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Corrosion rate of reinforced concrete incorporating recycled concrete aggregates

B M Ameen[1*] and B Al-Numan[1]

[1]Department of Civil Engineering, Tishk International University, Erbil, Iraq 46001

*E-mail: bnar.abubakir@tiu.edu.iq

Abstract. One of the main strategies to reduce environmental impact of the concrete industry is to recycle/reuse waste materials. However, one of the unknown aspects of recycled aggregate concretes is their durability in harsh environments. This study presents research work on the mechanical and durability properties of concrete incorporating recycled aggregate. Recycled aggregate was made by crushing the demolished concrete from a building site in Erbil. Six types of concrete mixtures were tested: concrete made entirely with natural aggregate as control concrete, and five types of concrete made with natural fine and recycled coarse aggregate (20%, 40%, 60%, 80%, and 100% replacement of coarse recycled aggregate). Superplasticizer was used to reduce water/cement ratio. Two tests were performed, including compressive strengths test and electrical resistivity test under chloride-contaminated environments, which indirectly measures corrosion rate of concrete. The results show that electrical resistivity decreases with increasing incorporation level of RCA. Regarding corrosion tests, the ER of 100%RCA concrete was about 57% of the corresponding ER of the control specimen. However, 49% reduction for control specimen and a 42.29% reduction for 100% RCA concrete under natural chloride attack. In addition, the chloride attack does not affect the compressive strength of recycled aggregate concrete.

1. Introduction

As sustainability matter, reusing of wasted materials in the construction industry is more crucial nowadays. The advantage of reusing demolished concrete comprises less pollution, limiting landfill space, and reserving natural aggregate resources. The concrete's strength and electrical resistivity are affected by the contents of the concrete, especially coarse and fine aggregates that make up most of the concrete. The cement pastes and the physical and chemical properties of the aggregates control the strength and durability of the concrete. These days environmentally safe materials are preferable as a matter of sustainability, improving durability, plus limiting usage of natural resources.

Reinforcement corrosion is an electrochemical reaction that appears when an electrically connected metal meets a solution with mobile particles. The electrode potential is presumed to be supported by the metal and essence of the mixture [1]. The risk of reinforcing corrosion can be indicated by the electrical resistivity of concrete regardless of mix design and exposure conditions. Corrosion of steel reinforcement is expected in the case of lower concrete resistivity (<10 kΩ cm) [2]. Cement matrix and porosity, as well as pore sizes, are intimately associated with electrical resistivity. Recycled concrete is presumed to have its own special microstructure and porosity that differ from ordinary concrete [3]. In the salinity environment, substituting half of the cement by industrial byproducts and all the natural aggregates by the recycled coarse aggregate, no immaterial changes were remarked [4]. CEM II/B-V and CEM III/A with two-thirds of recycled coarse aggregate concrete showed better performance in terms of risk of corrosion than the usual concrete [5]. Cement hydration decreases with the increase of coarse aggregate. However, increasing coarse aggregate causes increasing in bulk resistivity. Electrical resistivity inversely goes with recycled coarse aggregate, while water absorption is proportional to recycled coarse aggregate. However, it is vice versa for fine aggregate. Therefore, recycled coarse aggregate with fine aggregate together is more effective on water absorption to decrease more than the present one of the aggregates in the concrete mix. Consequently, it is more recommendable to manufacture concrete with recycled aggregates. Moreover, the recycled concrete mixture with the superplasticizer had better performance [7].

This study focuses on determining the relationship of mechanical and chemical properties between the recycled concrete (recycled coarse aggregate concrete) and the ordinary concrete (natural coarse aggregate concrete) and whether the concrete mixture containing local recycled concrete aggregate as a substitute for natural coarse aggregate would perform sufficiently in terms of durability and resistivity.

2. Materials and Methodology

The experimental work comprises of casting and testing twenty-four cubes and thirty cylinders, to investigate the change in compressive strength, and the corrosion rate by substituting natural coarse aggregate with recycled coarse aggregate, for 0%, 20%, 40%, 60%, 80%, 100% of recycled coarse aggregate mixes, Superplasticizer was used throughout the mixes.

2.1. Cylinders and Cubes Specimens Description

In this study, for each mix, 4 cubes of size 100mm x 100mm x 100mm and 4 cylinders of size 100mm x 100mm x 100mm are cast. cubes are used to determine the compressive strength of concrete at 28 and 56 days. And cylinders are used to determine the corrosion rate of the concrete by measuring the electrical resistivity of the concrete.

