Evaluation of Recycled Coarse Aggregates in Portland Cement Concrete Pavement

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Abstract
Sustainability of the environment has led to recycling of Portland Cement Concrete (PCC) with emphasis on the use of Recycled Concrete Aggregate (RCA) in rigid pavements and other construction applications. RCA from construction and demolition site in Centurion Pretoria, South Africa was used to evaluate its effect on PCC pavement. Natural Crushed Aggregate (NCA) was replaced with 0, 25, 50 and 75% of RCA in PCC with a targeted strength characteristic of 35 MPa. Compressive strength was determined at 7, 14, 21 and 28 days to be 25.8, 35.5, 39.9 and 43.8 MPa while flexural strength at 7 and 28 days of curing was 4.8 and 5.6 MPa respectively for NCA. RCA for all the proportions considered met the targeted compressive strength though the range of strength loss was 6.83-16.48%. The flexural strength was not affected negatively with the use of RCA.

Keywords: Recycled concrete aggregate; Portland cement concrete; pavement; compressive strength; natural crushed aggregate; flexural strength

Introduction
Interest in Portland Cement Concrete (PCC) recycling has increased steadily over the years with widespread use of Recycled Concrete Aggregate (RCA) in rigid pavement surfaces and many other construction applications (Fahtul *et al*. 2006; Hironaka *et al*. 1987; Salas *et al*. 2009a). Considering the fact that fine and coarse aggregate occupy about 75 to 80% (Ahmed, 2012), of the total concrete volume in rigid pavement, the partial replacement within recycled aggregate can be employed to reduce the cost of pavement construction (Maier and Durham, 2012) and this sustainable practice will assist in saving large areas of landfill space and provides potential cost savings to government or client. The future success of recycled PCC in rigid pavements depends on better characterization of the properties of recycled concrete aggregate and their influences on a PCC mixture for suitable paving applications. If RCAs are to be use in PCC pavements with the same confidence as that associated with the use of natural aggregates, research must identify the material and pavement design factors that have resulted in both good and unacceptable performance. RCA is typically regarded as a double phase material which consists of the original virgin aggregate and the adhered residual mortar (Tam *et al*. 2005; Tam *et al*. 2006). The RCA-made concrete will have more constituents: the new mortar and the new virgin coarse aggregates.

Two types of interfacial transition zones (ITZs) in RCA-made concrete mixtures have been identified: the old ITZ between the original virgin coarse aggregate and the adhered mortar and the other between the new mortar and the RCA. Due to high amounts of adhered mortar content in recycled aggregates, RCA can have higher water absorption, lower specific gravity, and higher porosity compared to natural aggregate (Kou *et al*., 2012). Due to high amounts of adhered mortar existing in RCA particles, the density of RCA is usually lower than that of virgin aggregates which in turn decreases the unit weight of concrete containing RCA (Tam *et al*., 2006; Xiao *et al*., 2012). Domingo-Cabo *et al* (2009) reported that a greater presence of recycled aggregates decreases the workability of the concrete, which may be related to the shape, texture and absorption characteristics of the recycled aggregate.

The use of RCA can lead to significant effect on compressive strength of concrete due to the inferior properties of the residual mortar phase of the RCA particles. However, this effect can be negligible for replacement levels up to 30% (Smith, 2009; Tam *et al*., 2006). Volz *et al* (2014) observed that there is no significant difference in compressive strength of the specimens made with up to 100%

replacement of coarse recycled aggregate with reference concrete. The RCA was produced from crushing concrete made with w/c=0.4, and the studied RCA-made concrete was proportioned with w/c=0.45. As in the case of compressive strength, RCA replacement mostly results in a decrease in splitting tensile strength of concrete. Ravindrarajah & Tam (1985) reported that the splitting tensile strength of concrete made was consistently 10% lower than that of conventional concrete without RCA. Tabsh and Abdelfatah (2009) reported that about 25% to 30% drop in the tensile strength was observed in concrete made RCA.

