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Investigation into Durability of Concrete Made of Recycled Masonry Coarse Aggregate and Pozzolan

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ABSTRACT

This study examines the effect of varying levels of recycled masonry coarse aggregates (RMCA) on the durability properties of recycled concrete (RC). Four series of RC were produced with RMCA replacement levels of 0%, 25%, 50%, and 100%. To enhance the properties of the RC, different dosages of silica fume (SF), natural zeolite (NZ), and fly ash (FA) were used as partial replacements for cement. A total of 40 mixed designs were prepared, and key properties, including compressive strength (CS), water absorption by capillarity (WAC), water absorption by immersion (WAI), electrical resistance (ER), and rapid chloride ion penetration (RCPT), were evaluated. The results indicated that the target CS of 40 MPa at 28 days could be achieved in RC containing up to 50% RMCA with 5% or 10% SF and 10% NZ. In terms of durability, significant reductions in WAI, WAC, ER, and RCPT were observed in RC with 100% RMCA. Furthermore, the combination of 10% NZ and up to 50% RMCA replacement resulted in a 19% reduction in WAI. A low risk of chloride ion penetration was found in mixtures containing 5% and 10% SF, regardless of the RMCA replacement level. However, the use of various percentages of class F of FA, due to its chemical composition and limited cementitious properties, did not lead to improvements in CS, WAC, WAI, ER, or RCPT.

Keywords: Durability, Recycled masonry coarse aggregates, Recycled concrete, Silica fume, Natural zeolite, Fly ash.

INTRODUCTION

Today, the construction industry is the largest consumer of natural resources and a major producer of waste, significantly contributing to environmental pollution. There are multi-faceted challenges of managing construction and demolition waste within the context of construction industry in some countries (Alshdiefat et al., 2023). Research shows that construction waste constitutes from 13% to 29% of total waste produced worldwide (Khayati, 2015). In the United States alone, the amount of construction waste generated has reached approximately 140 million tons annually, while the European Union estimates that construction waste production totals 970 million tons per year (Yuan et al., 2012). In recent decades, the use of recycled aggregates (RAs) in concrete production has gained more attention due to environmental concerns, necessitating the conservation of natural aggregate resources, resulting in a shortage of waste disposal sites, and increasing costs associated with waste treatment prior to disposal (Ibrahim et al., 2023). In structural applications, certain standards in countries like Brazil restrict the use of recycled aggregates (RAs) (Brazilian Association of Technical Standards, 2004), while the UK concrete code sets a maximum replacement limit of 20% (British Standard BS, 2006). However, Malazdrewicz (2023) has demonstrated that aggregates produced from construction and demolition waste can be effectively used for concrete production. Additionally, engineering societies are actively working to promote the broader use of recycled aggregates in various applications. Furthermore, engineering societies are working to expand the use of RAs in general applications. Although extensive information is available on the mechanical properties of RAs, there is less agreement among researchers regarding the durability of these concretes (Ayele Abera, 2022; Abdul Basit et al., 2023; Jalilifar et al., 2020). Several factors significantly influence both the compressive strength (CS) and the durability of concrete. These factors include the replacement levels of recycled aggregates (RAs), the moisture content of RAs, the quality of the original materials, the water-to-cement ratio, the use of chemical admixtures, and various pozzolanic additives. Studies by Dhir et al. (2005), Leite (2001), Khalaf (2006), Pavlu et al. (2021), Pereira et al. (2012), and Sajedi and Jalilifar (2019) underscored the critical role that these elements play in determining the performance of concrete. Many researchers have reported significant reductions in both mechanical and durability properties of recycled concrete (RC) at high replacement levels (Sajedi & Azhdarizadeh, 2021; Fernando Silva & Delvasto 2021; Jalilifar et al., 2020). Generally, the physical shortcomings of RAs, such as high porosity, high water absorption, and lower density, are among the most critical factors contributing to the loss of mechanical properties in concrete (Sajedi & Azhdarizadeh, 2021). Several studies have attempted to mitigate the adverse effects of RAs on the durability of RC by increasing density and filling the pores and micro-cracks in RAs through immersion in supplementary cementitious materials' (SCMs) slurry (Tam et al., 2005). Other researchers have shown that SCMs can improve the mechanical and durability properties of concrete at optimal replacement levels due to their filler and pozzolanic properties (Alsharie & Alayed, 2019; Pan et al., 2019).

In recent years, varios studies have been conducted to investigate the durability of concrete made from recycled masonry aggregates (Pavlu et al., 2021; Levy & Helene, 2020). Also, numerous researchers have used SCMs, such as silica fume (SF), natural zeolite (NZ), fly ash FA, ground granulated blast slag (GGBS) and marble powder (MP), to enhance the durability of concrete and reduce the negative effects of high RA replacement levels (Kou et al., 2011; Sajedi & Jalilifar, 2019; Gopalakrishna & Dinakar, 2023; Kurda et al., 2019; Majhi & Nayak, 2019; Murumi & Gupta, 2019; Sancheti et al., 2020). Some studies using pozzolanic materials have achieved desirable mechanical properties even at replacement levels above 50% (Sajedi & Azhdarizadeh, 2021; Azhdarizadeh & Sajedi, 2021). For instance, Toghroli et al. (2020) found that partially replacing cement with SF reduces the porosity of mixes through micro-filling and pozzolanic reactivity. Kou and Poon (2012) explored various cement replacement levels using FA and suggested that a mix containing 50% natural aggregates (NAs) and 25% FA is optimal for RC. Other studies have shown that the pozzolanic activity of NZ enhances the mechanical properties and durability of concrete (Ahmadi & Shekarchi, 2010; Bilim, 2011; Karakurt & Topcu, 2011). Furthermore, research has demonstrated that RC containing up to 50% RAs and 10% NZ can outperform natural concrete (Sajedi & Jalilifar, 2017). Kurda et al. (2019) studied the effect of FA on water absorption and electrical resistivity in RC and found that water absorption increased and electrical resistivity decreased with higher levels of recycled concrete coarse aggregates (RCCAs). Majhi and Nayak (2019) investigated the durability of RC made with 50% RCCA and 40% GGBS and found similar durability properties to conventional concrete (CC). Additionally, Jalilifar et al. (2020) reported that water absorption by immersion (WAI) and water absorption by capillarity (WAC) of RC increased with higher levels of RCCA and found that concretes containing NZ had higher WAI than those with SF. They also noted that increasing NZ content beyond 10% led to increased cavity spaces between silicate gels, thereby increasing WAC and rapid chloride penetration test (RCPT) in concrete. However, the use of 10% SF produced concrete with very low chloride-ion penetration.