2.2. Material

The used materials in this work are cement, sand, natural coarse aggregate (NCA), and crushed coarse aggregates (RCA) obtained from demolished concrete blocks from a building site in Erbil.

2.2.1. Cement

Cement The cement which used in this study was ordinary Portland cement (OPC) Type-I. Its physical and chemical properties comply with Iraqi specifications.

2.2.2. Recycled Coarse Aggregate, Natural Coarse Aggregate, and Fine Aggregate

The RCA was prepared by manually crashing waste concrete from a building site in Erbil. The NCA used in this study was locally produced. The NCA utilized in this work was locally manufactured Both RCA and NCA were produced with a maximum size of 25mm.

The FA used in this study was natural and locally manufactured aggregate. As (figure1) and (table 1) show the aggregates' sieve analysis and physical properties of the aggregates.

Table 1 Properties of RCA, NCA, & FA

Properties	Reycled course Aggregate	Fine Aggregate	Natural Course Aggregate
Specific gravity	2.7	2.74	2.63
Water absorption	2.67%	1.58%	0.67%
Density	2790 Kg/m^3	1755 Kg/m^3	1695 Kg/m^3

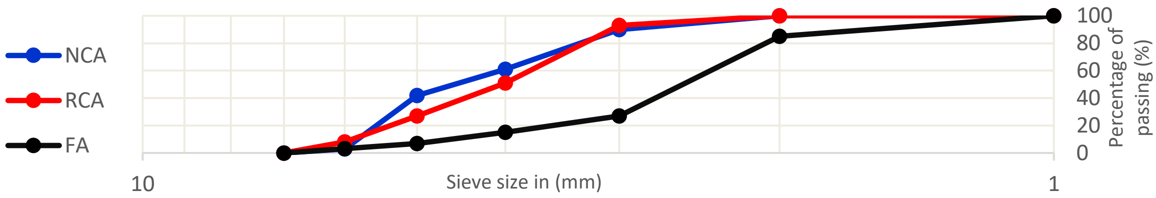

Figure 1 Aggregates sieve analysis

2.2.3. Superplasticizer
Superplasticizer is a retarder admixture that is added to concrete to increase its workability. And the properties of the used superplasticizer in this work.
Type Sika Viscocrete Super E4-S confirms to requirements of ASTM C494-Type G is used as a superplasticizer.

2.2.4. Water
As water is one of the main components of the concrete, pure and saline water was used in this work. Water: Ordinary clean portable water, free of particulate matter and chemical substances, was used for both mixing and curing concrete samples cast with fresh water.

Saltwater (saline solution): Seawater is water from a sea or ocean. On average, seawater in oceans has a salt content of around 3.5% (35 g / l). This means that every kilogram (about one-liter volume) of seawater contains about 35 grams of dissolved salts (mainly sodium (Na +) and chloride (Cl–) ions). After normal curing in pure water for 28 days, half of the samples, cylinder (for eight weeks), and cubes (for 28 days) were cured in saline using 35 g of salts in one liter of water up to the test days.

2.3. Electrical Resistivity
Electrical resistivity is "the ratio between the applied voltage and the electrical current flowing through a sample." or "the resistance of materials to the passage of electrical current." [7].

Indication of the electrical resistance would help to determine concrete corrosion of steel bars and the durability of concrete. The electrical resistivity apparatus comprises a set of cells: connecting cables, a sample holder - bulk, a pair of D100 contact sponges, a concrete probe, a controller, and a set of rods. The electrical resistivity apparatus measures the electrical resistivity of concrete in a non-destructive way to indicate the concrete's corrosion rate. The apparatus is the power source as well, which automatically supplies (60V) DC. Power applies to the outer probs, and the corrosion rate is determined by indicating the electrical resistivity of the inner probs electromotive (figure 2). This test is quick and instantly gives the corrosion rate, and it complies with ASTM Standard C1760-12.

In the bulk resistivity method (uniaxial method), the test conducts by locating the electrodes with a sponge between them on the surface of the concrete.

Figure 2 Electrical resistivity apparatus

2.4. Methodology
2.4.1. Mix Proportion
The weight of material used for one meter cubic are shown in (Table 2) for recycled coarse aggregate (0%, 20%, 40%, 60%, 80%, and 100%). Superplasticizer was used to improve the workability and to obtain a water-cement ratio of 0.3.

