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Original research article

Impact of Power-On Duration on Chloride Migration in Reinforced Reactive Powder Concrete with Recycled Aggregates, Fly Ash and Silica Fume

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ABSTRACT

This study aimed to examine the chloride migration characteristics of Reinforced Reactive Powder Concrete (RRPC) that is not in a steady state. The RRPC was formulated using pozzolans and recycled concrete aggregate (RCA). The study was mostly looking at how the chloride migration coefficient changed when two important things happened: how long the power was on and how much RCA was in the RRPC mixtures. Six separate categories of RRPC mixtures were formulated, each containing different ratios of silica fume (SF) and fly ash (FA), as well as varying amounts of RCA substituting for the traditional coarse aggregate. The results of this study uncovered a significant trend in the chloride migration coefficient as the duration of power-on increased from 12 to 36 h. The coefficient first showed an upward trend, then a downward trend. This trend indicates the existence of a curative and sealing mechanism within the concrete structure, which gradually improves its ability to resist the penetration of chloride over time. Adding RCA to reinforced reactive powder concrete (RRPC) mixtures also slowed down the movement of chloride, and the effect became more obvious as the RCA content increased. It also found that the effect of RCA content on chloride resistance was more noticeable during shorter durations but became less significant as the duration increased.

Keywords: Chloride migration; Fly ash; Reinforced reactive powder concrete; Silica fume

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1. Introduction

Chloride-induced corrosion of reinforced concrete structures is an acute problem of civil engineering, crucial for global safety, economy, and the environment. Reinforced concrete has been widely used in recent infrastructure, including bridges, highways, buildings, and dams. This has now become a serious concern because the corroding of reinforcement steel through chlorides badly jeopardizes the structural integrity of these infrastructures, apart from the fact that the problem is wide-ranging, incurring heavy economic expenditures to cope with the repairs and maintenance [1–3]. Normally, chloride-induced corrosion problems pertain to coastal areas, regions where deicing salts are used, and the industrial areas with high chloride concentrations. Consequently, scenarios associated with chloride-induced corrosion need to be dealt with to maintain the life and sustainability of concrete structures [4–7].

The impacts on the environment from the production and use of concrete are huge, particularly in terms of carbon dioxide emission. Corrosion due to chloride intensifies this since more structures will have to be replaced or repaired, adding to an increased carbon footprint from construction activities. The costs for repairing corroded structures are considerable; governments and industries all over the world spend huge amounts yearly [1,2,8–12]. The need for new materials, new construction methods, and new maintenance approaches is greater now than ever in an era when sustainability and resource efficiency are preeminent to solve the problems caused by chloride-induced corrosion. This is a problem that calls for further research and development, with international cooperation in this quest for effective solutions [13–15].

Accurate assessment of chloride penetration in concrete is the foremost requirement for ensuring the durability of concrete infrastructure. Nowadays, different techniques have been followed to determine chloride penetration, from in-situ methods for preventive maintenance to theoretical modeling based on laboratory experiments. Among these experimental techniques, the RCM test happens to be very common in laboratories for studying chloride penetration [1, 3, 8, 16–25]. Tang et al. [26] indicated the variability of this test duration, but noted that NT Build 492 standardizes these tests [27, 28]. The service life model of the European DuraCrete project, with the diffusion coefficient, shows the importance of predicting chloride ingress with accuracy [29]. The predictive models evolved from some basic applications of Fick's Second Law to more sophisticated flux-balance equations that have electrochemical interactions within the concrete matrix built in [30]. Advanced tools, like the STADIUM model [31] and the ClinConc model [32], are examples of models that already have said factors built in to provide better predictive modeling, considering the diversity of concrete behaviors under different environmental conditions. The developed models, in this respect, turn out to be quite accurate for service-life predictions and permit reliable design and maintenance of concrete structures both in marine and cold climates [33].

One such construction material that exhibits maximum strength and durability over traditional cement concrete is Reinforced Reactive Powder Concrete (RRPC). This material was invented by Professor Pierre Richard and his team working at Bouygues Laboratory in France way back in the early 1990s. It is essentially composed of fine-grained sand, quartz powder, and silica fume (SF) along with high-strength steel fibers for added tensile strength. It is the absence of coarse aggregates and high density in the microstructure that are the major reasons for improved mechanical properties of RRPC with strengths in excess of 200 MPa in compression and excellent resistance to environmental aggressors [34]. Fly ash (FA) and SF are supplementary cementitious materials. The motivation behind using FA and SF in concrete, and especially RRPC, is to exploit the salient properties of these materials to achieve high-performance and durability concretes. Also, a very fine aggregate from FA and the incorporation of superplasticizers, together with a low water-to-binder ratio, result in a dense matrix that ensures low chloride penetration and other forms of chemical attack. This makes RRPC particularly suitable for applications in aggressive environments, such as coastal areas and industrial zones.

