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# Chloride penetration resistance of fine recycled aggregate concrete

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**Abstract.** This study investigates the chloride penetration resistance of fine recycled aggregate concrete (FRAC). Six concrete mixes comprising 0.45 and 0.55 w/b were prepared using fine recycled aggregates (FRA) at 0, 25 and 50% by volume replacement of natural sand. The chloride penetration resistance of the concrete was tested using the surface electrical resistivity (SER), chloride conductivity index (CCI), and the bulk diffusion tests. The SER and CCI tests were conducted after 28 days and 180 days of wet curing, while the bulk diffusion test was carried out after 28 days of wet curing and 180 days of exposure to chloride solution. Results show that the SER of FRA concrete was comparable to the control concrete, at all ages tested. The 28-day CCI of the concrete was impacted as FRA replacement levels increased, whereas at 180 days of testing, the FRA concrete mixes showed more significant improvement in CCI than the control natural aggregate concrete (NAC). The bulk diffusion results indicate that, for each w/b, the chloride diffusion profiles of the control and FRA concrete are comparable.

**Keywords:** fine recycled aggregate concrete, chloride penetration resistance, chloride conductivity index, diffusion profile, surface electrical resistivity.

## 1 Introduction

Globally, reuse and recycling of construction and demolition waste (CDW) to produce recycled aggregate for concrete application is on the increase. This can be attributed to the greater availability of CDW, scarcity of landfills for disposal of CDW, increased infrastructural demand, greater awareness and recycling pressure by society, and the depletion of natural aggregate resources, particularly sand [1], [2]. Additionally, the use of recycled aggregate can reduce environmental issues associated with the extraction of natural aggregates, such as coastal erosion, loss of biodiversity at mining sites, as well as reduce the carbon footprint associated with the haulage of natural aggregate through the use of mobile recycling facilities [1], [3].

Despite these, the use of recycled aggregates for structural concrete application is limited. First, the presence of adhered cement paste (ACP) in the recycled aggregate matrix reduces the stiffness, increases the water absorption, reduces the density of the recycled aggregate thereby impacting the fresh, mechanical, and durability properties of the concrete produced. This effect is more pronounced in fine recycled aggregate (FRA) than coarse recycled aggregate (CRA) owing to the presence of more ACP in the FRA matrix [4]–[9]. Secondly, the lack of accepted design methods to optimize the quality of concrete containing recycled aggregate may have contributed to the apparent shortcomings in the properties of recycled aggregate concrete. For instance, with regards to the chloride ion penetration resistance of FRAC, different findings have been reported in literature owing largely to different design approaches for FRAC. Sim and Park [10] used a 0.35 w/b reference concrete comprising 100% CRA as coarse aggregate and 100% fine natural aggregate (FNA), and the experimental mix comprising different FRA replacement levels for FNA, observed that the electrical conductivity of FRAC was comparable to the reference concrete, therefore inferred that FRAC and the reference concrete had comparable chloride resistance. The study showed that at 21 days of testing, all concrete mixes had moderate chloride ion penetrability, while at 56 days of testing, all concrete showed very low chloride ion penetrability. Results indicate that curing up to 56 days was more beneficial to FRAC as mixes with up to 100% FRA replacement level had lower chloride conductivity than the control concrete at 56 days. Similarly, Mardani-Aghabaglou et al. [11] demonstrated that at a constant w/b of 0.45, the chloride conductivity of concrete with up to 60% FRA replacement level was comparable to the control concrete. Matias et al. [12] demonstrated that superplasticizers can improve the compactness of recycled concrete thus making the chloride penetration resistance of 100% CRA concrete

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comparable to the reference natural aggregate concrete (NAC).