Table 2 Mix proportions of the specimens

No	Replacement %	Water Kg/m^3	cement Kg/m^3	N.A. Kg/m^3	R.A. Kg/m^3	F.A. Kg/m^3	SP ml/m^3
1	0	102	340	1000	0	650	34000
2	20	102	340	800	200	650	34000
3	40	102	340	600	400	650	34000
4	60	102	340	400	600	650	34000
5	80	102	340	200	800	650	34000
6	100	102	340	0	1000	650	34000

*SP= superplasticizer (34000) per manufacturer's guidance * FA= Fine Aggregate * NA= Natural Aggregate
* RCA= Recycled Coarse Aggregate

2.4.2. Mixing Procedure, Casting, and Curing
Specimens' production started with bringing the crushed normal weight blocks, and further manual crushing was done with simple crushing tools until reaching the quantities required with a max size of 25 mm. Concrete mixture was prepared by mixing coarse and fine aggregate with cement, then water added to it, mixture poured inside the cylinders and cubes by two layers and tamped each layer with 35 strokes using Tamper. After casting and finishing the cylinders and cubes with fresh recycled coarse aggregate concrete, the specimens were kept in ambient temperate for 24 hours, de-molded, and placed in water for curing. Electrical resistivity measurement started from day 28 till day 90 once per week, and the specimens were placed in saline solution from day 28. Cubes were tested on day 28 tested for compressive strength, and the remaining cubes were cured in saline solution for the 2nd compressive strength test, which was on day 56.

3. Results and Discussion
3.1. Workability
The slump test determined the workability. The slump from the control specimen to 100% RCA was ranged from (90mm to 20mm) respectively. The natural coarse aggregate used in this work was more granular and softer. However, the recycled coarse aggregate was rough-textured, which caused low workability. However, adding the superplasticizer improved workability for RCA concrete.

3.2. Compressive Strength
Figures 3a and 3b show the 28-day and 56-day compressive strength. The 56-day compressive strength specimens were saline-cured during the last 28 days of age. The 28-day compressive strength ranged (32-47) MPa for 100% to 0% RCA replacement, with 38% strength reduction for 100% RCA. The regression is seen semi linear.

$$28\text{-day; } f_{cu} = 46.9297e^{-0.351(RCA)} \text{ (MPa)}$$

(RCA is in decimals) may give a best expression.

When the second half of cubes after 28 days of curing in pure water and 28 days in saline solution were tested in their compressive strength, the effect shown greater for greater RCA %, the respective range of strength was (47.55 – 54.1) MPa, with a 13% strength reduction. However, there is about a 14% increment for the control specimen and about a 39% increment for 100% RCA. The equation for fcu can be expressed as 56-day.

$$f_{cu} = 53.783e^{-0.126(RCA)} \text{(MPa)}$$

(RCA is in decimals).

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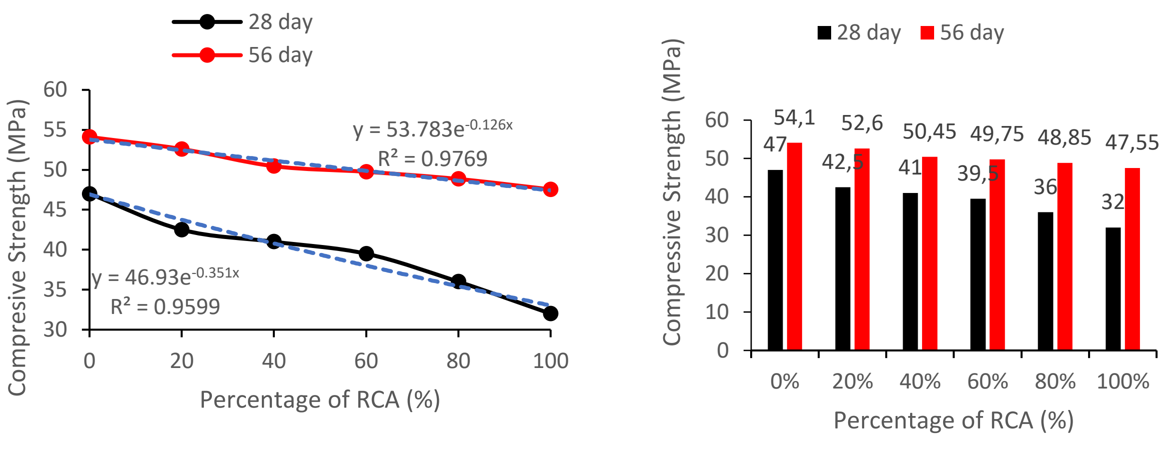
The weaker bond between the RCA and the mortar and the higher absorption and porosity of the RCA might contribute to the strength reduction that gives concrete a porous constitution. Hence, the ratio of 28-day to 56-day strengths, greater value for the control specimen (0.864), and a lower value for 100 % RCA (0.673). Thus, the RCA concrete has less ratio of 28-day to 56-day strength ratio than the control concrete.