Recent research has primarily concentrated on the utilization of recycled concrete aggregates in the production of concrete, while there has been comparatively less focus on RMCA. The limited studies conducted in this area have predominantly addressed the mechanical properties of concrete made with RMCA. Consequently, this study aims to investigate the impact of varying levels of RMCA replacement on the CS and durability of RC at both 28 days and 180 days of curing. To achieve this aim, four replacement levels of RMCA; namely, 0%, 25%, 50%, and 100%, were employed in the production of the RC samples.

Given the established benefits of SF in enhancing the quality of RC and the availability of NZ as an economical mineral material abundant in Iran, this research incorporates both SF and NZ to investigate their effects on the performance of RC. Additionally, FA, recognized for its pozzolanic properties and being widely studied, is included as a benchmark for comparison against the performances of SF and NZ.

In this study, varying percentages of these pozzolans were selected based on insights from previous research. Specifically, three different levels were utilized for each material: SF at 5%, 10%, and 15%; NZ at 10%, 20%, and 30%; and FA at 15%, 25%, and 35%. The aim is to evaluate how these pozzolans influence the CS and durability of the concrete, providing a comprehensive understanding of the effects of their addition in the context of RC.

The specific dosages of supplementary cementitious materials (SCMs) utilized in this research were carefully selected based on their successful application in previous studies, including the works of Sajedi and Azhdarizadeh (2021) and Kou et al. (2011). The primary aim of this paper is to examine the mechanical properties and durability performance of recycled masonry concrete that achieves a minimum CS of 40 MPa. This concrete is formulated using recycled masonry coarse aggregates, with a focus on determining the optimal percentage of both pozzolanic materials and recycled aggregates.

To assess the performance of the concrete, comprehensive testing was conducted, which included CS tests performed at 28 days. Additionally, a series of durability tests were executed at 180 days to evaluate various properties, such as water absorption capacity (WAC), water absorption index (WAI), electrical resistance (ER), and rapid chloride permeability (RCP). The outcomes of these assessments aim to provide insights into the effectiveness of the selected pozzolanic materials in enhancing both the mechanical strength and durability of recycled masonry concrete.

MATERIALS AND METHODS

a) Materials

The cementitious materials (CMs) used in this study included ordinary Portland cement (OPC), classified as ASTM C150 Type II, along with SF, NZ, and FA. The total amount of CMs used was 420 kg/m³.

River sand with a maximum particle size of 4.75 mm and a fineness modulus of 3.1 was used as the fine aggregate, while crushed aggregate with a maximum size of 19 mm was employed as the coarse aggregate in the concrete mixes. In this study, the natural coarse aggregate was replaced with RMCA, also with a maximum size of 19 mm. The RMCA was composed of broken bricks, cement plaster, tiles, and ceramics, all sourced from demolished buildings in Ahwaz. Initially, construction waste was collected from various depots in the required amounts, after which non-concrete debris, such as soil, gypsum, glass, and metals, was separated. The remaining construction waste was then crushed and graded using a grinding machine (Figure 1), followed by sieving. Figure (2) illustrates the RMCA used in the concrete mix design.

Figure (1): Grinding machine used for crushing and grading of construction waste

Figure (2): Recycled masonry coarse aggregate

The water used in this research was potable water from Ahwaz city. Additionally, a polycarboxylate-based superplasticizer (SP) with a density of 1.1 ± 0.02 g/cm³ was employed to achieve the desired workability. The maximum dosage of 1% by weight of the CM ensured the required workability.

b) Mixing Approach

Two types of concrete mixes were produced: CC and RC. The CC mix was prepared using 100% NA, while the RC mixes were prepared with 25%, 50%, and 100% replacement of natural coarse aggregate with RMCA. Three levels of SF (5%, 10%, and 15%), NZ (10%, 20%, and 30%), and FA (15%, 25%, and 35%) were incorporated into the RC mixes. The RC mixes containing SF, NZ, and FA were labeled as RCSF, RCNZ, and RCFA, respectively. All mixes were produced with a constant water-to-binder (W/B) ratio of 0.36 and a CM content of 420 kg/m³. The mixes were developed using a 150-liter laboratory mixer, following a method inspired by the two-stage mixing approach (TSMA) (Fernando Silva & Delvasto, 2021) and the three-stage mixing method (Jalilifar et al., 2016). This method aimed to ensure the complete penetration of pozzolanic slurry into the voids of the RMCA, creating a thin layer of CM on the RMCA and enhancing the concrete's overall properties. The procedure was as follows: first, all coarse aggregates, one-third of the water, and a half of the pozzolanic material were mixed for 1 minute. Next, a half of the natural sand, a half of the cement, and another third of the water were added and mixed for 2 minutes. Finally, the remaining materials (a half of the cement, a half of the natural sand, the remaining pozzolanic material, and the final third of the water) were added and mixed for additional 6 minutes. Further details of the mix proportions are provided in Table 1.

Table 1. Mix proportions of different mix designs (kg)

Notation	NCA	RMCA	S	CM	W	SP
CC	937	-	766	420	150	4.2
RC25	703	234	766	420	150	4.2
RC50	468.5	468.5	766	420	150	4.2
RC100	-	937	766	420	150	4.2

c) Research Program

In this investigation, four levels of coarse aggregate replacement (0%, 25%, 50%, and 100%) were studied, along with three levels of SF (5%, 10%, and 15%), NZ (10%, 20%, and 30%), and FA (15%, 25%, and 35%). The percentages of RMCA replacement were calculated based on the total aggregate weight. The mix design followed the guidelines of the Iranian Concrete Code (ICC) (2003), targeting a CS of 40 MPa at 28 days. The CS was determined using a hydraulic press with a maximum capacity of 2000 kN, set to a loading rate of 0.5 MPa/s. The CS test was performed at 28 days in accordance with ASTM C109 (2021) on 120 cubic specimens measuring 150 x 150 x 150 mm. The WAC, WAI, and RCP tests were conducted at 180 days in accordance with ASTM C1585 (2020), ASTM C642 (2022) and ASTM C1202 (2019), respectively, on sets of three disks measuring 100 x 50 mm. Additionally, the ER test was performed at 180 days in accordance with ASTM C1760 (2021) on sets of three cylindrical specimens measuring 150 x 300 mm for each replacement level. All specimens were cast under ambient conditions, demolded 24 ± 2 hours after mixing, and fully submerged in water at a temperature of 25 ± 2°C until the testing age, in accordance with ASTM C39 (2021).