One of the critical studies on RCM in concrete deals with chloride migration, where an acceleration of chloride ion migration through specimens of concrete by applying an electric field takes place. This paper investigates the use of recycled concrete aggregates (RCA) in RRPC and their effects on its chloride resistance and possible self-healing properties. The results give many insights into the use of RCA within concrete technology to establish more durable and sustainable concrete solutions. Mechanisms behind the observed self-healing properties should be further investigated in future studies, including more environmental factors in the study, increasing the applicability and knowledge of RRPC in sustainable construction practices.

2. Non-Steady-State Chloride Migration Theory

The theory of non-steady-state chloride migration in concrete structures provides a comprehensive framework that explains and predicts the process of chloride ion penetration. In contrast with steady-state models, which are based on an implicit assumption of time-invariant conditions of exposure, this theory shows a time-dependent nature of chloride ingress and hence is closer to reality. At its core, this includes the modification of Fick's second law of diffusion to contain the more complex interaction within the concrete matrix, for instance, chloride binding with hydration products and microstructure change with time. In this model of non-steady-state migration, the variation of the diffusion coefficient takes into account all factors that influence it, such as moisture content, age, and the degree of concrete hydration [17,26,35].

In this model, the non-steady-state migration coefficient accounts for several forms of complex interaction among chloride ions with concrete matrix constituents. These could be due to concentration gradients, moisture variation-linked changes in diffusivity, and interaction of chloride ions with the porous structure of concrete. Mathematically, this may be described through the solution of differential equations that indicate non-steady-state chloride ion movement. Numerical methods have often been resorted to in cases in which there are complicated boundary conditions or other complicating factors, such as temperature or mechanical stresses [26]. With this in mind, one must understand such dynamics in the quest for better predictive models, whereby more resistant concrete designs may ultimately be arrived at that help extend the life of infrastructural facilities against chloride-induced corrosion, exposed to aggressive environments [36].

The RCM test is based on Fick's laws of diffusion, which describe the movement of any chemical species down its concentration gradient under normal conditions [30]. During the RCM test, an electrical potential difference is generated, making this gradient even stronger and accelerating the migration of chloride ions from areas of higher to areas of lower concentration. Those factors that influence this process are the porosity of the concrete, which determines the permeability of the matrix, while tortuosity affects the pathway of ion migration. Other initial parameters that affect the mobility of chloride ions include the initial chloride concentration and moisture content. The flux of chloride ions, JJJ, through the concrete is described by the following Eq. (2.1)

$$J = -D \times (\frac{dC}{dx}), \qquad (2.1)$$

where J represents the flux of chloride ions, D represents the diffusion coefficient, C represents the concentration of chloride ions, and dx represents the differential distance in the direction of chloride migration.

RCM testing entails adding an electrical potential difference (V) to a concrete specimen and then measuring the resulting current (I) and time (t). The charge (Q) that took place during the test can be calculated by integrating the current-time curve, as determined by Eq. (2.2) [37].

$$Q = \int I(t) \times dt. \qquad (2.2)$$

The mean depth of chloride is the appropriate value for representation. After it was established [15], the chloride migration coefficient in cement-based materials or concrete was determined through the non-steady-state migration experiment using the NT BUILD 492 method [27]. This coefficient was then calculated using Eq. (2.3).

$$D = \frac{0.0239(273+T)L}{(U-2)t} \times \left(X_d - 0.0238\sqrt{\frac{(273+T)LX_d}{U-2}} \right) \qquad (2.3)$$

In the equation for calculating chloride ion flux in Rapid Chloride Migration (RCM) testing, (Dnssm) is the non-steady-state migration coefficient, given in units of × 10-12 m^2/s. This coefficient is pivotal as it quantifies the rate at which chloride ions migrate under non-steady-state conditions. The variable U denotes the absolute applied voltage in volts (V), integral in establishing the driving force for ion migration. The term T refers to the average temperature of the anolyte solution at the outset and conclusion of the experiment, measured in degrees Celsius (°C), acknowledging the temperature's influence on the migration kinetics. The specimen thickness is represented by L and is measured in millimeters (mm), while xd symbolizes the average penetration depth of chloride ions, also in millimeters (mm). The duration of the test, t, is measured in $h(h)$, framing the temporal context of the experiment.

A lower chloride migration coefficient indicates that the concrete matrix is denser and less permeable, hence offering greater resistance to chloride penetration and thus being more durable [38]. The RCM test turns out to be a very useful test for concrete durability and, more specifically, its resistance to chloride penetration. Such results from RCM testing can guide the process of formulating concrete mixtures and quality control processes in order to reduce the risk of chloride-induced corrosion and extend the service life of concrete structures.