Kou *et al*. (2012) observed that regardless of the type of the recycled aggregate used, the splitting tensile strength of the specimens decreased with an increase in RCA replacement ratio before the age of 28 days. However, for some types of the RCAs used, an increase in the splitting tensile strength at the age of 90 days is observed. Sagoe *et al*. (2001), reported that there is no significant difference between the splitting tensile strength of the reference and the recycled aggregate concrete specimens. Limbachiya *et al*. (2012) and Yong and Teo (2009) reported that while replacing up to 50% of coarse aggregate with RCA, there was no difference in splitting tensile and flexural strengths between the RCA and the reference, but at complete replacement results were improved for RCA due to better interlocking. The RCA replacement does not have significant negative effects on flexural strength of concrete. Xiao and Li (2005), Hu (2007), and Cheng (2005) reported that up to 100% RCA replacement at concrete mixtures of w/c varying from 0.43 to 0.57 only has marginal effects on flexural strength of concrete. Ravindrarajah and Tam (1985) also reported that increasing the RCA content does not have a significant effect on flexural strength. Absorption of water by RCA concrete is usually reported to be higher than that of virgin aggregate concrete which is mainly due to the attached porous mortar content of the RCA particles that can provide more water reservoirs, thus maintaining higher relative humidity inside the pore solution (Volz *et al*., 2014). Salas *et al*. (2010) used up to 100% RCA for producing concrete for rigid pavement applications as part of O'Hare Airports modernization project using the two stage mixing approach developed by Tam *et al*. (2005).

Choi and Won (2009) studied the performance of a continuously reinforced concrete pavement highway section made totally with fine and coarse RCA located in Houston, Texas. Based on the results by testing core samples, it was observed that the average compressive strength decreased due to use of RCA. The modulus of elasticity of the RCA concrete was lower than that of the virgin aggregate mixture. It is interesting to note that the coefficient of thermal expansion of the RCA concrete was similar to the virgin aggregate mixtures. Higher chloride ion concentrations were observed in the case of in the case of the RCA mixtures. The quality of recycled concrete aggregate will vary depending on the properties of the recovered concrete. It is therefore necessary to evaluate the properties of recycled aggregates and its strength in pavement construction for cost and material saving.

MATERIALS AND EXPERIMENTAL DETAILS

NCA is a crushed dolerite stone while RCA (plate 1) was obtained from construction and demolition of old mall site in Centurion, Pretoria, Gauteng South Africa. The building had undergone a crushing process where the required nominal size of 19 mm were stockpile. Sampling and tests were run on both NCA and RCA to determine specific gravity, water absorption, compacted bulk density, loose bulk density, flakiness, aggregate impact value, aggregate crushing value as well as the sieve analysis in accordance with relevant South African standards (TMH 1; SANS 201; SANS 5841; SANS 5842; SANS 5847). The results are presented in Tables 1-3, specific gravity and water absorption of 2.68, 0.5% and 2.69, 2.1% were obtained for natural and RCA respectively while fineness modulus of 1.7 and specific gravity of 2.63 was obtained for natural river sand.

The mix design of the concrete was done according to SANS 863 method with targeted strength characteristic of 35 MPa with strength margin of 8.5 MPa at 28 days and slump of 85 mm. Commercial Portland cement-limestone blended type CEM II/ B-L 42.5 N (SANS 50197) and average amount of water (210 l/m^3) were selected based on the size of aggregate. The target strength characteristic and type of cement was used to established water-cement (w/c) ratio. Constant w/c ratio was used for both NCA and RCA mixes. The mixture compositions of all mixes are presented in Table 4. Four types of mixture were prepared by replacing the natural crushed coarse aggregate with RCA at 0, 25, 50, and 75% of the total coarse aggregate content in the production of RCA-made concrete. The percentage of replacement was to identify the influences of the RCA in the concrete strength and the calculation was based on the total weight of the coarse aggregate content.