RESULTS AND DISCUSSION

Table 2 presents the physical and chemical compositions of the cementitious materials.

According to ASTM C618, materials that have total weight percentages of silica (SiO_2), iron oxide (Fe_2O_3), and alumina (Al_2O_3) exceeding 70% qualify as pozzolanic materials. Consequently, materials such as SF, NZ, and FA can be utilized as pozzolans. However, based on the observed physical properties and average particle size of fly ash, it is anticipated that its performance may not be optimal in this context.

It is important to note that the primary rationale for substituting pozzolanic materials for a portion of cement in concrete is their favorable reaction with calcium hydroxide $Ca(OH)_2$ released during the hydration process. This reaction helps enhance the binding properties and overall performance of the concrete, potentially improving both its mechanical strength and durability. Despite this, the specific characteristics of FA, including its particle size and other physical attributes, may hinder its effectiveness as a pozzolan in the recycled masonry concrete being studied. Further investigation is warranted to fully understand the implications of using fly ash in this application. The pozzolanic recation related to these materials is shown in Equation (1)

$$Ca(OH)_2 + SiO_2 = Ca(SiO)_3 \, . \, H_2O \qquad (1)$$

Figure (3) presents the grading curves for the recycled concrete aggregate used in the concrete mix design. The physical and chemical properties of the recycled concrete aggregate are detailed in Tables 3 and 4, respectively. The data indicates that the chemical composition of pozzolanic materials shares significant similarities with that of traditional pozzolanic and cementitious materials.

As long as the RMCA's physical properties, such as porosity, water absorption, and mortar adhesion, do not lead to detrimental effects on the concrete, these materials can contribute positively to the performance of concrete made with RA. In particular, the pozzolanic reaction can enhance the binding capabilities within the concrete matrix, promoting improvements in mechanical strength and durability. It is crucial to continue monitoring and testing the physical attributes of RMCA to ensure that any deficiencies do not impede the overall effectiveness of the concrete mixture. Additionally, understanding the interaction between these materials and the cementitious components will be essential for optimizing the concrete's performance and sustainability in applications that utilize recycled materials.

Table 2. Physical and chemical composition of cementitious materials (%)

Composition	**SiO_2**	**Fe_2O_3**	**Al_2O_3**	**CaO**	**MgO**	**SO_3**	**LoI**	**Others**	**Specific gravity (g/cm^3)**	**Specific surface (m^2/kg)**	**Average particle size (µm)**
Cement	19.8	3.9	3.1	65.3	2.5	2.8	2.2	0.4	3.15	295	26
SF	94.7	0.9	1.2	0.5	1.0	0.1	-	1.6	2.26	20000	0.15
NZ	68	2.5	11.5	2.5	-	-	14.2	1.3	2.20	320	16.8
FA	56.7	5.3	26.2	2.8	5.2	0.68	2.7	0.42	2.30	440	37.9

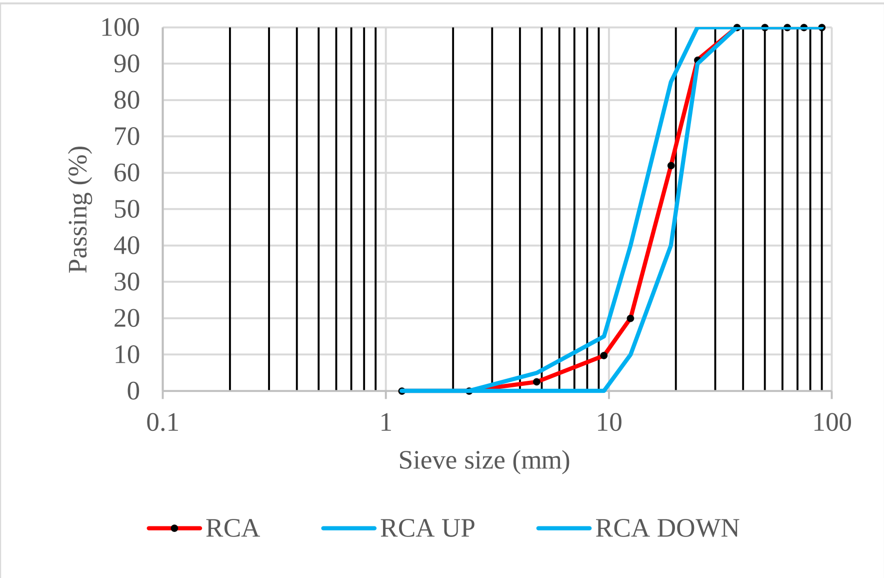

Figure (3): Recycled concrete aggregate particles' grading

Table 3. Physical properties of RMCA

AM (4-9.5) (%)	AM (9.5-19) (%)	Water Absorption (%)	Saturated Surface Dried (t/m^3)
53-66	47-62	14.04	2.32

AM: Attached Mortar.

Table 4. Chemical properties of RMCA (%)

Composition	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	SO_3	CO_3	Others
Amount	40.87	5.36	6.44	25.9	5.72	0.54	12.7	2.47

a) Compressive Strength

The 28-day CS results for CC and RC containing various pozzolans are presented in Table 5and Figures (4-6). The results indicated that for concretes without pozzolanic materials, up to 25% replacement of RMCA did not lead to significant CS losses compared to CC, as they achieved the target CS of 40 MPa due to the presence of 75% NA. Previous research has reported a 24% reduction in the CS of RC containing 50% RMCA (Arulrajah et al., 2016). This research confirms those findings, revealing a 31% reduction in CS compared to CC, attributed to the inherent physical weaknesses of RA relative to NA, such as the weak structure of RMCA compared to NA, as well as the inherent cracks within them. Complete replacement of RMCA resulted in a substantial drop in CS compared to CC, with a reduction of 37%. The reason for this could be the possible weakness in the transition zone of RC due to the low quality and large number of transition zones compared to CC. For RC, the maximum CS was observed in the concrete mixes containing 5% and 10% SF and 10% NZ at the 25% RMCA replacement level. This result can be attributed to the spherical and fine surfaces of SF and NZ, resulting in complete and proper mixing. The addition of SF and NZ can effectively fill the voids of RMCA and the cement paste, enhancing the quality of the interfacial transition zone (ITZ) due to the silicate gels formed on the surface of RMCA.

