Short term durability of recycled coarse aggregate concrete – the influence of sodium and magnesium sulphate on compressive strength

Shodolapo Oluyemi Franklin*, Omphemetse Sebangane
Formerly, Department of Civil Engineering, University of Botswana, Gaborone, Botswana

ABSTRACT: *The present study forms part of a continuing investigation into the problem of durability of recycled coarse aggregate concrete (RCAC) in the Republic of Botswana. For this purpose, recycled coarse aggregates (RCA) obtained from a laboratory stockpile of crushed and uncrushed cubes and beams which had been manufactured earlier using broken kerb stones taken from the University of Botswana Academic Hospital construction site was employed for the production of five different concrete mixes. The ratio of RCA to the total aggregate for these mixes was altered in the proportion 0%, 25%, 50%, 75% and 100%. The manufactured specimens were cured in water containing 5% magnesium sulphate or 5% sodium sulphate by weight. Similar specimens were also cured using clean potable water as alternative, for comparative purposes. The change in mass of the concrete specimens in addition to the compressive strength of the concrete was assessed after 7, 14, 21 and 28 days. With respect to mass change, only the results of those specimens immersed in potable water or sodium sulphate solution appeared to show a discernible trend. The mass change for those specimens immersed in 5% magnesium sulphate solution did not show any distinctive pattern. With reference to compressive strength, it was found that in all cases this increased with increase in curing age but decreased with increasing RCA replacement of natural coarse aggregate (NCA) in the concrete mix. Furthermore, curing in magnesium sulphate solution at 5% concentration had a more pronounced effect on the compressive strength reduction as compared to immersion in sodium sulphate solution. It was also concluded that RCA replacement levels of up to 75% could probably be utilized in infrastructural applications like concrete pavements and blocks.*

KEYWORDS –*Coarse aggregate,compressivestrength,concrete, recycled, sulphate*

I. INTRODUCTION

The use of recycled coarse aggregate (RCA) has gained increasing popularity in the past few decades due to a number of reasons. Firstly, there is a growing awareness of the need for sustainable construction in view of the rapid depletion of the earth's natural aggregates. Secondly, the rapid urbanization and construction programmes in different countries of the planet has led to massive increases in the quantity of construction and demolition wastes which in turn has resulted in overcrowded landfills and disposal sites. The latter as a consequence has produced serious environmental issues and concerns regarding the impact of such waste management practices on societal health and well-being. Finally, in view of the large volume of investigations and research carried out to date, there is growing favourable opinion that RCA can to some extent replace natural coarse aggregate (NCA) in the manufacture of fresh concrete for various structural applications. All the afore-mentioned issues have been succinctly covered by Franklin and Gumede (2014) and Gumede and Franklin (2015), amongst others.

In spite of the above however, and the increasing use of recycled coarse aggregate concrete (RCAC) for a growing number of structural uses of diverse kinds, it would appear that the problem of durability of such concrete still has to be resolved. This consideration is of major importance as noted by Said et al. (2017), if RCAC is to gain wider acceptance in civil engineering practice. The problem is even more complex than this because as noted by Thomas et al. (2013), a survey of the literature on the issue of durability reveals that the heterogeneity of recycled aggregates, water-cement ratios and types of cement used would make any comparison of results found by previous investigators somewhat difficult.

The durability of RCAC has been studied by several investigators including Sagoe-Crentsil et al. (2002), Fung (2005), Tam and Tam (2007), Thomas et al. (2013), Xiao et al. (2013), Jimenez and Moreno (2015), Yehia et al. (2015), Gangaram et al. (2015), Jolly and Mathew (2016), Said et al. (2017) and Guo et al. (2018). The work reported by these researchers taken collectively has included such aspects as the deformation and permeability characteristics of RCAC, performance levels for both short-term and long-term, absorption and drying shrinkage, resistance to carbonation and chloride penetration, the effect of recycled aggregate quality, comparison of durability properties of self-compacting concrete and RCAC, resistance to reinforcement corrosion, fire resistance, alkali-silica reaction, freeze-thaw resistance and sulphate attack to a relatively minor extent.