(a) *(b)*

Figure 3 Result of compressive strength

3.3. Electrical Resistivity

Reinforced concrete structures life span controlling by the corrosion rate. Oxygen availability, the anodic/cathodic area ratio, relative humidity (RH), and concrete electrical resistivity play a significant role in increasing corrosion rate. In the presence of sufficient oxygen exposing to anodic current cathodic could not be controlled. Therefore, Electrical resistivity can be a way to limit corrosion rate.

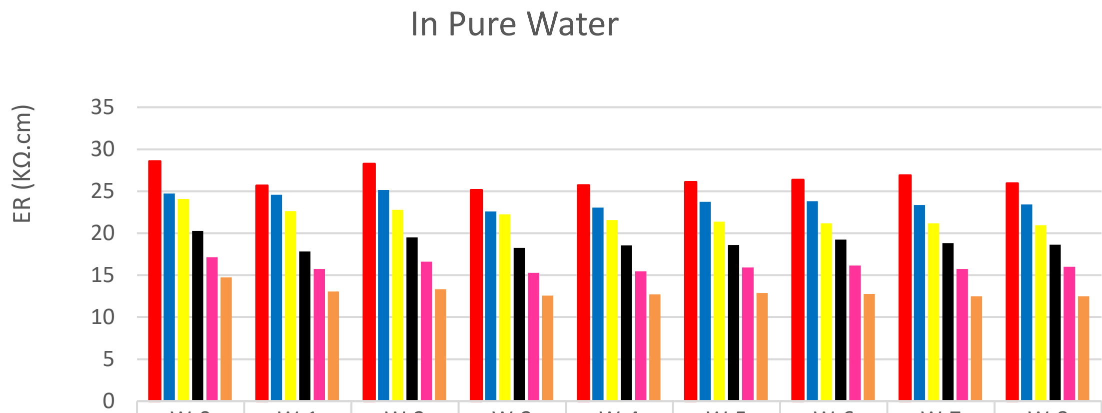
Scholars approved that corrosion of reinforcement concrete is in an inverse relation with electrical resistivity. Thence when electrical resistivity increases corrosion rate of steel reinforcement decreases.

The corrosion potential of concrete plays a vital role in varieties' corrosion rates. ASTM C876 technique for mapping half-cell potential is the only standard test. Thus, the corrosion potential and corrosion rate of steel reinforcement might be determined efficiently by electrical resistivity. Some researchers and commercial manuals for Wenner probe instruments (Proceq and Giatec Scientific Inc.) provided general guidance on the risk of corrosion. They grouped the value of conventional concrete resistance into four broad types for which the risk of corrosion of the reinforcement is high, moderate, low, and negligible when interpreting electrical resistivity measurements, as shown in (table 3).