Furthermore, Figure (6) illustrates that RC containing FA exhibited lower CS at 28 days compared to concretes without pozzolans. This reduction can be attributed to the size particles, chemical composition and lower cementitious properties of class F of FA.

Table 5. 28-day CS of specimens (MPa)

Mixture	Aggregate Replacement (%)			
	0	25	50	100
RC	42.5	40.8	29.4	26.9
RC-SF5	52.0	51.9	45.1	36.1
RC-SF10	55.7	45.3	40.8	36.2
RC-SF15	43.3	41.5	33.2	28.5
RC-NZ10	47.7	45.8	43.7	33.2
RC-NZ20	56.3	41.3	30.6	27.2
RC-NZ30	52.3	43.6	35.6	30.5
RC-FA15	36.1	34.2	32.4	27.2
RC-FA25	36.4	35.4	30.6	27.5
RC-FA35	32.6	27.2	26.7	25.9

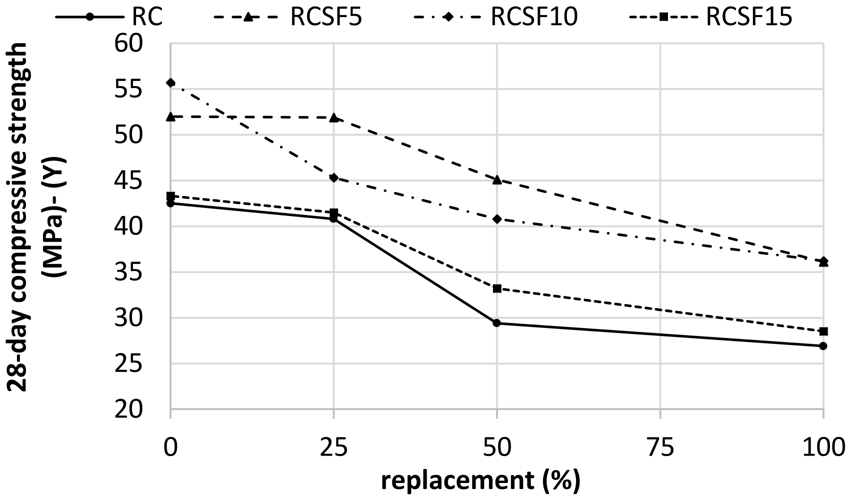

Figure (4): 28-day CS of specimens containing SF

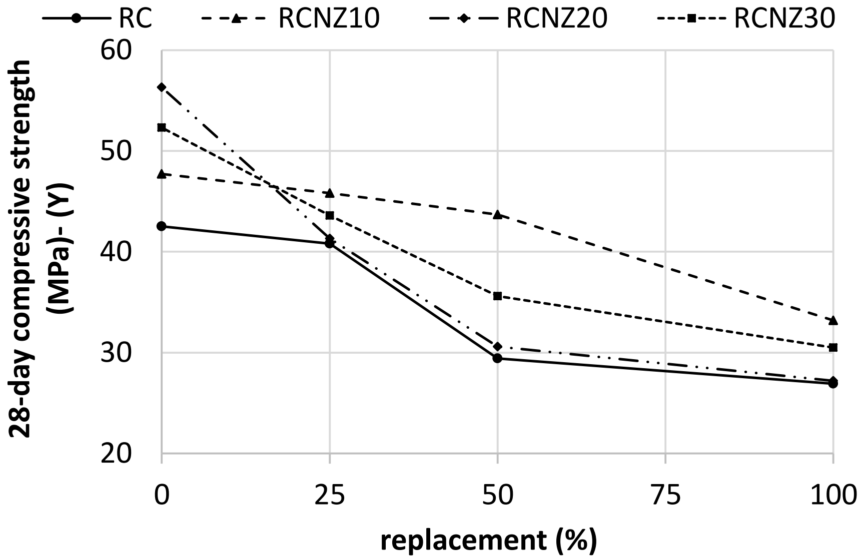

Figure (5): 28-day CS of specimens containing NZ

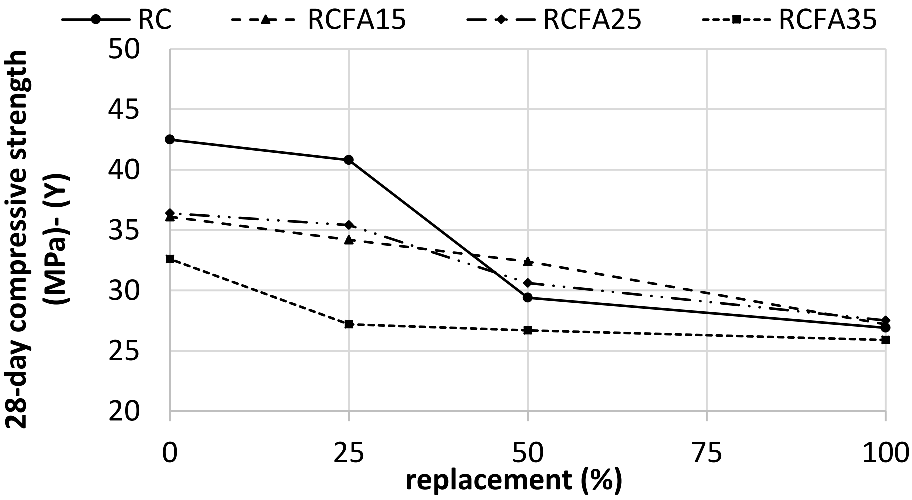

Figure (6): 28-day CS of specimens containing FA

b) Water Absorption by Capillarity (WAC)

The results in Table 6 and Figures (7-9) depict the WAC tests for both CC and RC, with and without pozzolans. A 25% replacement of RMCA showed a negligible increase in WAC, while a full replacement of RMCA resulted in an 89% increase in WAC compared to CC. This increase is attributed to the significantly lower physical properties of RMCA, such as higher pore structure and higher water absorption, compared to NA, which led to an increase in the size and volume of capillary pores at higher RMCA replacement levels. Furthermore, looser and less compacted cement paste and more discontinuity along with a large number of voids in ITZ of RC100 could also be possible causes.

