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Performance of recycled aggregate concrete monitored by durability indexes

F.T. Olorunsogo[a,*], N. Padayachee[b]

[a]Civil Engineering Discipline, School of Engineering, University of Durban-Westville, P/Bag x54001, Durban, South Africa
[b]LTA Civil and Earthworks, Johannesburg, South Africa

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Abstract

The report of an investigation into the performance of concrete manufactured with recycled aggregate (RA) using durability indexes as indicators is presented in this paper. Durability indexes, such as chloride conductivity, oxygen permeability and water sorptivity, of three different concrete mixes containing 0%, 50% and 100% RA were monitored at ages 3, 7, 28 and 56 days. The results show that durability quality reduced with increase in the quantities of RA included in a mix; however, as expected, the quality improved with the age of curing. At the age of 56 days, increases in index value of a concrete mix made with 100% RA over that made with 100% natural aggregate were 86.5% and 28.8%, respectively, for chloride conductivity and water sorptivity. The corresponding value of oxygen permeability index (OPI) for the same concrete mixes was a reduction of 10.0%. For 50% RA concrete, the reductions in chloride conductivity and water sorptivity indexes at the curing age of 56 days compared to 3 days were 62.7% and 42.7%, respectively. The corresponding figure for OPI was an increase of 37.6%. The poor performance of the RA concrete is associated with the cracks and fissures, which were formed in RA during processing, thereby rendering the aggregate susceptible to permeation, diffusion and absorption of fluids.

Keywords: Aggregate; Concrete; Diffusion; Durability; Permeability

1. Introduction

The use of recycled aggregate (RA) for manufacture of concrete started as far back as the end of World War II. Rubble obtained from demolition of concrete road pavement, runways, foundations and building structures has been reused successfully around the world. During the post World War II era in the United States, rubble from demolished concrete pavement was crushed and reused as aggregate in unstabilised base course of a number of road construction projects. And, in one form or another, concrete has been recycled successfully in other countries such as South Africa, the Netherlands, United Kingdom, Germany, France, Russia, Canada and Japan, to mention a few. The reuse of old concrete not only conserves the finite raw materials, but also reduces energy consumption and therefore the overall construction costs [1].

Many research studies are carried out on the use of RA in concrete in an attempt to understand the properties of RA concrete; however, most of the studies are focused on the mechanical properties of the resulting concrete. Limited work is carried out on the understanding of the durability aspects of the emerging construction material as is probably with concrete that is made with natural aggregate [2,3].

Today, engineers are beginning to accept that many of the problems experienced in structures made with concrete are due, largely, to lack of adequate knowledge concerning factors affecting durability of concrete as a material and inability to apply, effectively, the knowledge already gained. Durability of concrete may be defined as its ability to resist the damaging actions inherent in the environment in which it is employed. Perhaps, the most important of these factors is the ability of concrete to resist flow of fluids through it: a property that is referred to as permeability. Properties of concrete as a porous material depend not only on the nature of the solid constituents, but also on the pore structure. Concrete can be damaged by the influence of the environment in which it is located by means of a variety of mechanisms. In most cases, it is not always possible to prevent concrete from deteriorating. For instance, if concrete is kept wet and subjected to repeated cycles of freezing and

* Corresponding author. Tel.: +27-31-204-4308; fax: +27-31-204-4291.
E-mail address: sogo@pixie.udw.ac.za (F.T. Olorunsogo).

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thawing, it will eventually fail. To control the rate of deterioration in concrete, it is essential to design for durability by restricting deterioration mechanisms near the concrete surface as many deterioration mechanisms involve ingress of a harmful substance from the environment into the concrete. Therefore, it is important to understand the nature of the intrinsic characteristics of concrete, such as permeability and diffusivity (which is the ease with which dissolved solids and ions are transported through a saturated or partially saturated porous material). Although the specific values of permeability and diffusivity for certain concrete vary, depending on the substance that is moving though it, the same principles are applicable for obtaining significantly low values. Permeability commences and continues to increase the moment a continuous pathway exists, in such a manner that connected pores contribute much more to permeability than large discrete pores.

The reasons for the widespread lack of durability in concrete structures can be attributed to poor understanding of deterioration processes by designers, inadequate acceptance criteria of concrete on construction sites and changes in cement properties and construction practices [4]. In an attempt to contribute to the existing pool of knowledge in this regard, durability indexes, such as chloride conductivity, oxygen permeability and sorptivity, of three concrete mixes containing 0%, 50% and 100% RA were monitored at 3, 7, 28 and 56 days using an indexing method that has been devised by researchers [5–7] at the Universities of The Witwatersrand and Cape Town in South Africa.