In respect of sulphate attack, Tang et al. (2014) studied the resistance to sodium sulphate solution of fly ash based geopolymeric recycled concrete. Hassan et al. (2013) assessed the effect of magnesium sulphate on self-compacting concrete containing supplementary cementitious materials. Habieb et al. (2015) evaluated the durability assessments of cementitious materials under sodium sulphate attack. Zega et al. (2016) studied the performance of recycled concretes exposed to soil containing 1.0% of sodium sulphate for 10 years, while Arafa et al. (2017) investigated the effect of magnesium sulphate attack on the compressive strength of recycled aggregate concrete. Franklin and Botshelo (2019) investigated the short-term durability of RCAC cubes exposed to 5% calcium sulphate solution. They found that such specimens generally had lower compressive strengths than similar specimens exposed to potable water, at 28 days; the reduction ranged from 1.3% to 8.6%.

It is commonly accepted that the severity of the attack of sulphates on concrete is dependent on the type of sulphate. Magnesium sulphate ($MgSO_4$) causes more damage than sodium sulphate (Na_2SO_4) which in turn is more damaging than calcium sulphate ($CaSO_4$). For each case however, the rate of attack increases with the concentration of sulphates present. The rate of attack also increases if the sulphates are replenished (Domone, 1994). The present investigation attempts to extend the work carried out by Franklin and Botshelo (2019) and also seeks to supplement the existing information on the effect of sulphates on the mechanical properties of RCAC. For these purposes, 5% sodium sulphate and 5% magnesium sulphate by weight in solution have been utilized, as these limits are reasonably representative of conditions existing in practice.

II. EXPERIMENTAL PROGRAMME

2.1 Materials, mix proportions and casting

The natural fine aggregate (NFA) used was a locally available river sand passing through a 4.75 mm sieve and possessing a fineness modulus of 3.24. Dolomite natural coarse aggregate (NCA) purchased from a local quarry at Belabela and having a maximum nominal size of 19 mm was utilized. The recycled coarse aggregate (RCA) was extracted from the Civil Engineering Structures Laboratory stockpile of crushed and uncrushed cubes and beams. The latter was initially crushed with a hammer and then the different sizes of aggregates (larger and smaller than 19 mm) were separated; the larger sizes underwent secondary crushing. Additional or further crushing was conducted using a laboratory crushing machine consisting of a top feeding hopper and a fixed jaw crusher at the bottom. The sizes of aggregates could be varied by adjusting the spacing of jaws via a knob provided on the side of the crusher. The particle size distributions for the NFA as well as the coarse aggregates (that is, NCA and RCA) are shown in Figs. 1 and 2 respectively. It is obvious that the fine aggregates are well graded. Also the NCA and RCA fall almost entirely within the 9.5 mm and 19 mm sieve sizes, and in fact, the gradation curves for both aggregates are quite similar.