The incorporation of various types and dosages of pozzolans, particularly 20% NZ, led to a reduction in WAC. This reduction can be attributed to the pozzolanic reaction between calcium hydroxide (C-H) and the pozzolanic materials, resulting in a denser and more compact cement paste and ITZ. Consequently, this process reduced the capillary pores and improved the overall density of the paste and ITZ. The most effective performance among the pozzolanic materials was observed at 20% NZ, where a 59% reduction in WAC was recorded for CC-NZ20, while a 96% increase was noted for RC100-FA30, compared to CC.

Table 6. 180-day WAC of specimens (mm)

Mixture	Aggregate Replacement (%)			
	0	25	50	100
RC	6.1	6.4	7.5	11.5
RC-SF5	4.6	5.2	6.2	9.9
RC-SF10	4.1	5.7	6.3	9.3
RC-SF15	5.5	6.8	7.4	10.2
RC-NZ10	3.9	4.5	6.0	7.5
RC-NZ20	3.6	4.5	5.5	7.7
RC-NZ30	4.6	6.2	7.4	8.8
RC-FA15	5.5	6.1	9.0	9.5
RC-FA25	5.2	5.9	9.4	11.0
RC-FA35	6.5	8.4	11.5	12.0

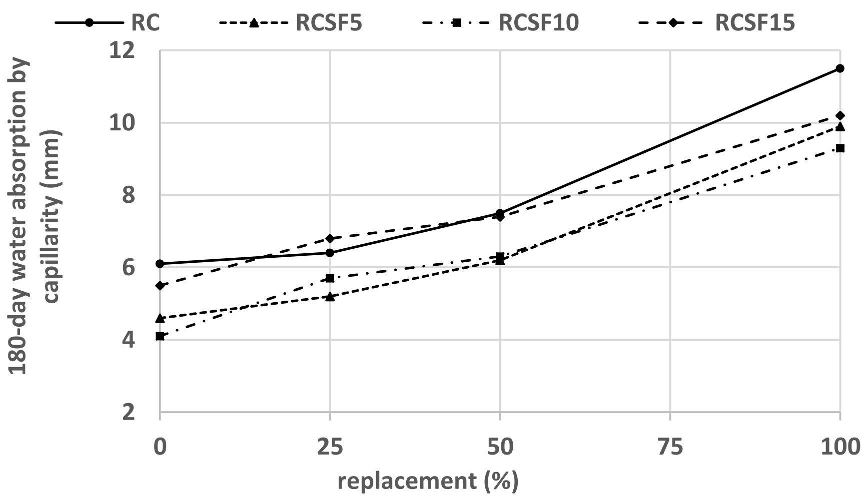

Figure (7): 180-day WAC of specimens containing SF

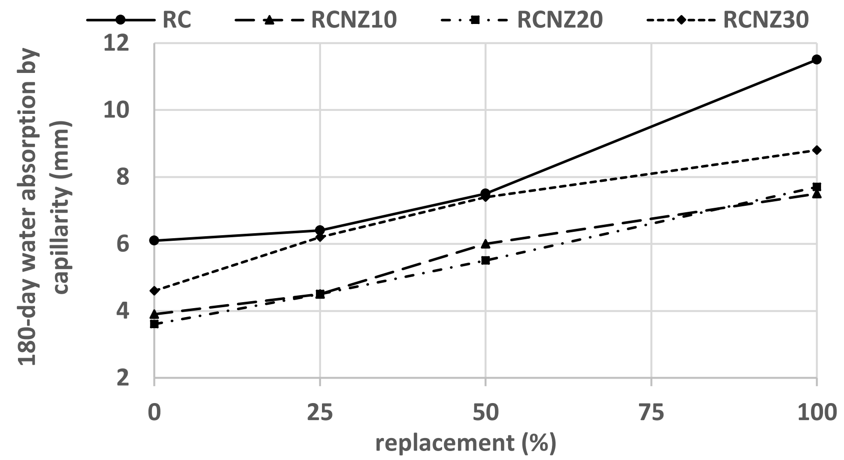

Figure (8): 180-day WAC of specimens containing NZ

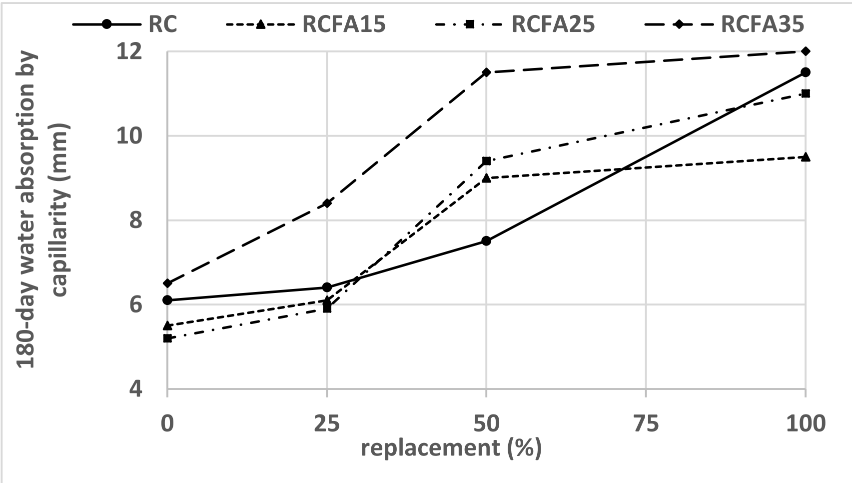

Figure (9): 180-day WAC of specimens containing FA

c) Water Absorption by Immersion (WAI)

Table 7 and Figures (10-12) present the WAI of CC and RC with and without pozzolans at 180 days. The WAI of CC is recorded at 2.7 mm, with a linear increase observed as the replacement of RMCA increases from 25% to 100%, resulting in an increase ranging from 11% to 93% compared to CC, respectively. This phenomenon can primarily be attributed to the increase in the porous structure of RC, which occurs due to the higher quantity of attached mortar present at elevated levels of RMCA replacement (Pedro et al., 2014). Jalilifar et al. (2020) indicated that at higher recycled concrete aggregate replacement levels, a greater volume of air is entrained in the mixture, leading to the recorded increase in WAI. The findings indicate that increasing the replacement level of RMCA leads to greater osmotic pressure within the concrete, resulting in higher WAI. This phenomenon can be attributed to inherent cracks present in the RMCA and the adhered mortar, contributing to elevated water absorption rates.