Table 3 Guidelines for corrosion resistance

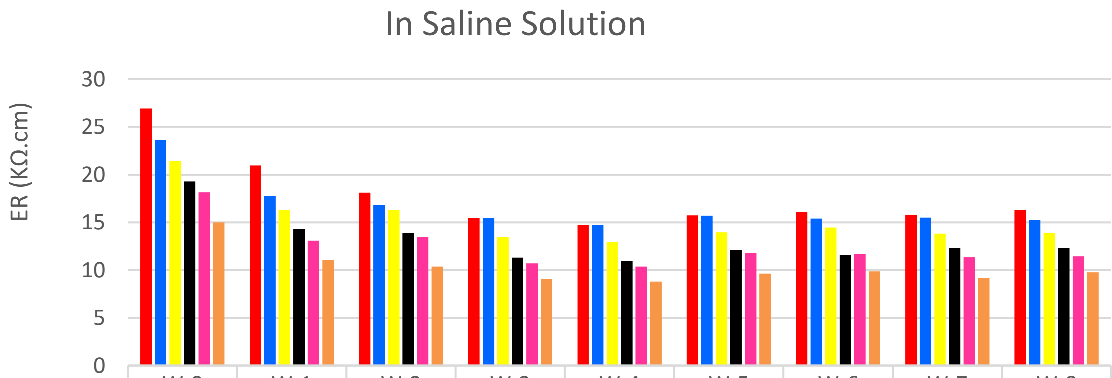
Concrete resistivity and risk of corrosion of steel reinforcement. Reistivity values (kΩ cm)		
Corrosion risk	**Polder**	**Commercial wenner probeinstrument manuals**
High	<10	≤10
Moderate	10-50	10-50
Low	50-100	50-100
Neglible	>100	≥100

The electrical resistivity was measured for recycled concrete in pure water and saline solution for nine weeks (figure 4 and 5). As expected, the electrical resistivity decreases with increasing RCA percentage and with exposure time. The electrical resistivity ranged (28572-14734) Ω.cm in week 0, as shown in (figure 4). The greater value is for the control specimen and the lower value for the 100% RCA in their first reading, with a 63.91% reduction in the resistivity, which signifies an increment in corrosion rate with increasing RCA percentage.



	W-0	W-1	W-2	W-3	W-4	W-5	W-6	W-7	W-8
P-0% RCA	28572	25691	28260	25133	25704	26094	26382	26890	25946
P-20% RCA	24728	24574	25133	22608	23069	23737	23832	23349	23442
P-40% RCA	24062	22635	22789	22247	21575	21359	21195	21195	20962
P-60% RCA	20272	17820	19513	18252	18551	18582	19258	18814	18647
P-80% RCA	17133	15749	16624	15276	15485	15931	16149	15741	15984
P-100% RCA	14734	13078	13325	12585	12727	12879	12753	12502	12478

Figure 4 ER in pure water



	W-0	W-1	W-2	W-3	W-4	W-5	W-6	W-7	W-8
S-0% RCA	26937	20944	18115	15447	14722	15725	16090	15793	16261
S-20% RCA	23623	17780	16843	15447	14722	15705	15380	15478	15242
S-40% RCA	21409	16261	16261	13468	12914	13945	14450	13824	13891
S-60% RCA	19275	14286	13901	11317	10920	12119	11556	12294	12306
S-80% RCA	18142	13083	13468	10710	10357	11774	11660	11343	11423
S-100% RCA	14987	11084	10353	9058	8804	9645	9879	9152	9755

Figure 5 ER in saline solution

Therefore, the corrosion risk for the control specimen can be considered moderate to negligible, and for the 100%, RCA is moderate or low as shown in (figure 6), according to the scholars' guidelines (table 3).

Resistivity reduction increases to 70.1% (W8-P0%RCA to W8-P100%) after eight weeks' exposure to the pure water, which ranged (25946-12478) Ω.cm. as shown in (figure 4), with a 10% reduction for the control specimen, and 16.58% reduction for the 100% RCA, as in (figure 4) shown. No changes were observed in the corrosion risk after the exposure (figure 6).