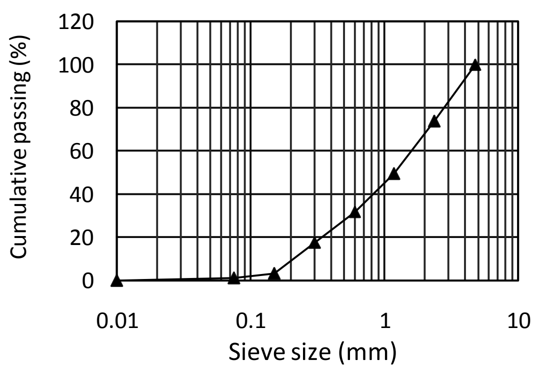

Fig. 1. Particle size distribution of natural fine aggregate

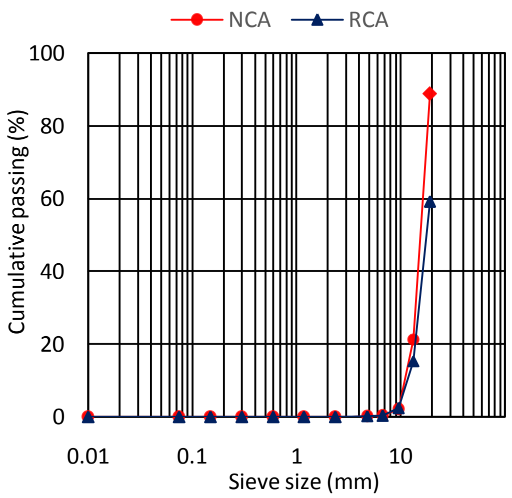

Fig. 2. Particle size distribution of natural and recycled coarse aggregates

The cement used was BOTCEM an Ordinary Portland Cement of designation CEM II/B-W 32.5R, containing between 21% and 35% of fly ash and manufactured to SANS 50197-1/EN 197-1. This cement possesses slower than average rate of hydration.The mix design method was essentially based on the Department of Environment (DoE) revised procedure described by Teychenne et al. (1997). The selected characteristic strength was 25 MPa at 28 days, and the target mean strength was 38.1 MPa. The calculated mix proportions were ascertained using trial mixes, the latter being assessed for consistency and cohesiveness. Slight adjustments were made as required to the mix proportions and the final selection is shown in Table 1. Mixing was carried out using a laboratory batch mixer in order to prevent loss of water or material. All mixes were prepared with a water-cement (w/c) ratio of 0.58. The control mix RC-0 had proportions of 1 (cement), 2.29 (NFA) and 2.11 (NCA) but had no recycled aggregates. Four different additional mixes were utilized in order to investigate the effect of adding recycled coarse aggregates (RCA) on the mechanical properties of concrete. In mixes RC25, RC50, RC75 and RC100, the natural coarse aggregates were substituted with 25%, 50%, 75% and 100% RCA in that order. For each mix, thirty six 100 mm cubes were cast and subsequently covered with polythene sheets shortly after manufacture for 24 hours. Afterwards, one-third of the concrete specimens were cured in a regulated water bath using clean potable water. The remaining two-thirds in equal proportions were cured in water containing 5% magnesium sulphate in solution, or 5% sodium sulphate in solution..

Table 1: Mix quantities for 1 m^3 fresh concrete

Mix type	Cem. (kg)	NFA (kg)	NCA (kg)	RCA (kg)	Water (kg)
RC-0	401	918	847	0	233
RC25	401	918	635	212	233
RC50	401	918	424	424	233
RC75	401	918	212	635	233
RC100	401	918	0	847	233

2.2 Testing procedures

Slump and compacting factor tests were carried out on the fresh concrete in order to determine the workability of each mix. For the slump test which gives a reasonable measure of the mobility and stability of the concrete, the fresh mix is placed in the frustum of a steel cone and hand tamped in three successive layers. The cone is lifted off, and the slump is defined as the downward movement of the concrete. In the compacting factor test the concrete is placed in an upper hopper and then dropped into a lower hopper so as to bring it to a standard state, and subsequently allowed to fall into a cylinder. The resulting degree of compaction of the concrete is measured by a comparison of its weight with the weight of concrete in the cylinder when fully compacted. Although in comparison to the slump test the compacting factor test is more realistic in assessing the compactibility of the concrete, it remains a fact that the amount of work done on the concrete in falling into the cylinder is considerably less than the energy input from practical compaction equipment such as vibrators.

Compression tests were also carried out in accordance with BS 1881-108:1983. Three 100 mm cubes were subjected to loading at 7, 14, 21 and 28 days, the loading being applied at constant rate up until failure. The same procedure was employed for all specimens cured in clean potable water as well as those cured in water containing 5% sodium sulphate in solution or 5% magnesium sulphate in solution. As a general rule, in practically all cases, the compressive strength was taken as the average value of the three cube test results.

III. RESULTS AND DISCUSSION

3.1 Workability tests on fresh concrete

The results of the slump tests are shown in Fig. 3 from which it is obvious that the slump decreases progressively with increase in the RCA content. For the range 25% – 100% RCA content, there was a corresponding reduction in slump of 21.5% – 76.9%. At the higher RCA contents of 75% and 100%, the results are significantly higher than those of Gumede and Franklin (2015) and Franklin and Botshelo (2019). This may be due to the fact that the recycled concrete aggregates were not initially saturated prior to being used, and the same water-cement (w/c)ratio was maintained for the test series. RCA has a relatively greater amount of old mortar paste, and with no additional water provided to cater for such mortar paste, any water introduced in the mix would be partially absorbed by the paste, resulting in less water being available for the hydration process. Consequently the concrete becomes less workable and there is a reduction in slump and compacting factor.

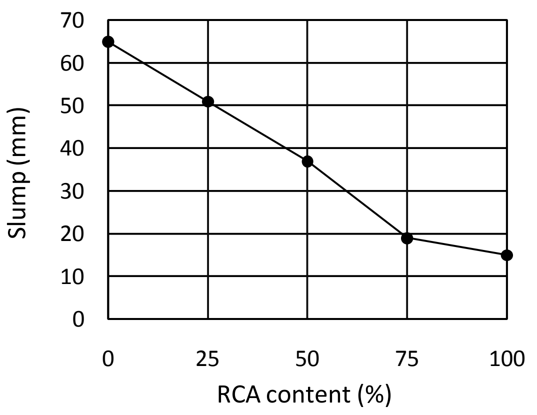

Fig. 3. Relationshipof slumpto RCA content

In order to test the above assertions, some water absorption tests were carried out on the natural coarse aggregates as well as the recycled coarse aggregates. Samples of the aggregates were thoroughly washed to remove finer particles and dust, then drained and subsequently placed in a perforated wire basket which was then immersed in distilled water at a temperature of between 22°C and 32°C. Further details of the test method are not reported here, but the results indicate that the average value of water absorption in the RCA was 5.58% while that of the NCA was 0.41%. Hence it may be concluded that the slump value and the compacting factor decreased due to the higher water absorption for the RCA concrete. The results of the compacting factor tests are shown in Fig. 4, from which it is apparent that at the higher RCA contents of 75% and 100%, the concrete is less workable.