By contrast, and with reference to NAC, [13] and [14] reported a 14 - 34% increase in chloride ion diffusion coefficient for wholly FRA concrete at test ages of 28 and 91 days. However, all the concrete mixes were classified as moderate to good quality concrete [14]. Sasanipour and Aslani [15] reported significant increase in electrical conductivity and therefore inferred a reduction in chloride resistance as FRA content increased from 25 to 100% in self-compacting concrete. It is worth noting that these studies introduced additional water during FRA concrete mixing [13], [14], or by pre-soaking the FRA [15] so as to attain similar workability as the reference concrete, thus the chloride penetrability of the FRA concrete may have been impacted. This effect was demonstrated by Bravo et al. [16] in their study of recycled aggregate from different sources, where results showed that the FRA concrete mixes with the most additional water gave the least chloride resistance. Further, [17] buttressed this in a study where they varied the amount of additional water in two series of FRA concrete containing similar FRA content of 25 to 100% each. The result showed that, for similar FRA replacement level, concrete mixes with less additional water consistently gave better chloride resistance at 28 and 90 days of test.

These studies, in addition to being few, show that the chloride penetration resistance of recycled concrete requires further investigation. Also, these studies use test methods that rely on electrical conductivity to measure the chloride ion resistance of recycled aggregate concrete. These test methods though quick, convenient, and relatively low cost, have been reported to have shortcomings such as: the measured current is related to all ions such as $Na^+$, $K^+$, $OH^-$ etc. in the pore solution not just chloride ions, the presence of conductive materials in the concrete matrix can influence readings, and the applied voltage may increase temperature which may impact results [18], [19]. Further, electrical methods may be imprecise for concrete containing pozzolanic materials as the $OH^-$ ions which are involved in the conductivity of the pore solution is consumed, thereby impacting conductivity readings [20]. Therefore, in addition to electrical methods, there is a need to assess the chloride ion penetration resistance of FRA concrete using other methods to widen the knowledge base on recycled aggregate concrete. To address this, the bulk diffusion test was used in this research to investigate the chloride penetrability of concrete by diffusion- which is the principal transport mechanism of chloride ions in real life concrete structures.

For comparison, the surface electrical resistivity (SER) and the chloride conductivity index (CCI) tests, both relying on electrical conductivity, were used in this study to measure the chloride penetrability of the concrete. Studies have shown that the SER test [20]–[22] and the CCI test [23] - [24] have good correlation with other chloride resistance tests and durability parameters.

## 2 Experimental programme

### 2.1 Materials

CEM II/A-L 52.5N was used as binder. A polycarboxylate ether superplasticizer (SP) was used to attain the design slump. Greywacke aggregate from a local quarry was used as coarse aggregate. The fine aggregate comprised natural fine aggregate and FRA. The natural fine aggregate is a blend of crushed greywacke and natural dune sand. The FRA was produced by crushing concrete slabs used for culverts and wing walls on a regional highway construction project. Details of the source concrete has been reported in previous publication [6]. See Table 1, Figures 1 and 2, for the physical properties and the grading of the aggregates respectively.

Table 1: Physical properties of aggregates

| Material | Oven-dry density (kg/m³) | Water absorption (%) | Moisture content (%) | Fineness modulus |
|---|---|---|---|---|
| Dune sand | 2548 | 1.11 | 0.17 | 2.2 |
| Crusher sand | 2576 | 2.52 | 0.08 | 3.7 |
| FRA | 2148 | 8.20 | 4.04 | 3.5 |
| Coarse aggregate | 2690 | 0.31 | 0.07 | - |