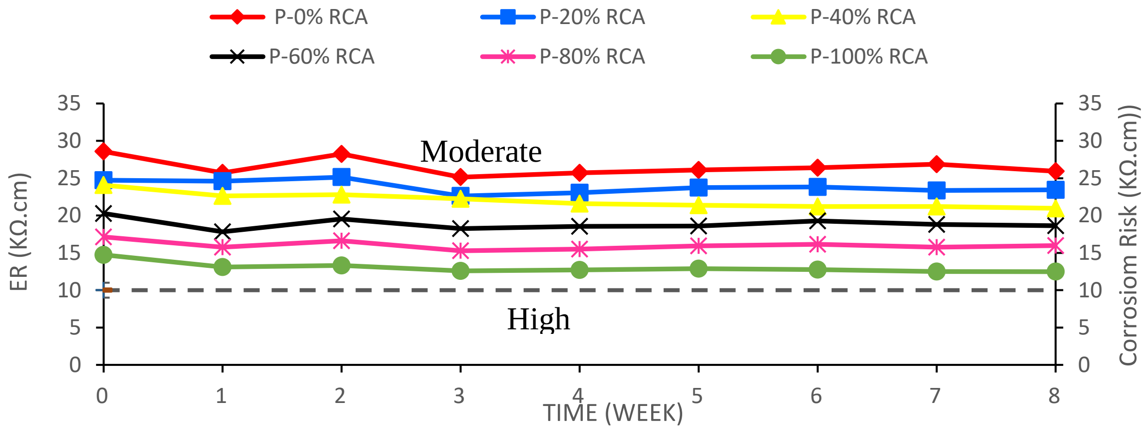


Figure 6 Corrosion risk for pure water

Figure 5 shows the results in saline solution with salinity (3.5%). After eight weeks' exposure to saline solution, the resistivity ranges (16260.5- 9755) Ω.cm. with 50.01% (W8-S0%RCA to W8-S100%) reduction, 49.43% reduction for the control specimen, and 42.29% reduction for the 100% RCA.

Corrosion risk changed to moderate or high after exposure to the saline environment. It indicates that salinity plays a vital role in increasing corrosion risk.

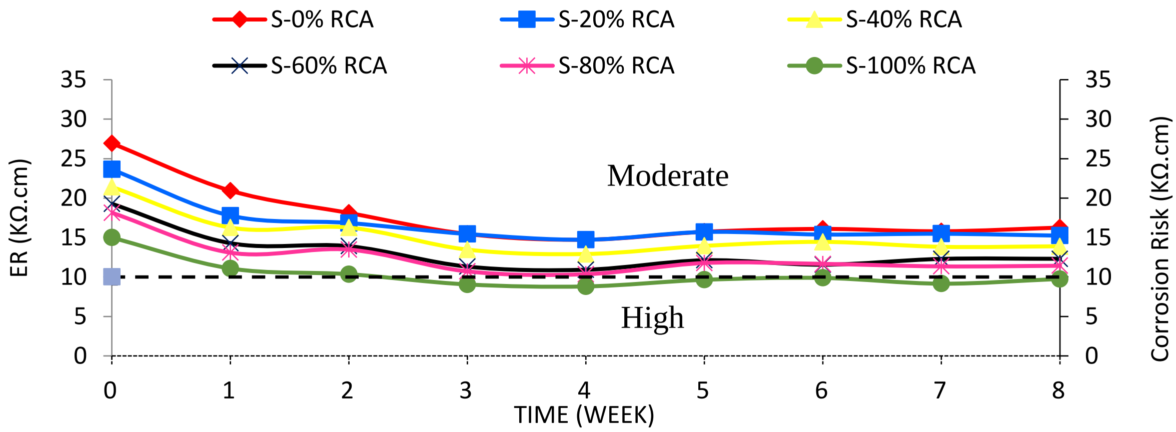


Figure 7 Corrosion risk for saline solution

From (figure 8.a to 8.f) and (figure 9), the decrement in electrical resistivity can be observed, strongly related to the increase in RCA%. It can be observed from (figure 8.a) that the decrement increases from 20.5% to 45.9%, week 1 to week 8 for the 0% RCA. However, for the 60% RCA increases from 24.51% to 46.27% (figure 8.d), and for the 100% RCA increases from 16.5% to 24.5%. as shown in (figure 8.f).

It indicates that electrical resistivity decreases with increasing RCA%, with increasing RCA% negative effect of salinity on concrete decreases, and a significant decrease of the negative effect of salinity is found with increasing RCA% as (figure 5 and 7) reveal. In general, RCA concrete has a lower ER than ordinary concrete of 14% in w0 for pure curing and 10% after w8 for pure curing) for 20% RCA concrete to (64% in w0 for pure curing & 70% after w8 for pure curing) for 100% RCA concrete, cannot be agreed with Dodds et al. (2017) that RCA concrete may outperform control concrete and may have a lower risk of corrosion (figure 10).