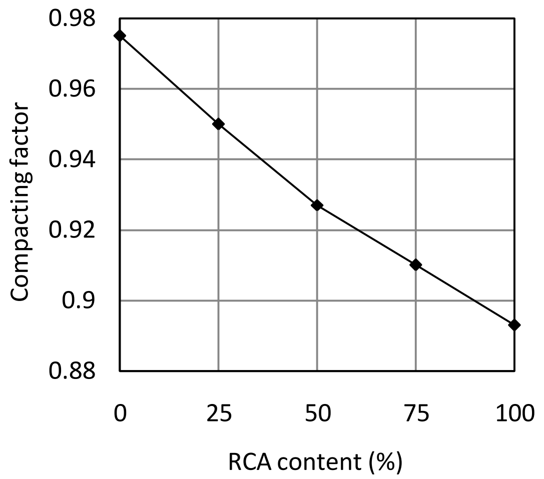

Fig. 4. Relationship of compacting factor to RCA content

3.2 Mass changes in immersed specimens

For concrete cubes immersed in clean potable water, the variation of the mass change with age of curing for different RCA contents is illustrated in Fig. 5.

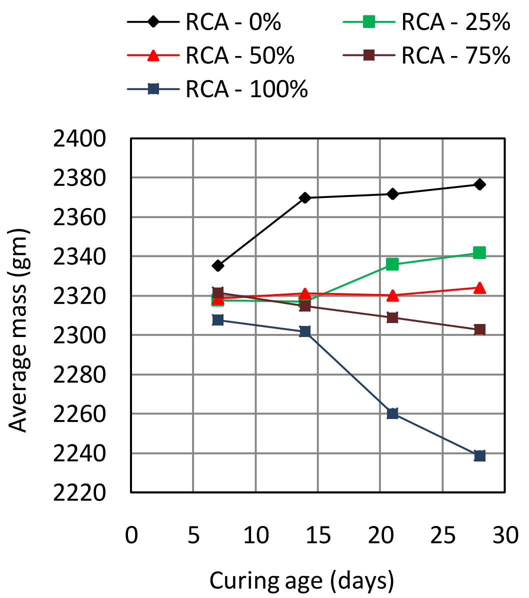

Fig. 5. Variation in mass for specimens immersed in water

It is clear that for 0% to 50% RCA content, there is a progressive increase in cube mass with curing age. However for the 75% and 100% RCA contents, there is a gradual mass loss with increase in curing age. For the concrete specimens immersed in 5% sodium sulphate solution, the situation is somewhat less certain as illustrated in Fig. 6. For the 0% RCA content, there is a progressive mass loss with increase in curing age. The opposite appears to be the case for the 25% and 50% RCA contents as there is a definite mass gain between 7 and 21 days. For the 75% and 100% RCA contents, there is a mass loss between 7 and 14 days followed by a mass gain at 21 days and afterwards a mass loss at 28 days. All the afore-mentioned observations would tend to suggest that measurement of mass changes only gives a clue of tolerable performance, and not much significance should be attached to the results. In fact for concrete cubes immersed in 5% magnesium sulphate solution, there are no distinctive trends whatsoever, and consequently, the results are not presented here.