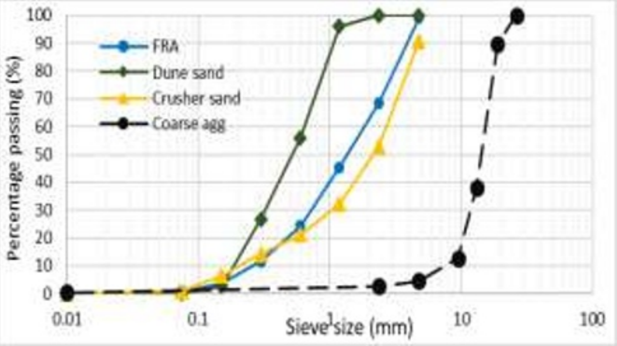


Figure 1: Particle size distribution of aggregates

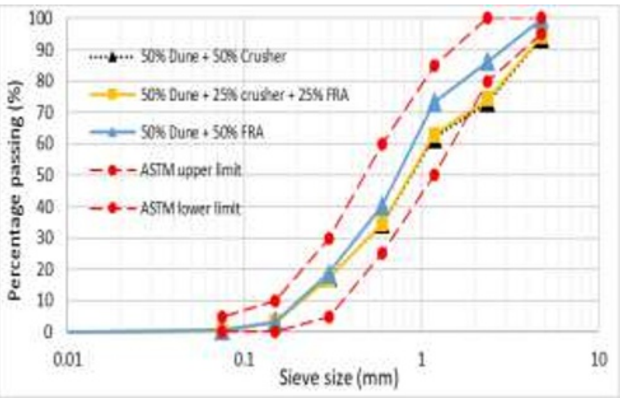


Figure 2: Particle size distribution of blended fine aggregates

### 2.2 Method

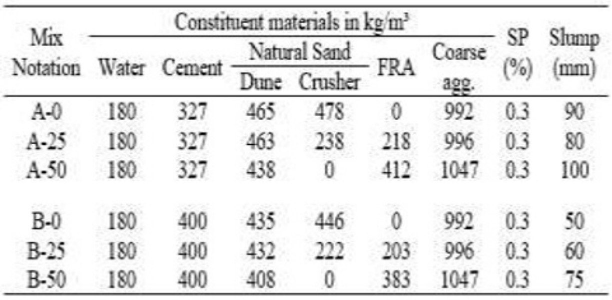
The concrete mix composition is shown in Table 2. All aggregates were used in air-dried state in accordance with findings by [25] and [26]. No additional water or water reduction was carried out in the concrete mix, however, a superplasticizer was used to attain the design slump of 75 ± 25 mm. To limit the influence of the superplasticizer on the concrete mixes, the dosage was kept constant, which is the lower limit of the 0.3 to 3% by mass of binder, as specified by the manufacturers.

Each w/b comprise of a control mix, a 25% and a 50% FRA replacement for fine natural aggregate, while the coarse aggregate is kept relatively constant. The fine aggregate for the control mix is a 50%–50% blend of crushed greywacke sand and dune sand (that is, 0% FRA). For the experimental mixes, the FRA replaced the crusher sand at 25% and 50% of the total fine aggregate content. Figure 2 shows that all the fine aggregate blends complied with the grading limits of ASTM 33, thus eliminating the influence of different particle gradings on the test results.

For referencing purposes, the mixes are denoted as X-Y. Where X could be A or B representing 0.55 and 0.45 w/b, respectively. Y is the replacement level of natural sand with FRA, that is 0, 25, or 50%.

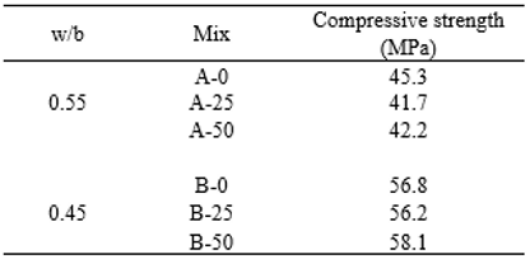
An adaptation of the modified two stage mixing approach (TSMA) developed by Tam and Tam [27] was used for the concrete mixing. After mixing, the fresh concrete was cast into 100 mm cubes, and 200 mm height by 100 mm Ø cylinder moulds. Plastic sheet covering was used to maintain a relative humidity of at least 90% for 20–24 hours, before demoulding. The concrete was then cured in a temperature-controlled water tank at 23 ± 2°C until the test date.

Table 2: Composition of concrete mixes



| Mix Notation | Constituent materials in kg/m³ | | | | | | SP (%) | Slump (mm) |
|---|---|---|---|---|---|---|---|---|
| | Water | Cement | Natural Sand | | FRA | Coarse agg. | | |
| | | | Dune | Crusher | | | | |
| A-0 | 180 | 327 | 465 | 478 | 0 | 992 | 0.3 | 90 |
| A-25 | 180 | 327 | 463 | 238 | 218 | 996 | 0.3 | 80 |
| A-50 | 180 | 327 | 438 | 0 | 412 | 1047 | 0.3 | 100 |
| B-0 | 180 | 400 | 435 | 446 | 0 | 992 | 0.3 | 50 |
| B-25 | 180 | 400 | 432 | 222 | 203 | 996 | 0.3 | 60 |
| B-50 | 180 | 400 | 408 | 0 | 383 | 1047 | 0.3 | 75 |