2. Durability index techniques

There are a number of tests, based on a variety of mechanisms, which can be used for measurement of rates of fluid transport through concrete. Highly sophisticated equipment, complex monitoring and lengthy testing periods are, however, required to accurately model these mechanisms. While these techniques provide useful research information, they often have restricted practical value for site use consequent upon the constraints of the test methods. Therefore, in response to the need for more practical durability tests, the philosophy of durability index testing of concrete has been formulated [5].

2.1. Philosophy

The development of this indexing technique is based on the fact that improved durability can be attained in concrete if certain pertinent durability characteristics can be accurately determined. The philosophy of durability index technique can be likened to the concept of concrete strength that employs a simple quality control test, i.e., the cube or cylinder compression test, which itself bears little resemblance to the conditions in a real structure [5]. Nonetheless, experience shows that structures can be designed for different levels of stress by correlating the results of compression test with structural performance. Consequently, the test may be regarded as an ''index'' test that characterises the intrinsic potential of the material to resist applied stresses.

Alexander et al. [5] have employed this concept of ''indexing'' of material for application in the attainment of adequate durability in concrete structures by means of characterising the quality of the concrete cover or surface layer with the aid of parameters associated with the transport mechanisms, such as gaseous and ionic diffusion, water absorption, etc., and are characterised by quantifiable physical or engineering properties like permeability and water sorptivity. These engineering properties are sensitive to material processing and environmental factors, such as cement type, water–binder ratio, type and degree of curing, etc. They are a reproducible engineering measure of microstructure and properties of importance to concrete durability at a relatively early age (e.g., 28 days). Similarly, they allow the material to be placed in an overall matrix of possible values depending on the factors mentioned above. Therefore, it is possible to produce concrete of similar durability via a number of different routes, e.g., additional curing, lower water–binder ratio, choice of a different cement type or extender.

2.2. Index parameters

Three durability index tests were developed [5] in order to characterise fluid and ion transport mechanisms in concrete. These are oxygen permeability index (OPI) for permeation, chloride conductivity for diffusion and sorptivity for water absorption.

2.2.1. OPI

Permeation describes the process of movement of fluids through the pore structure under an externally applied pressure, whilst the pores are saturated with a particular fluid. Therefore, permeability refers to a measure of the capacity of concrete to transport fluids by permeation and is dependent on the concrete microstructure, the moisture condition of the material and the characteristics of the permeating fluid.

Alexander et al. [5] employed the falling head permeameter that was developed by Ballim [8] at the University of The Witwatersrand for the determination of OPI. This technique involves measuring the pressure decay of oxygen gas that is passed through a concrete sample. In this study, the sample was placed in a falling head permeameter. Oven-dried samples were subjected initially to a pressure of 100 kPa using oxygen gas. Readings of decrease in pressure were then taken over a period of time. Coefficient of permeability, k, was determined from the slope of a straight line produced by plotting the natural log of the ratio of initial pressure to pressure at a given time against time, as shown in Eq. (1):

$$k = \left(\frac{\omega V g d}{R A \theta}\right)\left(\frac{\ln P_0}{P}\right)\frac{1}{t} \quad (1)$$

where k is coefficient of permeability (m/s); ω molecular mass of permeating gas (kg/mol); V volume of pressure cylinder (m^3); g acceleration due to gravity (m/s^2); d sample thickness (m); R universal gas constant (N m/k mol); A cross-sectional area of the sample (m^2); θ absolute temperature (K); t time (s); P_0 initial pressure (kPa); P pressure at any time t (kPa).

OPI was then calculated by obtaining the negative log of the coefficient as in Eq. (2):

$$\mathrm{OPI} = -\log k. \tag{2}$$

2.2.2. Chloride conductivity

Alexander et al. [6] used a chloride conductivity test to monitor the diffusion characteristics of concrete. Diffusion may be regarded as the process by which liquid, gas or ion moves through a porous material under the action of a concentration gradient. It may occur in partially or fully saturated concrete and is an important fluid transport mechanism for most concrete structures that are exposed to salts. In concrete, high surface salt concentrations are initially developed by absorption — the salt migrating internally by diffusion towards the low concentration zone. Rates of diffusion are dependent on temperature, internal moisture content of concrete, type of diffusant and the inherent diffusibility of the material. Diffusion into concrete may be complicated by chemical interactions, partially saturated conditions, defects such as cracks and voids and electrochemical effects due to steel corrosion and stray currents. In marine environments, diffusion of chloride ions is of particular importance due to the depassivating effects of chlorides on embedded steel, which ultimately may lead to corrosion.