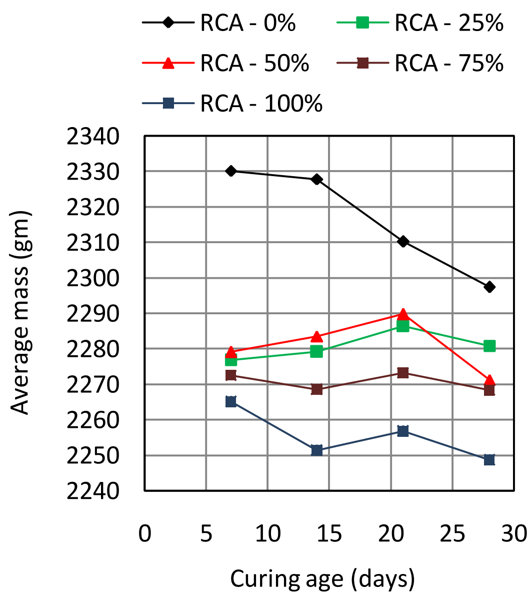

Fig. 6. Variation in mass for specimens immersed in sodium sulphate solution

3.3 Compressive strength

For the specimens cured in clean potable water, the variation of compressive strength with curing age for the different percentages of RCA contents is shown in Fig. 7. The results demonstrate that in general, the compressive strength decreases as the percentage of RCA increases. Interestingly however, concrete of higher RCA replacement levels may produce higher compressive strengths than concrete of lower RCA contents. For example at 7 days, specimens of 50% RCA contents exhibit higher compressive strengths than specimens of 25% RCA replacement levels. However the situation changes at 14 days, and this alteration is maintained at 21 and 28 days where for all proportions there is a constant strength loss. It is also evident that in general, concrete with 100% RCA content produces the lowest compressive strength. Furthermore the compressive strength at 28 days of concrete specimens with 75% RCA content drops by 17.8% in comparison to that of the reference concrete. Notwithstanding, its value is 29.6 MPa which exceeds the selected characteristic strength of 25 MPa. Hence it is obvious that RCA up to a level of 75% replacement could probably be used as a substitute for natural coarse aggregates in practical applications such as concrete blocks or pavements. However more testing would need to be carried out in order to verify this observation for certainty.

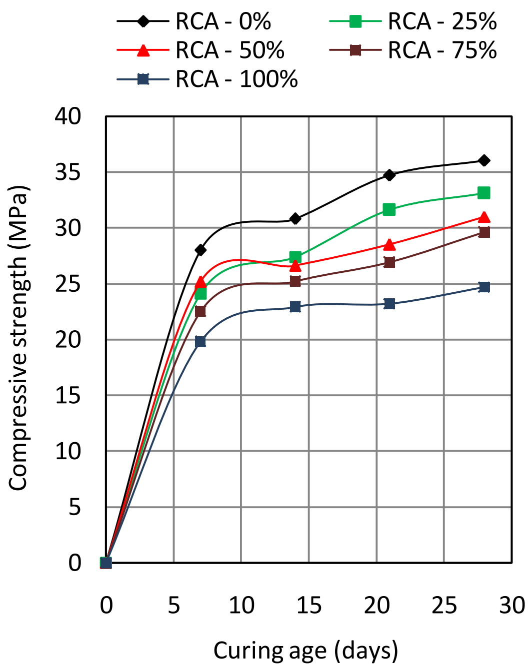

Fig. 7. Compressive strength at various ages for curing in clean potable water

The resistance of concrete to sulphate attack was assessed based on Figs. 8 and 9 shown.

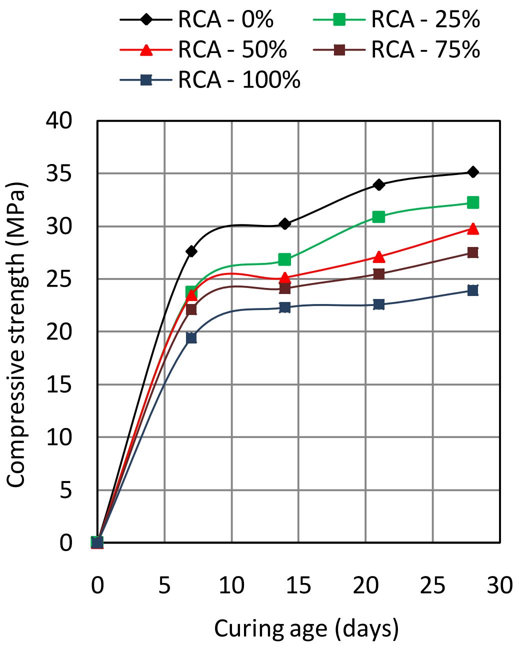

Fig. 8. Compressive strength at various ages for curing in magnesium sulphate solution