Table 3: 28-day average compressive strength



| w/b | Mix | Compressive strength (MPa) |
|---|---|---|
| 0.55 | A-0 | 45.3 |
| | A-25 | 41.7 |
| | A-50 | 42.2 |
| 0.45 | B-0 | 56.8 |
| | B-25 | 56.2 |
| | B-50 | 58.1 |

## 2.3 Testing

The slump test in accordance with SANS 5862–1 [28], was used to measure and ensure the consistency of all mixes were within the design slump of 75 ± 25 mm. To characterise the concrete mixes, the average 28-day compressive strength result is presented in Table 3. These results have been discussed in previous publication [6].

### *2.3.1 Surface electrical resistivity test*

The surface electrical resistivity (SER) test was carried out using a 4-pin Wenner probe array on the 200 mm height by 100 mm Ø concrete cylinders according to AASHTO T 358 [29]. The samples were tested after 28 and 180 days of curing, at saturated surface dry state under laboratory condition of 23 ± 2°C. Three specimens were tested for each concrete mix, and the average result reported.

### *2.3.2 Chloride Conductivity Index*

The chloride conductivity index (CCI) test is one of the South African Durability Index tests, and it is detailed in SANS 3001-CO3-3 [30]. The test was carried out after 28 and 180 days of curing using cored 70 ± 2 mm Ø by 30 ± 2 mm thick concrete discs as shown in Figure 3. The concrete discs were preconditioned by oven drying at 50°C for 7 days, followed by vacuum drying for 3 hours, and then vacuum saturation in 5M NaCl solution. A 10 V potential difference was applied across the specimen, and the current was measured. The CCI of each specimen is determined from equation (1) and the average of four readings is recorded:

$$\sigma = \frac{id}{VA} \qquad (1)$$

Where σ is the chloride conductivity of the specimen (mS/cm); i is the electric current (mA); d is the average thickness of specimen (cm); V is the voltage difference across the specimen (V); A is the cross-sectional area of the specimen (cm$^2$).

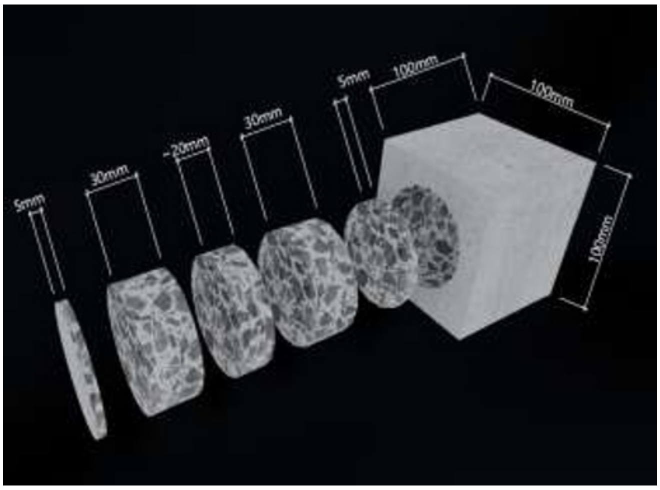


Figure 3: Chloride conductivity index test specimen

### *2.3.3 Bulk diffusion test*

The test was carried out according to ASTM C1556 [31]. After 28 days of water curing, 80 mm height by 70 mm Ø sample cores were obtained, see Figure 4(a). Epoxy coating was used to seal test sample on every side, except for the exposure face. The sample was then saturated for 48 hours in limewater, thereafter, exposed to a NaCl solution for 180 days. Afterwards, 8 slices were cut on the specimen at 5 mm intervals, see Figure 4(b). The epoxy coating was removed and the slices were pulverised to determine the acid-soluble total chloride content through titration using a potentiometric titrator according to ASTM C1152M [32]. Two specimens were tested for each concrete mix, and the average result reported.