Plate 1 Appearance of NCA and RCA

Table 1: Physical properties of natural and recycled coarse aggregates

	LBD	CBD	ACV	AIV	10% FACT	Water absorption	Dry bulk density	Apparent bulk density	Flakiness
NCA	1345	1453.5	14	19.7	289	0.5	2.592	2.692	29.5
RCA	1190	1340	20	23.7	160	3.9	2.611	2.713	35.3
Sand	1233.5	1320	-	-	-	2.1	2.530	2.672	-

Table 2: Sieve analysis for fine aggregates

Sieve size, mm	Sand	Specification
4.75	100	90-100
2.36	100	
1.18	98	
0.600	91	
0.425	84	
0.300	35	
0.150	7	5-25
0.075	1.0	0-10

Table 3: Sieve analysis for recycled coarse aggregates

Sieve size, mm	Natural crushed aggregate	Recycled concrete aggregate	Specification
26.5	100	100	100-100

19.0	93	87	85-100
13.2	25	19	0-50
9.5	5	3	0-25
6.7	1	1	0-5
4.75			

Table 4: Concrete mix proportions

	0	25%	50%	75%
Cement (kg/m^3)	330	330	330	330
Fine aggregate (kg/m^3)	668	668	668	668
NCA (kg/m^3)	1120	840	560	280
RCA (kg/m^3)	0	280	560	840
Water (kg/m^3)	210	210	210	210
w/c	0.64	0.64	0.64	0.64

All concrete mixtures were prepared and produced in the laboratory and referenced as NCA, RCA-25, RAC-50 and RCA-75%. All the samples were cast in steel moulds, kept in wet conditions for a day in the moulds before demoulding at a temperature of 23^0 C (Figure 1). Cube samples of 150 x 150 x 150 mm size for each mixture and three cubes from the same sample of concrete were water cured until the day before the test date. The cubes were used to measure average compressive strength while 100 x 100 x 500 mm prism was used to test for flexural strength. Development of the compressive strength was monitored by testing the cubes at 7, 14, 21 and 28 days and flexural strength test was monitored for 7 and 28 days.

Figure 1 Batching, Mixing and cast concrete

RESULTS AND DISCUSSION

Table 1 show that both the loose and compacted bulk density as well as the absorption capacity of NCA were higher than RCA. The aggregate crushing strength and impact value, the results show that RCA had an average 20% and 23.7% more losses than NCA correspondingly. As expected, the strength of the crushed concrete affects the ACV and AIV of the aggregate. Nevertheless, all the results of RCA are within the acceptable limit for structural application.

The test results of the compressive strength of the concrete for both NCA and RCA are presented in Table 5 and shown in Figure 2. The results show that the compressive strength at 28th day for all the concrete considered was higher than the 7th day which was as a result of increase in amount hydration with higher curing age. Generally, the 7-day compressive strength is 60-70% of the 28-day compressive strength for the RCA concrete and this falls within the range of normal concrete cured with water i.e. 60-80% (Mindess *et al*., 2003; Neville, 1996). It was observed that there is a gradual decrease in compressive strength as the percentage of RCA increases. After 28 days of curing the RCA for all the percentages considered achieved target compressive strength (35 MPa) though RCA-25, RCA-50 and RCA-75 produced compressive strength that were 6.83, 11.39 and 16.4% lower than NCA concrete, respectively. These values confirmed the trends found in the literature that reported a decrease in compressive strength when NCA is replaced with RCA (Obla and Kim, 2009; Chen *et al*., 2003; Xiao and Li, 2005). Though, the reduction observed in this study was only 16.4% in comparison with NCA but RCA did not significantly decrease the compressive strength of concrete. This was due to a better interfacial bond between aggregate and cement paste in the presence of rough RCA. The weakness of RCA was due to porous adhered cement paste prevailed over its surface roughness and high water absorption, resulting to decrease in the compressive strength of concrete.