A rapid chloride conductivity test that was developed at the University of Cape Town [9] is used to monitor chloride diffusion. The test is based on the ionic flux that occurs by conduction due to voltage potential difference. The apparatus consists of a two-cell conduction rig in which concrete core samples are exposed on both faces to sodium chloride solution. Chloride conductivity, σ, which can be computed using Eq. (3), is determined by measuring the current that flows through the concrete specimen. Flow of current is accelerated by the application of a voltage potential difference:

$$\sigma = \frac{it}{VA} \tag{3}$$

where σ is chloride conductivity (mS/cm); i current (mA); V voltage (V); t thickness of specimen (cm); A cross-sectional area of specimen (cm^2).

For the purpose of experimentation in this investigation, a voltage potential difference of 10 V was applied across a concrete sample and electrical current was passed through the sample, which had been saturated with 5 M NaCl (sodium chloride) solution before commencement of test. The current passing through was then measured. Chloride conductivity was calculated using Eq. (3) based on the sample dimension. Values of the conductivity are expressed as milliSiemens per centimetre.

2.2.3. Water sorptivity

Absorption is regarded as the process whereby fluid is drawn into a porous, unsaturated material under the action of capillary forces. The capillary suction is dependent on the pore geometry and the saturation level of the material. The water absorption that is caused by wetting and drying of concrete is an important fluid transport mechanism near the surface, but becomes less significant with depth. The rate of movement of a wetting front through a porous material under the action of capillary force is defined as sorptivity.

For water sorptivity index, Alexander et al. [5] adopted a modified version of the sorptivity test apparatus of Kelham [10]. In this experiment, concrete specimens are subjected to a unidirectional flow of water. The test surface of concrete sample facing downwards is exposed to a few millimetres deep of water. At regular time intervals, the specimen is removed from the water and the mass of absorbed water is determined using an electronic balance. Measurements are terminated before saturation is reached and the specimen is then vacuum-saturated in water in order to determine the effective porosity. Plotting the mass of water absorbed against the square root of time gives a linear relationship. The sorptivity, S, of concrete is calculated from the slope of the straight line plot, so that Eq. (4):

$$S = \left(\frac{\Delta M_{\mathrm{T}}}{t^{1/2}}\right)\left(\frac{d}{M_{\mathrm{sat}} - M_{\mathrm{o}}}\right) \tag{4}$$

where S is sorptivity (mm/$\sqrt{h}$); ΔM_{T} change of mass with respect to dry mass (g); M_{sat} saturated mass of concrete (g); M_{o} dry mass of concrete (g); d sample thickness (mm); t period of absorption (h).

The sorptivity test is able to characterise concrete for similar influences as the permeability test, but with emphasis on near-surface effects such as curing. The initial degree of curing affects the quality of the concrete near-surface, which in turn influences the sorptivity of the material.

2.3. Performance-based specifications

According to Alexander et al. [5,7], the suggested ranges of index values for durability classification of concrete are shown in Table 1.

Table 1
Suggested ranges of index values for concrete durability classification [5,7]

Durability class	OPI (log scale)	Sorptivity (mm/$\sqrt{h}$)	Chloride conductivity (mS/cm)
Excellent	> 10.0	< 6.0	< 0.75
Good	9.5–10.0	6.0–10.0	0.75–1.50
Poor	9.0–9.5	10.0–15.0	1.50–2.50
Very poor	< 9.0	>15.0	> 2.50

Table 2
Constituents of the RA

Ash (%)	Mortar (%)	Brick (%)	Stone/Mortar (%)	Total (%)
1.90	7.10	6.40	84.60	100

3. Experimental work

3.1. Materials

The materials used in this study were cement type CEM I, natural fine aggregate (Umgeni sand), natural coarse (crushed granite rock) aggregate and RA. All the materials including the RA were obtained from local suppliers. The RA that was processed to 19-mm maximum aggregate size by using the conventional method for preparation of natural coarse aggregate was obtained from concrete and brick recyclers. Constituents of the finished RA are shown in Table 2. Due to the nature of the original demolished structure, it can be seen that the finished product (i.e., RA) consists of materials such as dust, mortar, brick and stone/mortar conglomerate. The dust and stone/mortar constituted the lowest (1.90%) and highest (84.60%) proportions, respectively. Table 3 shows the physical properties of all the aggregates in terms of relative density, moisture content, fineness modulus, and compacted and loose bulk densities. The moisture content refers to the moisture in excess of the saturated surface dry state of the aggregates.