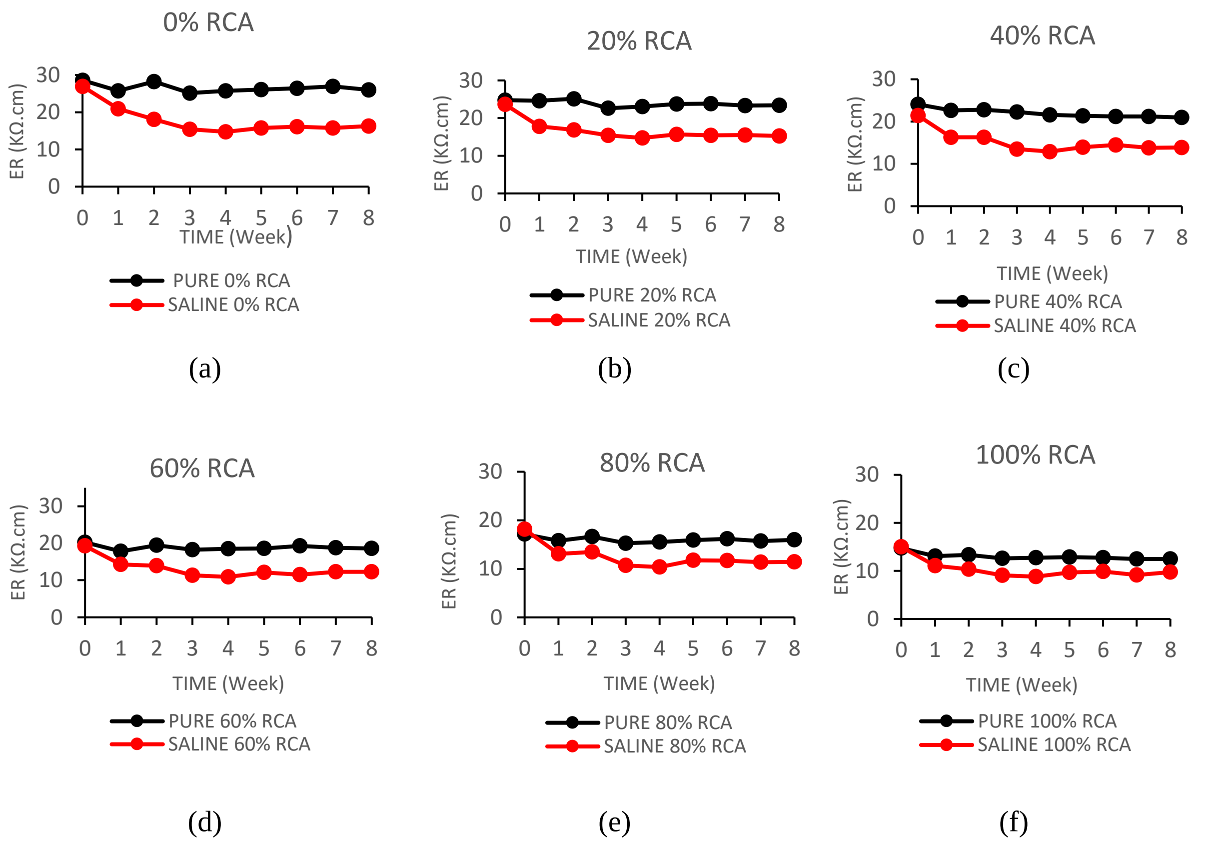


Figure 8 Electrical resistivity of RCA concrete

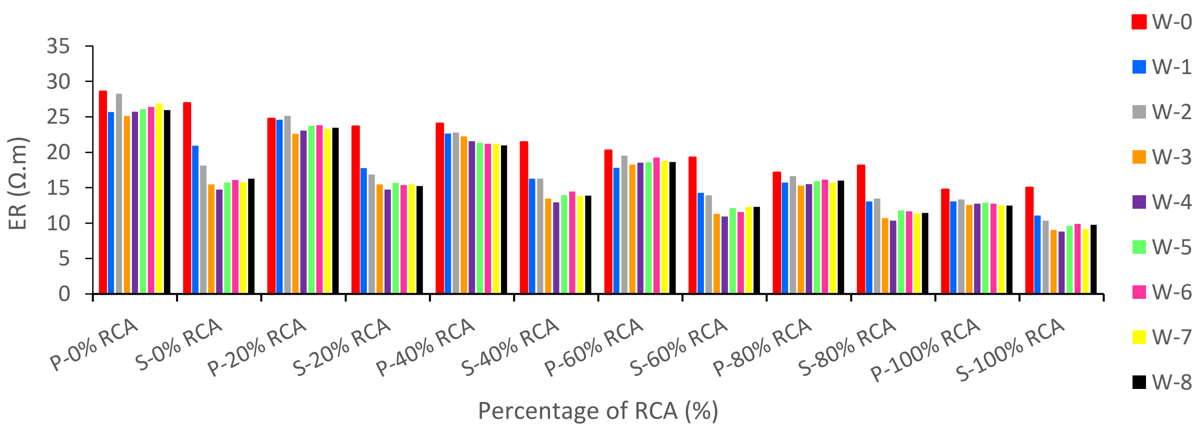


Figure 9 Comparison of resistivity in pure and saline solution

In general, RCA concrete has a lower ER than ordinary concrete of 14% in w0 for pure curing and 10% after w8 for pure curing) for 20% RCA concrete to (64% in w0 for pure curing & 70% after w8 for pure curing) for 100% RCA concrete, cannot be agreed with Dodds et al. (2017) that RCA concrete may outperform control concrete and may have a lower risk of corrosion (figure 10).

However, this work agrees well with Arredondo et al. work [3]. The RCA concretes of this work lie within ranges of "Moderate to Hight" risk of corrosion, as shown in (figure 8). In a research work made by Abdulla et al. [10], which used recycled brick aggregate to replace NCA, the risk is increased to the higher side, as shown in (figure 11).

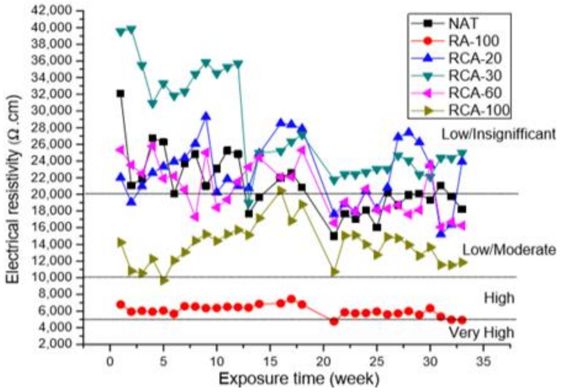


Figure 10 Progression of ER with RCA (Arredondo-Rea et al.)

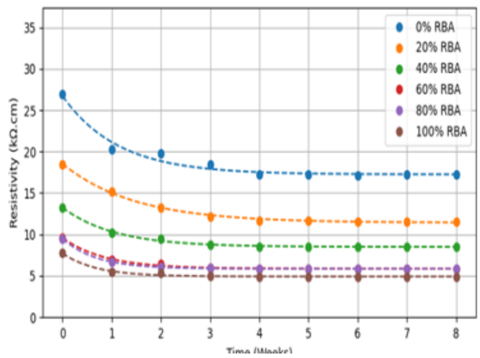


Figure 11 RBA concrete ER exposed to 3.5% NaCl solution. (Azba A. et al.)

4. Conclusion

In addition to the strength of RCA concrete, this study also focuses on the electrical resistivity (ER) of recycled concrete for durability evaluation. This study can draw the following conclusions. The 28-day compressive strength ranged (32-47) MPa, which decreased RCA% with 38% strength max reduction. The 56-day compressive strength ranged (47.55 – 