## 3 Results and discussion

### 3.1 Surface electrical resistivity

The surface electrical resistivity result is shown in Figure 5. The figure contains error bars that indicate the standard deviation of three specimens tested per test date. Generally, the electrical resistivity of the 0.45 w/b mixes are higher than the 0.55 w/b owing to the denser nature and thus less conductivity of the 0.45 w/b concrete mixes. Over time, there is an increase in the resistivity value of all concrete mixes from 28 days to 180 days. This can be attributed to the densification of the concrete microstructure due to cement hydration, thus a reduction in electrical conductivity. With reference to the 28-day result, the 180-day result showed an increase of 7.4 to 11.6%, and 15.9 to 20.6% for the 0.45 and 0.55 w/b respectively. This indicates that prolonged curing was more beneficial to the 0.55 w/b mixes. It is expected that since higher w/b concretes have a more porous microstructure initially, these concretes have more scope for densification of the microstructure and thus improvement in resistivity with continued curing than lower w/b concretes (especially, w/b around 0.4), which have a highly dense microstructure to begin with.

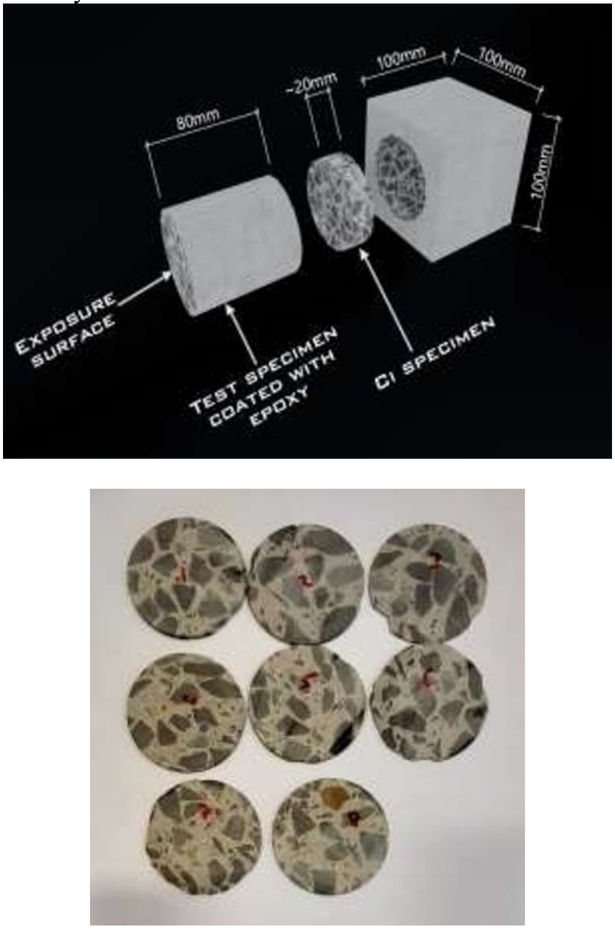


Figure 4: Bulk diffusion test: (a) concrete specimen; (b) sliced specimen

Results also show that for each w/b, at all FRA replacement levels and all testing ages, the concrete resistivities are comparable. This indicates that the addition of up to 50% FRA did not impact the surface resistivity of concrete. Similar results were obtained by [10] and [11].

Based on the criteria given by AASHTO T 358 [29] in Table 4, the concrete mixes can generally be categorised as having a high to moderate chloride ion penetrability. This is regardless of the w/b ratio or test age, which is to be expected in concretes made using Portland cement without any supplementary cementitious materials.