3.2. Mix design

Three concrete mixes, as shown in Table 4, were prepared. Since there is no existing standard method of designing concrete mixes incorporating RA, the method of mix design proposed by the Cement and Concrete Institute (C&CI) [11] was employed to design a concrete mix containing 100% natural coarse aggregate. The mix was designed to have a 28-day target compressive strength of 30 MPa. The RA mixes were derived simply by partially replacing (by mass) the natural coarse aggregate proportion in the control OPC mix with RA at 50% and 100% replacement levels.

Table 3
Physical properties of aggregates

Type of aggregate	Relative density	Moisture content (%)	Fineness modulus	Compacted bulk density (kg/m^3)	Loose bulk density (kg/m^3)
Natural fine aggregate (FA)	2.60	4.53	2.9	1441	1200
Natural coarse aggregate (NA)	2.61	5.13	–	1458	1344
Recycled coarse aggregate (RA)	2.60	5.32	–	1397	1362

Table 4
Mix proportions

Mix number	Cement (kg/m^3)	Percentage of RA	Fine aggregate (kg/m^3)	Coarse aggregates (kg/m^3)		Water (l)
				Recycled	Natural	
1	395	0	563	0	1196	198
2	395	50	563	598	598	198
3	395	100	563	1196	0	198

3.3. Procedures

3.3.1. Sample preparation and conditioning

For all three tests, the samples used were concrete disks of 25 ± 2 mm thickness and 68 mm diameter. The samples were obtained by coring through the exposed face, and then cutting the 100-mm concrete cubes. The samples were thereafter placed in an oven that was maintained at a temperature of 50 ± 2 °C and at a relative humidity of less than 20% for a minimum of 7 days prior to testing. Four samples were prepared for each test result. One test result was calculated from the mean of three test determinations on the same material. The fourth sample was kept aside in case of a failed test determination.

3.3.2. Index tests

Detailed description of the three index tests that were considered in this investigation can be found in the appropriate research monograph [7]. However, brief summaries of these tests have been given previously in Section 2.2.

4. Results and discussions

4.1. Oxygen permeability

Fig. 1 shows the effects of RA content and curing age on the permeability of RA concrete. The repeatability of the measurement of OPI is 1.46%, as determined by the coefficient of variation that was based on all the tested sample results. Fig. 1a shows that, at a given curing age, OPI decreased with increases in the proportion of RA included in a concrete mix. For concrete mixes cured for a period of 3 days, increasing the RA content from 0% to 100% led to a 15.0% reduction in the value of OPI. Corresponding reductions for the concrete mixes that were cured for a period of 7, 28 and 56 days are 16.0%, 10.0% and 10.0%, respectively.

In Fig. 1b, it can be seen that for a given percentage of RA content, OPI of the concrete samples increases, the longer the duration of curing. Between the curing periods of 3 and 56 days and for the concrete mix containing 0% RA (i.e., 100% natural aggregate), OPI increased by 33.6%. Similar increases of OPI for the concrete mixes incorporating 50% and 100% RA were 37.6% and 38.2%, respectively.

Comparing the recommended values of OPI for concrete durability classification as shown in Table 1, the 100% NA

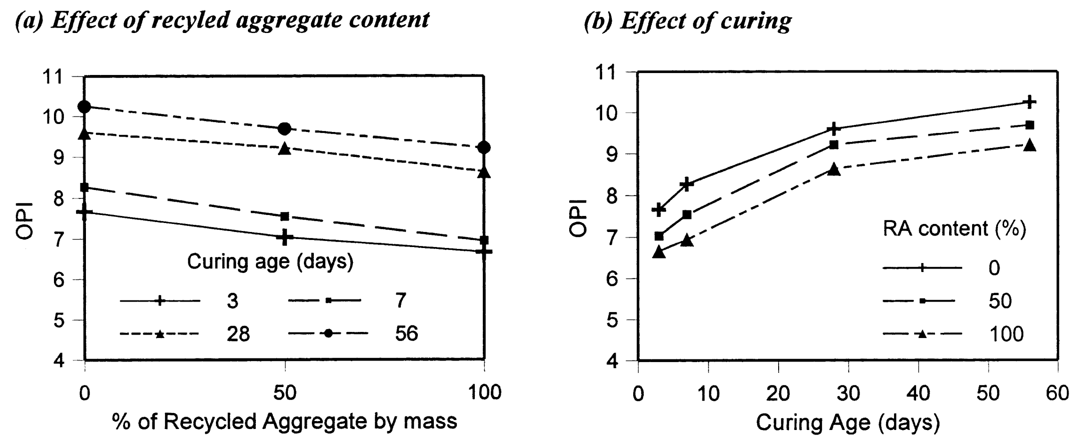

Fig. 1. OPI.