Among the various concrete mixtures that included SF, a 5% replacement rate demonstrated the most pronounced improvement in reducing WAI. Specifically, WAI for the mix designated as RC100, which includes 5% SF, showed a 15% improvement compared to the reference mix (RC100). However, even with this enhancement, WAI of the RC100 mix remained approximately 63% higher than that of CC. This disparity can primarily be explained by the higher volume of adhered mortar present in the fully replaced RMCA, which contributes to an increase in air content in the RAC and subsequently raises WAI. It is essential to note that variations in WAI results across different studies can stem from several factors, including the type and quality of RMCA, its moisture content, and the specifics of the crushing processes utilized. These variables can significantly influence the performance characteristics of the concrete, leading to a range of outcomes in research findings regarding WAI. Therefore, careful consideration and standardized testing procedures are critical to obtaining reliable results when evaluating the properties of RMCA-based concrete mixtures.

In terms of other pozzolans, NZ demonstrated a notably higher effectiveness. The 10% replacement level of NZ resulted in RC25-NZ10 exhibiting lower WAI than CC. The beneficial impact of this pozzolan was substantial, as the fully replaced RMCA led to a 44% increase in WAI compared to CC. For mixtures containing FA, the optimal result was observed with 25% FA, yielding results comparable to those of mixtures containing 10% NZ.

Table 7. 180-day WAI of specimens (mm)

Mixture	Aggregates Replacement (%)			
	0	25	50	100
RC	2.7	3.0	4.5	5.2
RC-SF5	2.3	2.8	3.8	4.4
RC-SF10	2.0	3.0	3.6	4.6
RC-SF15	2.5	3.0	4.1	4.8
RC-NZ10	2.2	2.5	3.2	3.9
RC-NZ20	1.9	2.7	3.3	4.1
RC-NZ30	1.9	3.6	4.6	5.2
RC-FA15	2.3	2.8	3.4	4.2
RC-FA25	2.2	2.7	3.3	4.3
RC-FA35	2.7	3.1	4.4	5.0

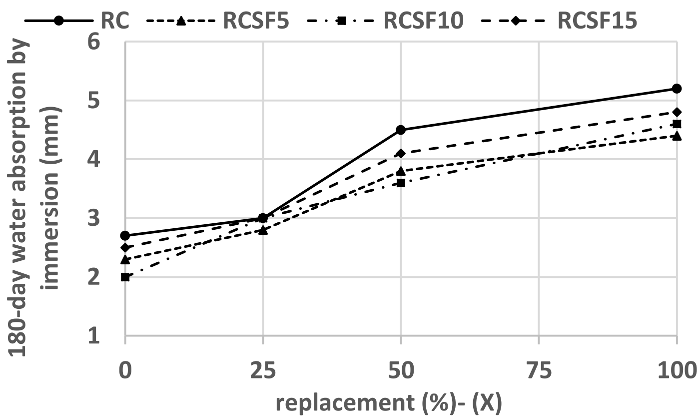

Figure (10): 180-day WAI of specimens containing SF

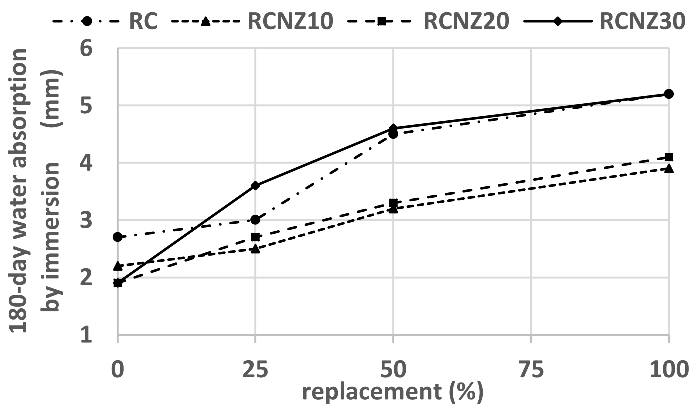

Figure (11): 180-day WAI of specimens containing NZ

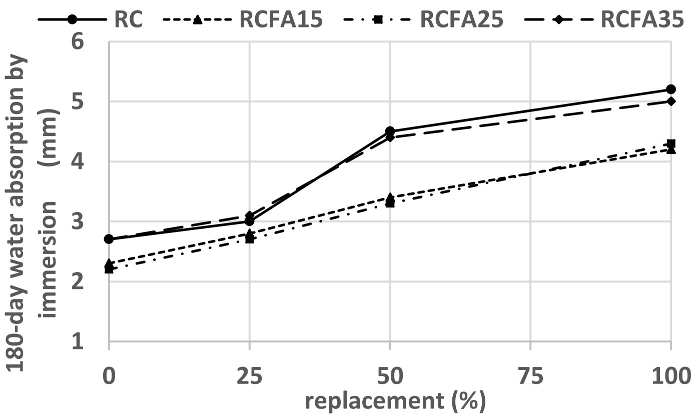

Figure (12): 180-day WAI of specimens containing FA

d) Electrical Resistivity (ER)

The results of the ER test are presented in Table 8 and Figures (13-15). As shown, increasing the replacement levels of RMCA leads to a decrease in ER compared to CC. According to the classification defined by Malhorta and Carino (2003), the risk of corrosion for CC is considered negligible, while it becomes imperative for RC100. In all concrete mixtures containing SF, the risk of corrosion was recorded in the moderate range, with the best results observed at a 5% replacement level of SF. Similar to the findings of Jalilifar et al. (2020) and Kurda et al. (2019), the increase in the RMCA replacement level results in a decrease in ER. However, the addition of SF and NZ to the concrete mixtures mitigates this trend of decreasing ER. Overall, the best results were obtained in RC containing NZ. Even at a 50% RMCA replacement level, the mixtures with various dosages of NZ exhibited a better quality than CC. Nonetheless, the detrimental effect of complete RMCA replacement is evident, as RC100 containing varying levels of NZ experienced a significant drop in quality. In fact, RC100 with 30% NZ fell into the category of concrete with an imperative risk of corrosion.

The least improvement in ER was observed in RC containing FA. For instance, RC100 with 15% and 25% FA was situated at the lower boundary of moderate corrosion risk, while RC100 with 35% FA faced an imperative risk of corrosion. The slower pozzolanic reaction of FA may account for these results; however, the marked differences between the results obtained with FA and those with other pozzolanic materials used in this research highlight the limitations of using FA. In comparison to the WAI and WAC results, the ER findings indicate that even in fully RC mixtures, the overall corrosion risk remains relatively moderate. Jalilifar et al. (2020) suggested that this phenomenon occurs, because tests based on measuring the intensity of current passing through the concrete cross-section are more influenced by the pore solution and the chemical effects of the materials used than by the concrete's pore structure. The authors believed that although the use of pozzolans cause an increase in hydration products and lead to a lower capillarity and discontinuity in the internal structure of concretes, the ER results were influenced by internal chemical and pore solution changes rather than the porosity of concrete; especialy NZ seems to reduce the ionic concentration of concrete and increase the ER of concrete.