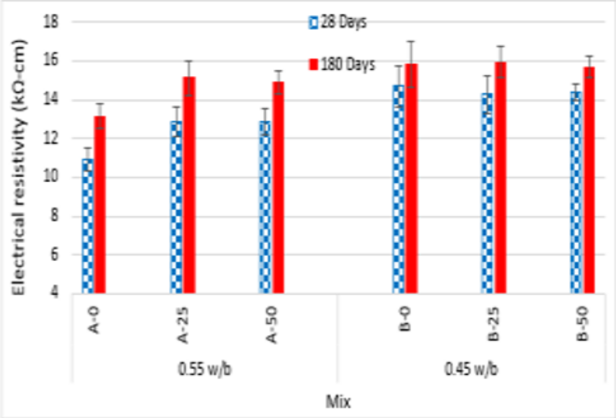


Figure 5: Surface electrical resistivity results

Table 4: Surface electrical resistivity classification of concrete based on AASHTO T 358 [29]

| Chloride ion penetrability | Surface Resistivity (kΩ-cm) |
|---|---|
| High | < 12 |
| Moderate | 12 - 21 |
| Low | 21 - 37 |
| Very Low | 37 - 254 |
| Negligible | > 254 |

### 3.2 Chloride Conductivity Index

The result of the CCI test is shown in Figure 6. Generally, it can be observed that the 0.45 w/b mixes have lower conductivity (better chloride resistance) than the 0.55 w/b owing to a denser microstructure. At 28 days, for each w/b, it was observed that the conductivity values increase as FRA replacement level increased, particularly for the 0.55 w/b. With reference to the control mix, an increase of 35% and 6.7% was observed for the 50% FRA replacement level in the 0.55 and 0.45 w/b ratio respectively. This indicates that the effect of FRA replacement is more prominent in the 0.55 w/b mixes. The increase in CCI with increasing FRA content can be attributed to the increase in the relatively porous adhered cement paste (ACP) of FRA [14]. Additionally, the presence of multiple interfacial transition zone (ITZ) between the natural aggregate, ACP and new cement paste, can increase the penetrability of the concrete [33].

At 180 days, all concrete mixes showed a reduction in CCI values owing to the formation of more hydration products and improved microstructure through prolonged curing, therefore reduced conductivity. With reference to the 28-day CCI results, the control mixes showed a decrease of 7% and 16% for the 0.55 and 0.45 w/b respectively. For the experimental mixes containing 50% FRA replacement, a decrease of 35% and 38% was observed for the 0.55 and 0.45 w/b respectively. This indicates that curing is more beneficial to FRA concrete mixes. Similar observation was made by [10] for FRA concrete cured for 21 and 56 days.

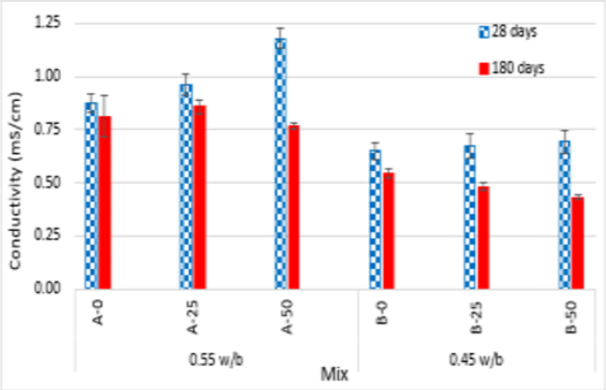


Figure 6: Results of chloride conductivity index

Table 5: Concrete classification based on chloride conductivity index [34]

| Quality of concrete | Chloride conductivity index (mS/cm) |
|---|---|
| Excellent | < 0.75 |
| Good | 0.75-1.50 |
| Poor | 1.50-2.50 |
| Very poor | > 2.50 |

According to the criteria stipulated by Alexander et al. [34] as shown in Table 5, all the 0.55 w/b concrete mixes can be regarded as having good quality while all the 0.45 w/b mixes have excellent quality, thus the performance of FRA concrete is comparable to natural aggregate concrete, see Figure 6. Compared to the surface electrical resistivity results, there is a clear disparity in the concrete classification criteria for the two electrical based tests for chloride resistance of concrete. The result also indicates that the CCI test is more sensitive to changes in w/b, curing duration, and the incorporation of FRA to the concrete mix. One possible explanation for the disparity between CCI and SER is the wall effect of concrete. The wall effect considers the near-surface concrete as having a high paste content and relatively porous which may lead to high electric conductivity, more so in SSD condition which can increase pore connectivity. Therefore, the wall effect may have contributed to low surface resistivity values. Unlike the CCI test, the wall effect is eliminated, and the paste volume is reduced (relative to the aggregate volume) by the use of concrete cores and slicing off the 5 mm cover zone. Studies by [21] and [35] demonstrate the influence of wall effect, as [21] reported that at SSD condition, the resistivity of limestone aggregate is significantly greater than that of the cement paste.