concrete attained the class status of 'good' at the curing age of 28 days with an OPI of 9.60, whilst the 50/50 (RA/NA) concrete attained similar class status at 56 days with an OPI of 9.69. However, the 100% RA concrete only achieved a class status of 'poor' with the OPI value of 9.22 at the curing age of 56 days. It is, however, possible that this value will increase the longer the curing duration.

This trend of reduction in OPI with increases in the replacement levels of RA in a concrete mix is expected, since the RA is mainly made up of conglomerates of mortar and stone that have undergone a crushing process, which is likely to leave cracks and fissures in the weaker mortar compared to the stone. These cracks and fissures would in turn create paths for ease of passage of fluids through the resulting concrete mix in which they are incorporated.

4.2. Chloride conductivity

In Fig. 2, the effects of RA content and duration of curing on the chloride conductivity of RA concrete are illustrated. For the chloride conductivity test, repeatability of the test, as determined by coefficient of variation of all the tested sample results, was 5.4%. Fig. 2a shows that chloride conductivity increased with increases in the replacement levels of RA for a given curing duration of concrete mixes. At a curing age of 3 days, the concrete mix that contained 100% RA showed 41.4% increase in the value of chloride conductivity over the mix that contained 0% RA. Similar figures for increases in chloride conductivity of RA concrete that were cured for 7, 28 and 56 days were 53.6%, 73.2% and 86.5%, respectively.

Considering the effect of curing age on the chloride conductivity of RA concrete, Fig. 2b shows that the longer the duration of curing, the lower the conductivity of the concrete mix at a particular replacement level of the RA. For instance, for a 0% RA (i.e., 100% NA) concrete, the mix that was cured for 56 days showed 69.0% increase in chloride conductivity over the mix that was cured for 3 days. Corresponding percentage increases in conductivity for the 50% and 100% RA concrete were 62.7% and 59.2%, respectively.

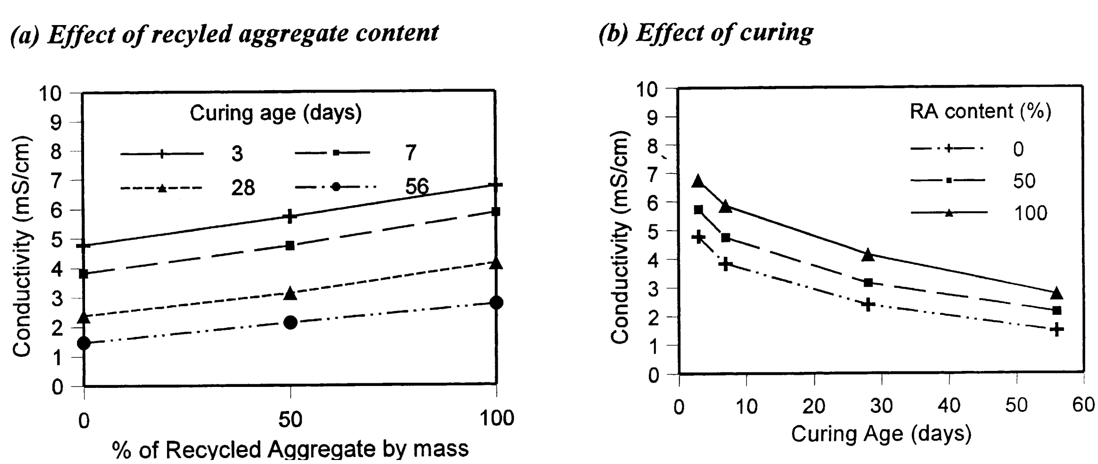

Fig. 2. Chloride conductivity.