Table 8. 180-day ER of specimens (kΩ.cm)

Mixture	**Aggregate Replacement (%)**			
	0	**25**	**50**	**100**
RC	16	12	8	3
RC-SF5	17	16	16	10
RC-SF10	18	16	13	9
RC-SF15	23	18	10	6
RC-NZ10	31	32	29	9
RC-NZ20	45	34	22	11
RC-NZ30	24	20	16	6
RC-FA15	17	13	11	6
RC-FA25	17	14	12	6
RC-FA35	16	10	7	3

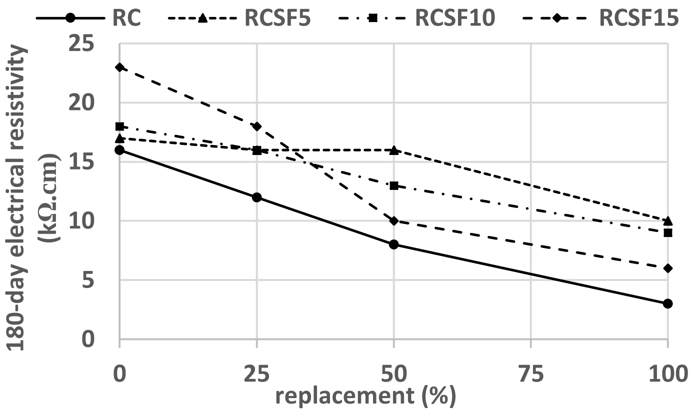

Figure (13): 180-day ER of specimens containing SF

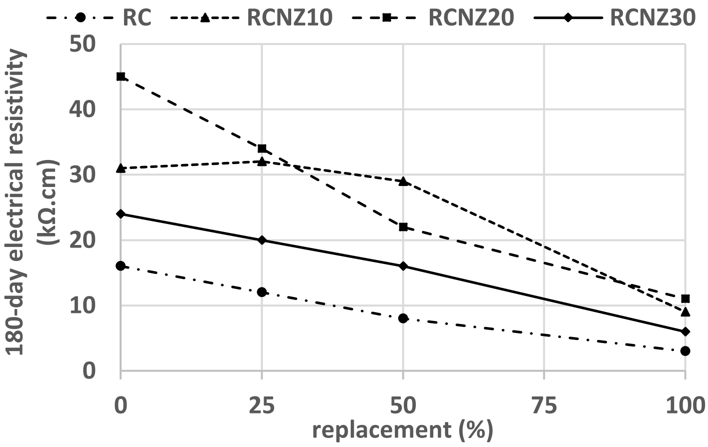

Figure (14): 180-day ER of specimens containing NZ

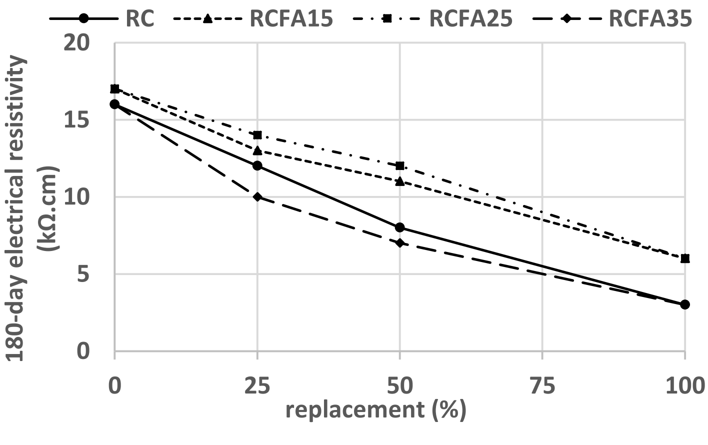

Figure (15): 180-day ER of specimens containing FA

e) Rapid Chloride ion Penetration Test (RCPT)

Table 9 and Figures (16-18) present the results of the RCPT. According to the classification presented in ASTM C1202 (2019) (Table 10), CC has a total charge passed that places it in the moderate risk category for chloride ion penetrability. The results indicate that, up to a 50% replacement of RMCA, there is no significant change in concrete quality regarding this criterion. However, with a total charge passed of 85%, RC100 falls into the category of high-risk concrete. This phenomenon can be attributed to the lower quality of RMCA or the increased porosity of the attached mortar to the aggregates (Pedro et al., 2014; Jalilifar et al., 2020). Among the tested mixes, only RC25-SF10 is categorized as having a very low risk of chloride ion penetration. The combination of different levels of RMCA replacement with 5% and 10% SF improves the quality of RC favorably, allowing even the mixtures with full RMCA replacement to be placed in the low-risk category. Conversely, the use of 15% SF in either CC or RC significantly increases the risk of chloride ion penetration.

As illustrated in Fig. (17), the combination of NZ with varying levels of RMCA replacement not only increases the risk of chloride penetration, but also shows that higher NZ replacement levels significantly elevate the total charge passed. Most RC mixtures containing NZ achieved a quality level similar to that of concrete without pozzolans. This could be influenced by the porous structure of NZ, which, despite being more porous than other pozzolans, leads to a greater number of unreacted NZ particles in the concrete. This situation results in a wider pore solution and contributes to an increased total charge passed. FA, as a slow-reacting pozzolan, exhibited a balanced behavior. The total charge passed in concretes with 15% and 25% FA indicated that even fully RC mixtures fell within the range of low risk for chloride ion penetration. However, at a 35% replacement level of FA, the quality of RC decreased, placing it in the medium risk category for chloride ion penetration.