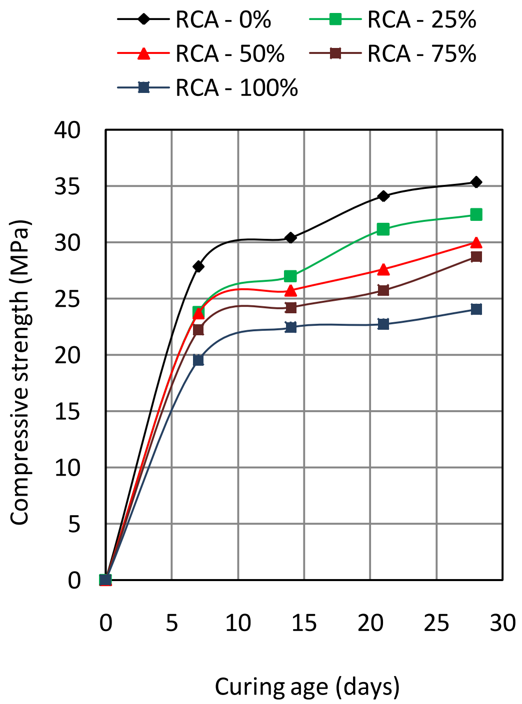

Fig. 9. Compressive strength at various ages for curing in sodium sulphate solution

The results in Figs. 8 and 9 give an estimate of the loss of compressive strength of concrete cubes immersed in sulphate water having 5% of magnesium sulphate ($MgSO_4$) or 5% of sodium sulphate (Na_2SO_4) by weight of water. These results are for the different RCA replacement levels of 0%, 25%, 50%, 75% and 100%. At 28 days, the compressive strength for 75% RCA content drops by 23.6% and 20.3% for $MgSO_4$ and Na_2SO_4 respectively in comparison to that of the reference concrete. Their values of 27.5 MPa and 28.7 MPa respectively, exceed the selected characteristic strength of the design concrete of 25 MPa. Here again it is apparent that RCA up to a level of 75% replacement could probably be used as a substitute for natural coarse aggregates in civil engineering applications. However as mentioned earlier, further testing might be needed in order to confirm this assertion.

Additionally, with regards to the influence of sulphates, there was a strength reduction of 1.4%, 1.9%, 2.3% and 2.5% when the concrete specimens of 0% RCA content were exposed to $MgSO_4$ solution at 7, 14, 21, and 28 days in that order, compared to specimens cured in clean potable water. In contrast, when similar specimens were cured in Na_2SO_4 solution, the strength reductions were 0.7%, 1.3%, 1.7% and 1.9% at 7, 14, 21 and 28 days respectively. These differences were observed for other levels of RCA replacement. For instance at 50% RCA content, concrete exposed to $MgSO_4$ solution showed strength reductions (relative to potable water curing for similar specimens of 50% RCA content) of 6.7%, 5.6%, 4.9% and 0.6% at 7, 14, 21 and 28 days in that order. The corresponding reductions for Na_2SO_4 curing were 6.0%, 3.4%, 3.2% and 3.2% respectively. Furthermore at 100% RCA content, curing in $MgSO_4$ solution produced compressive strength reductions of 2.0%, 2.6%, 2.6%, and 3.2% at 7, 14, 21 and 28 days respectively. The corresponding values for Na_2SO_4 curing were 1.5%, 2.2%, 2.2% and 2.8% in that order. Hence from the foregoing it may be concluded that magnesium sulphate has a slightly more deleterious effect on the compressive strength of recycled coarse aggregate concretes compared to sodium sulphate.

IV. CONCLUSIONS

The present study has dwelt on the problems of durability of recycled coarse aggregate concrete, an issue which is of current interest. Here an attempt has been made to assess the influence of short-term exposure of RCAC to magnesium sulphate or sodium sulphate solutions on the compressive strength. Based on the experimental work carried out, a number of conclusions can be drawn. Firstly there is a progressive decrease in slump and compacting factor with increase in the RCA replacement level. At higher RCA contents, the workability of the fresh RCAC mixes may be significantly lower than that of the natural coarse aggregate concrete mixes, particularly if no prior allowance had been made for the issue of the adhered mortar in the recycled coarse aggregate. Secondly, only those concrete specimens cured in clean potable water or sodium sulphate solutions showed distinctive trends in mass change; for curing in magnesium sulphate solution, the experimental results did not reveal any discernible pattern. Thirdly, irrespective of the mode of curing of the concrete, the compressive strength reduces as the RCA content increases. However RCA contents up to a level of 75% replacement could probably be used as a substitute for natural coarse aggregates in practical applications, although additional testing is recommended in order to ascertain this. Finally regarding the influence of sulphates, magnesium sulphate had a slightly more pronounced effect on the compressive strength of RCAC than sodium sulphate.

V. ACKNOWLEDGEMENTS

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