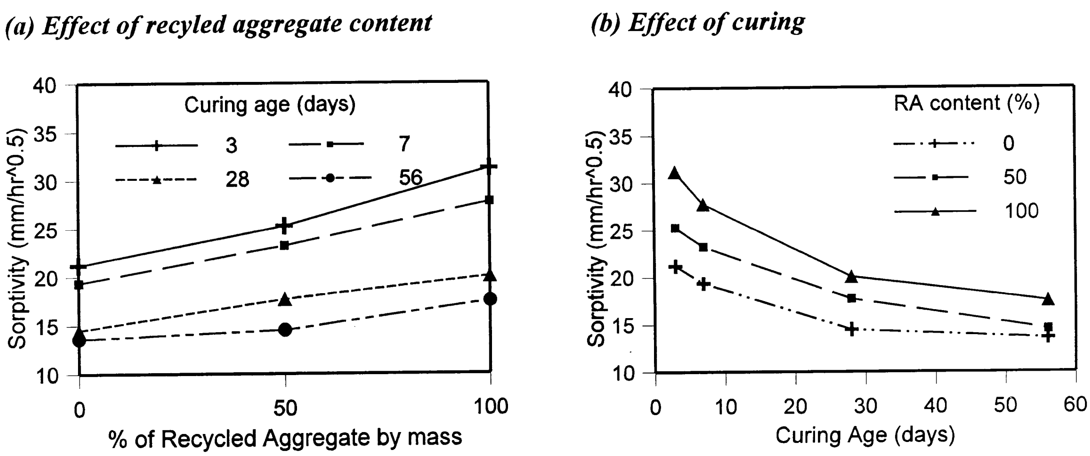

Fig. 3. Water sorptivity.

In comparison with the recommended values of chloride conductivity for concrete durability classification presented in Table 1, only the 100% NA (i.e., 0% RA) concrete attained a 'good' classification with a value of 1.48 mS/cm at the curing age of 56 days. All other mixes fall under the 'poor' or worse classification. Again, the weaker nature and formation of cracks and fissures in the RA can explain the tendency for RA concrete to diffuse chloride ions easily.

4.3. Water sorptivity

The effects of RA and curing age on the water sorptivity of RA concrete are illustrated in Fig. 3. Repeatability of the sorptivity test as determined by the coefficient of variation is 6.9%. At a constant age of curing, water sorptivity of RA increased with increases in the proportion of RA in concrete mixes. Fig. 3a shows that at the curing age of 3 days, water sorptivity increased from 21.21 mm/h$^{1/2}$ for the 0% RA concrete to 31.24 mm/h$^{1/2}$ for the 100% RA concrete, leading to an increment of 47.3%. For mixes cured for durations of 7, 28 and 56 days, the corresponding increments were 43.6%, 38.5% and 28.8%, respectively. It should be noted that these percentage increments decreased with duration of curing, indicating that if mixes were cured for a considerable length of time, there may be little or no difference in the sorptivity values.

Fig. 3b shows that water sorptivity decreased, the longer the curing age of concrete mixes for a given proportion of RA in the mix. A reduction of 35.9% was observed for 0% RA (i.e., 100% NA) concrete mix that was cured for 56 days over that cured for 3 days. Similar reductions for the 50% and 100% RA concrete mixes were 42.7% and 44.0%, respectively.

None of the concrete mixes achieved a 'good' or better durability classification for all the ages of curing. However, the 0% RA concrete attained the 'poor' category at the age of 28 days with a sorpivity value of 14.48 mm/h$^{1/2}$. Because all the index parameters are based on the nature of the microstructural characteristics of the concrete mixes, similar explanation for the OPI and chloride conductivity holds for the behaviour of the concrete mixes regarding poor performance in water sorptivity.

5. Conclusions

Inclusion of RA decreased the permeability index of concrete mixes at a given curing age, whilst for a concrete mix containing a specific amount of RA, the index increased the longer the curing duration.

Chloride conductivity increased with increases in the replacement levels of RA for a given curing duration of concrete mixes. However, at a particular replacement level of the RA, the longer the duration of curing, the lower the conductivity of a concrete mix.

At a constant age of curing, water sorptivity of RA concrete increased with increases in the proportion of RA in the mixes. Sorptivity decreased the longer the curing age of concrete mixes for a given proportion of RA in the mix.

Overall, durability quality of RA concrete reduced with increases in the quantities of RA that were included in a mix and, as expected, the quality improved with the age of curing. This phenomenon can be explained by the fact that cracks and fissures created in RA during processing render the aggregate susceptible to ease of permeation, diffusion and absorption of fluids.

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