is an everlasting process, the drying shrinkage is also an everlasting process when concrete is subjected to drying conditions. Drying shrinkage was measured by finding the difference between the total shrinkage and the basic shrinkage of the concrete prisms.

Drying shrinkage occurs mostly because of the reduction of capillary water by evaporation and the water in the cement paste. The more amount of water in the fresh concrete, the greater the drying shrinkage effects.

The drying shrinkage curve of the normal concrete variable, as shown in Fig. 7 has an undulating pattern. The drying shrinkage curve of the CRCA, also in Fig. 7, rose gradually for the first 50 days and then assumed an undulating pattern. The maximum drying shrinkage of normal concrete is 0.1200mm/m while that of CRCA is 0.3075mm/m. In other words, the drying shrinkage of CRCA (with 25% replacement) is 2.56 times more than the drying shrinkage of normal concrete.

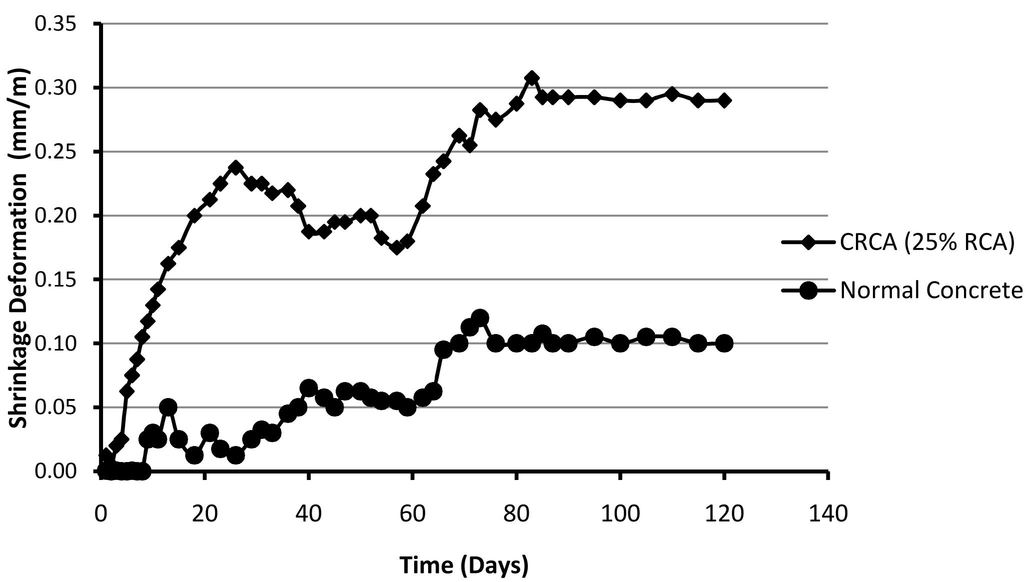

Fig. 7. Drying shrinkage of normal concrete and CRCA (25% RCA)

The drying shrinkage of concrete with RCA was much higher than that of concrete with natural aggregate and the curves do not follow a regular pattern neither are they similar. In general, these curves show that the presence of RCA in concrete leads to increased shrinkage. The increase in drying shrinkage of concrete RCA is imputable to the old mortar adhering to the natural aggregate, and also due to the content, interconnection and distribution of pore size. Thus, the higher volume of porosity in RAC results in a relatively higher free shrinkage rate than normal concrete. The increase in the availability of water and hence the possibility of movement until water balance is attained with the surrounding environment may have caused both the drying shrinkage and its rate to increase in the concrete containing RCA.

The high rate of drying shrinkage in RCAC should have been connected with the fact that the RCA was pre-washed and dried but not pre-wetted. The adhering mortar on the surface of the recycled aggregate which normally contributes to significant absorption of water could have contributed to the high drying shrinkage.

Another factor that may have influenced the shrinkage of concrete is the absorption ability of the aggregate. A higher absorption value indicates a higher percent of aggregate voids filled with water, which may lead to an increase in drying shrinkage. From the results of the properties of the recycled aggregate, the water absorption of the recycled coarse aggregate was about four times more than that of natural aggregate; this therefore must have caused a higher drying shrinkage observed in the concrete containing RCA.

4. CONCLUSIONS AND RECOMMENDATIONS

The water absorption of Recycled Coarse Aggregate (RCA) is more than that of virgin aggregates. Thus, the workability of concrete containing RCA reduces as the RCA content increases. Whenever recycled aggregate is used, water content in the concrete mix has to be monitored carefully because the water absorption capacity of recycled aggregate will always vary. The RCA may therefore not be used for pre-mixed concrete and in the arid environment.

The density of normal concrete was more than that of the corresponding concrete containing RCA irrespective of the age. The percentage reduction in density for 25%, 50% and 100% replacement of RCA was 2%, 7.5% and 11% respectively.

The compressive strength of concrete containing RCA reduces as the RCA content increases owing to factors such as the adhered mortar on the RCA, the low specific gravity of the RCA particles, high water absorption capacity of RCA. However, the compressive strength of the concrete containing 25% RCA compare favorably with that of the normal concrete. Therefore, concrete with RCA with about 25% RCA content in a mix proportion of 1:1.7:2.5 by weight and water-cement ratio of 0.52 could be recommended for use as load bearing structural elements.

Temperature and humidity have been shown to affect shrinkage deformation of concrete in that the total shrinkage of the concrete irrespective of the RCA content was always greater than the basic shrinkage.

Both the normal and the recycled aggregate concretes displayed similar rates of shrinkage development; especially at the early ages. The total shrinkage of concrete containing RCA (with 25% replacement) is 1.26 times more than that of normal concrete. The total shrinkage of concrete containing RCA was affected by factors such as the porosity of the recycled aggregate, and the unhydrated mortar that adhered to the recycled aggregate. The basic shrinkage of normal concrete is 1.07 times more than the basic shrinkage of concrete containing RCA (with 25% replacement). This is attributed to a better hydration process that occurs in concrete containing RCA. The drying shrinkage of concrete containing RCA (with 25% replacement) is 2.56 times more than the drying shrinkage of normal concrete. The increase in the availability of water and hence the possibility of movement until water balance is attained with the surrounding environment caused both the drying shrinkage and its rate to increase in the concrete containing RCA.

The results have shown that concrete with RCA can be used for structural elements in low-cost housing to reduce the acute housing shortage in developing countries and achieve a more ‘green’ process, free of environmental degradation.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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