Table 5: Results of Compressive Strength

Days	NCA	RCA-25	RCA-50(MPa)	RCA-75
7	25.8	25.4	22.7	21.6
14	35.5	30.2	29.7	28.2
21	39.9	36.6	34.1	32.3
28	43.9	40.9	38.5	36.7

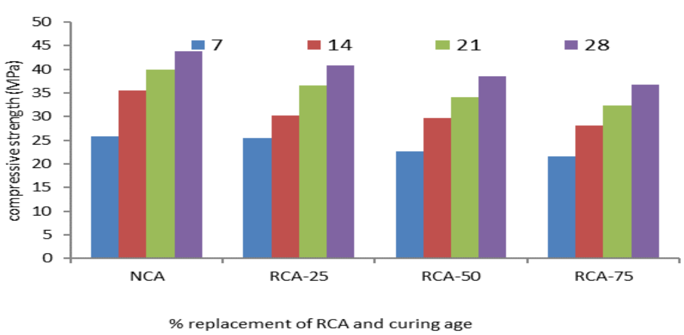

Table 6 and Figure 3 showed that the flexural strength of concrete also increase with curing age for all proportions of RCA. The highest flexural strength obtained at 28 days was 5.4 MPa for RCA-25 which is 14.82% lower than the 7-day flexural strength of 4.6 MPa. It is obvious from Figure 3 that RCA has no negative effect on the flexural strength of the concrete though there were reduction in values of 3.57, 7.14 and 7.14% for RCA-25, RCA-50 & RCA-75, respectively. The aggregate characteristics of RCA contributed to the production of better interfacial bond and mechanical interlocking.

Table 5: Results of flexural strength (MPa)

Days	NCA	RCA-25	RCA-50(MPa)	RCA-75
7	4.8	4.6	4.5	4.5
28	5.6	5.4	5.2	5.2

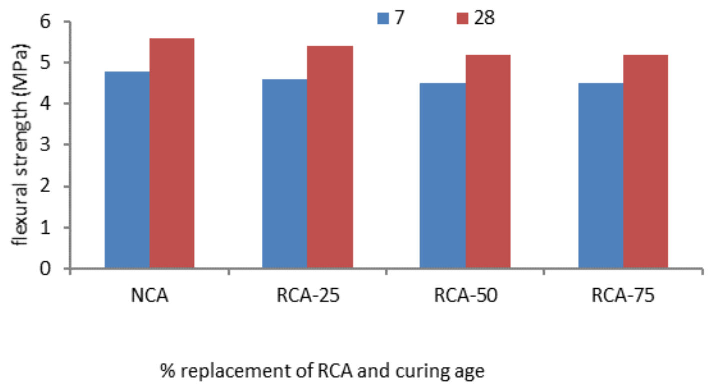

Figure 3: Flexural strength of NCA & RCA

CONCLUSION

The following conclusions can be drawn based on the study carried out:

1. The RCA had higher water absorption and density of concrete decreased with increase in proportion.
2. Compressive strength after 28-day curing for all the proportions was higher than that of 7-day.
3. The 28-day compressive strength for all proportions exceeded the target strength of 35 MPa although there is decrease in compressive strength as the proportions of RCA increases.
4. RCA had no significant adverse effect on the compressive strength of PCC. For instance, the 28-day compressive strength of RCA-75 decrease by only 16.4% (that is, from 43.9 MPa for the control to 36.7 MPa). Though, RCA was less strong than NCA but has better interfacial bond between aggregate and cement paste in the presence of rough RCA.
5. The 28-day flexural strength of the concrete was higher than 7-day flexural strength for all the proportions of RCA. The highest flexural strength value of 5.4 MPa was obtained after 28-day curing for R-25, which is 14.82% lower than the 7-day flexural strength value of 4.6 MPa.

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