54.1) MPa, with a 13% strength max reduction. There is about a 14% increment for the control specimen and about a 39% increment for 100% RCA. In general, curing cubes in saline solution for 28 days after 28 days of normal curing did not negatively impact the compressive strength of recycled concrete, as expected and reported from previous studies.

The electrical resistivity in pure water ranges (28572-14734) Ω.cm, greater value is for the control specimen and the lower value for the 100% RCA in their first reading, with 63.91% reduction. The corrosion risk for the control specimen can be considered moderate or negligible, and for the 100%, RCA is moderate or low. The reduction of resistivity increases to 70.1% after eight weeks' exposure to the pure water, ranges (25946-12478) Ω.cm., with 10.04% reduction for the control specimen 16.58% reduction for the 100% RCA (pure to saline). Electrical resistivity After eight weeks' exposure to saline solution ranges (16261- 9755) Ω.cm. with 50% reduction, 49.43% reduction for the control specimen, and 42.29% reduction for the 100% RCA (pure to saline). The corrosion risk is moderate or high after exposure to the saline environment. It might conclude that salinity environmental harms the concrete by increasing the corrosion rate of concrete and recycled concrete. The corrosion risk rises from 20.5% to 45.9%, week 1 to week 8 for the 0% RCA. However, for the 100%, RCA increases from 16.5% to 24.5%.

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