Table 9. 180-day RCPT of specimens (colomb)

Mixture	Aggregate Replacement (%)			
	0	**25**	**50**	**100**
RC	2246	2448	3661	4169
RC-SF5	1303	1145	1681	1778
RC-SF10	1081	983	1226	1725
RC-SF15	2165	2349	2625	2685
RC-NZ10	1999	1774	1966	2191
RC-NZ20	2583	2156	2493	3263
RC-NZ30	2426	2875	3100	4021
RC-FA15	1416	1552	1351	1397
RC-FA25	1253	1303	1689	1746
RC-FA35	1602	2043	2819	3663

Table 10. RCPT of concretes based on charge passed proposed by ASTM C1202

Charge passed (Colombs)	Chloride ion penetratrability
> 4000	High
2000-4000	Modarate
1000-2000	Low
100-1000	Very low
< 100	Negligible

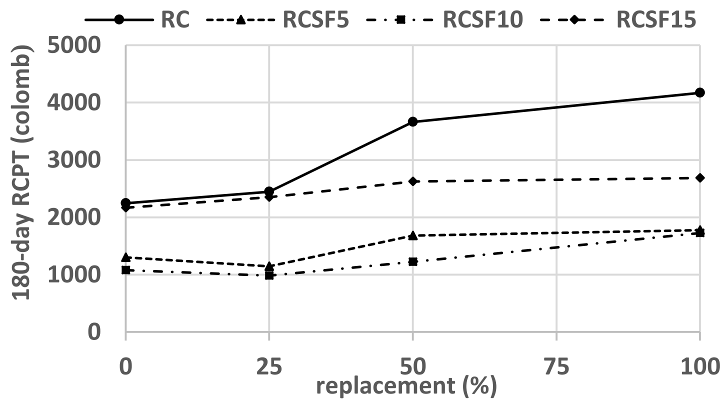

Figure (16): 180-day RCPT of specimens containing SF

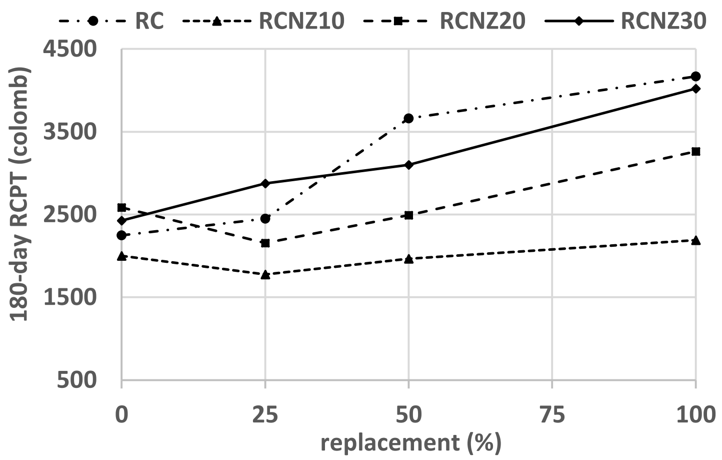

Figure (17): 180-day RCPT of specimens containing NZ

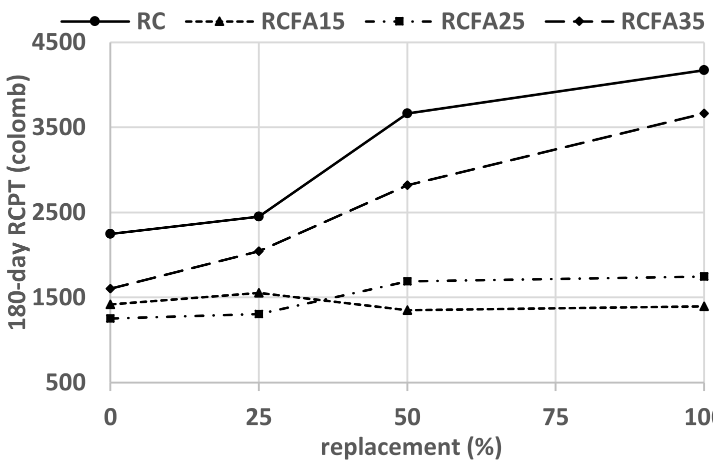

Figure (18): 180-day RCPT of specimens containing FA

CONCLUSIONS

The following conclusions are drawn from the results of this investigation:

1. Up to a 25% replacement of RMCA showed no significant losses in CS compared to CC. However, 50% and 100% replacements of RMCA resulted in reductions of 30% and 37% in CS, respectively. This

decrease is attributed to the significantly lower physical properties of RMCA compared to NA, which led to an increase in the size and volume of capillary pores at higher RMCA replacement levels.

2. The presence of SF and NZ effectively filled the voids in RMCA and the cement paste, along with improvements in the ITZ, enabling RC with 25% and 50% RMCA containing 5% and 10% SF and 10% NZ to achieve the target CS of 40 MPa at 28 days. Similar results were observed for RC made with 25% RMCA across all dosages of NZ. But, the chemical composition and lower cementitious properties of class F of FA illustrate that RC containing FA exhibited lower CS at 28 days compared to concretes without pozzolans.
3. A 25% replacement of RMCA showed a negligible increase in WAC, while a full replacement of RMCA resulted in an 89% increase in WAC because of an increase in the size and volume of capillary pores due to higher dosages of RMCA replacement. The most effective performance among the pozzolanic materials was observed at 20% NZ, where a 59% reduction in WAC was recorded for CC-NZ20 because of the pozzolanic reaction between calcium hydroxide (C-H) and the pozzolanic materials.
4. The WAI of CC is recorded at 2.7 mm, with a linear increase observed as the replacement of RMCA increases from 25% to 100%, resulting in an increase of 11% to 93%, respectively, due to the large pores and a greater volume of air present in recycled aggregates. The use of 10% NZ had a notably favorable effect compared to all other pozzolans. Specifically, a 19% decrease in WAI was recorded for RC25, while RC100 exhibited a 44% increase compared to CC and reduced the capillary pores, improving the overall density of the paste and ITZ.
5. Increasing the replacement levels of RMCA leads to a decrease in ER compared to CC. Increase in hydration products leads to a lower capillarity and discontinuity in the internal structure of concretes resulting from NZ, which improved ER of RC50 with all dosages of NZ compared to CC. However, the detrimental impact of complete RMCA replacement did not mitigate the drop in ER for NZ-containing RC.
6. Up to a 50% replacement of RMCA, there is no significant change in concrete quality regarding RCP. However, with a total charge passed of 85%, RC100 falls into the category of high-risk concrete in the RCPT. A very low risk of chloride-ion penetration was observed for RC25 with 10% SF. The combinations of 5% and 10% SF with all levels of RMCA replacement positioned RC in the low-risk category. Conversely, the combinations of NZ and FA with RMCA did not demonstrate favorable effects in the RCPT compared to SF.

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