### 3.3 Bulk diffusion

Figures 7 and 8 show the average chloride diffusion profile of the 0.55 and 0.45 w/b concrete mixes after 180 days of chloride exposure. From Figures 7 and 8, it is observed that the chloride concentration on the exposure surface (2 mm concrete depth) is high due to the concrete wall effect.

For each w/b, it is observed that the control NAC, the 25% and 50% FRA concrete mixes all have comparable chloride diffusion profile. This indicates that the incorporation of up to 50% FRA as natural fine aggregate replacement did not negatively impact the chloride diffusion of concrete. As the FRA for this research was used at air-dried state, [26] and [25] posit that during concrete mixing, water may be absorbed by FRA, thereby leading to reduced water in the cement paste and consequently improved ITZ and concrete properties. Another factor that may be responsible for the comparable chloride resistance of FRA concrete to the reference concrete could be the continuous hydration of concrete in the exposure environment. Richardson [36] reports that chloride diffusion may be affected by the continuous hydration of concrete. This effect may be more significant for FRAC mixes, as FRAC has been reported to have higher degree of hydration than natural aggregate concrete especially over an extended curing period [6], [14], [37].

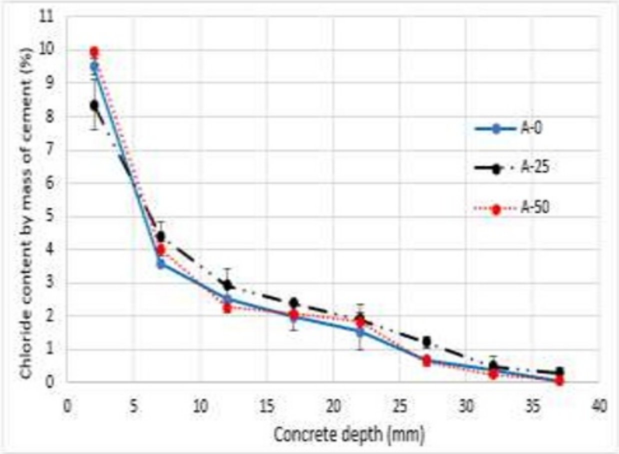


Figure 7: Chloride diffusion profile for 0.55 w/b concrete mixes

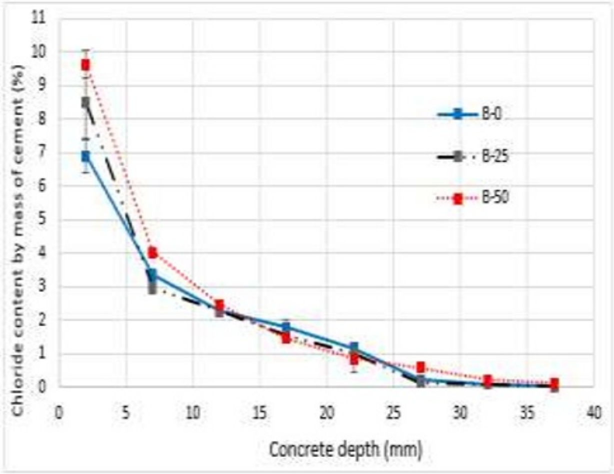


Figure 8: Chloride diffusion profile for 0.45 w/b concrete mixes

## 4 Conclusion

Based on the results of this study, the following conclusions can be made:

- For a given w/b, the surface electrical resistance and the chloride conductivity index of concrete containing up to 50% FRA, is comparable to the reference natural aggregate concrete (NAC).
- Extended curing is more beneficial to FRA concrete than NAC as the electrical resistance of FRA concrete is more significantly improved than NAC.
- Incorporating up to 50% FRA in concrete did not impact the chloride ingress resistance of concrete, as the chloride diffusion profile of NAC and FRA are similar.

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