3. Materials and Methods

3.1 Materials

3.1.1 Cement and supplementary materials

The investigation incorporated OPC produced by the Siam Cement Public Company, Thailand, conforming to the ASTM C150 standards [39]. The OPC's chemical composition and constituent percentages were established based on standard values. It exhibited a specific gravity of 3.15 and a specific surface area of 693 m^2/kg, reflecting its material characteristics. The study also utilized FA sourced from a regional power plant, adhering to the Class F categorization. The FA was distinguished by an average particle size of 20.84 μm and a specific surface area of 882 m^2/kg. Its chemical makeup was predominantly composed of SiO_2, Al_2O_3, and Fe_2O_3, collectively constituting over 95% of its total composition. SF, recognized for its high pozzolanic reactivity, was characterized by ultrafine particles averaging 0.51 µm in size and exhibiting a specific surface area of 1,443 m^2/kg. The SF had a bulk density of 1,664 kg/m^3, with its chemical composition being predominantly silicon dioxide (SiO_2), accounting for over 91% by mass. The Loss on Ignition (LOI) value, indicative of volatile matter, was recorded at less than 0.95%.

Table 1 in the study presents a comprehensive overview of the physical and chemical attributes of these cementitious materials. Fig. 1 shows images from a field emission scanning electron microscope that show how the shapes of OPC, FA, and SF particles change over time. The images highlight the distinctively irregular shapes of OPC particles, contrasted with the spherical morphology of FA and SF particles. It was very important to follow the rules set out in ASTM C618 [40] and ASTM C1240 [40] when choosing FA and SF for

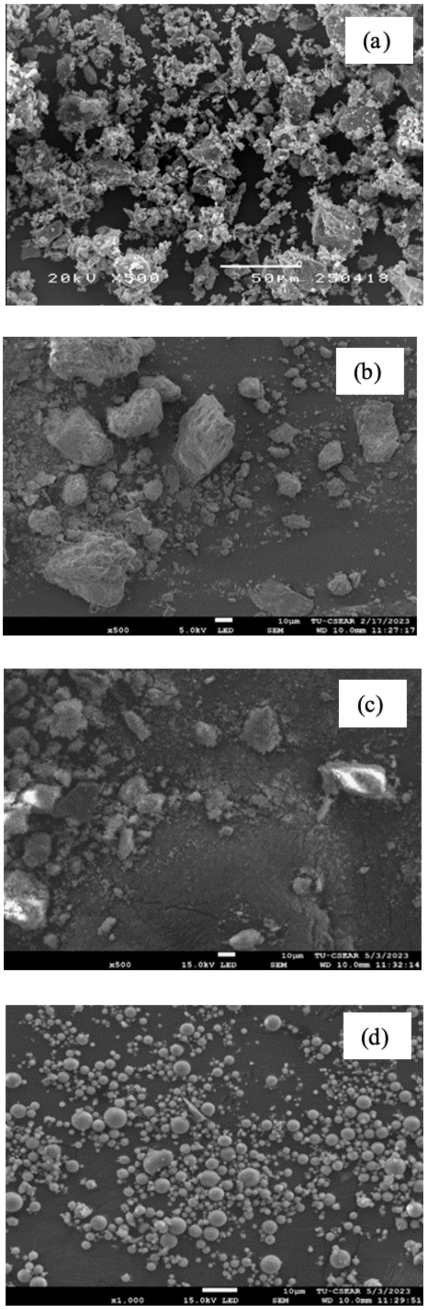


Fig. 1. Scanning electron micrographs of (a) OPC, (b) RCA, (c) FA, and (d) SF.

the study. This made sure that the materials used were reliable and consistent.

Table 1. Analysis results of the chemical composition and examination of the physical properties of OPC, FA, and SF.

Composition and properties (mass%)	OPC	FA	SF
Silicon dioxide (SiO_2)	15.45	75.23	91.78
Aluminum oxide (Al_2O_3)	3.63	12.06	0.24
Iron oxide (Fe_2O_3)	3.46	3.03	0.02
Magnesium oxide (MgO)	1.65	0.25	0.42
Calcium oxide (CaO)	65.16	1.12	0.53
Sodium oxide (Na_2O)	0.12	0.35	0.29
Potassium oxide (K_2O)	0.52	0.71	2.11
Sodium oxide (SO_3)	3.35	0.43	2.21
Titanium dioxide (TiO_2)	0.34	0.67	0.24
Loss on ignition (%)	1.72	1.36	0.64
Physical properties			
Particle-size diameter, $D_{v,50}$ (μm)[a]	20.84	36.13	0.52
Bulk density (kg/m^3)	986	1598	1664
Specific gravity	2.16	3.15	2.24
Specific surface area (m^2/kg)	882	693	1433

Remarks: a The volume distribution (micrometers, μm) has a median value of $D_{v,50}$.

3.1.2 Aggregates

When this study looked at aggregates, it looked at two different types: coarse aggregates and fine aggregates. Both types were tested thoroughly according to ASTM C33 standards [40]. The fine aggregate component comprised naturally sourced river sand, characterized by a maximum granular dimension of 4.75 mm. This fine aggregate boasted a specific gravity of 2.61, a fineness modulus of 2.75 and demonstrated an absorption capacity of 0.82%. Conversely, the coarse aggregate was composed of limestone, meticulously crushed to ensure a maximal particle size threshold of 25 mm. The coarse limestone aggregate exhibited a specific gravity of 2.65 and an absorption rate of 1.3%. The study's focus extended to the utilization of RCA, all procured from a singular origin to maintain consistency. The sourcing involved the collection of standard-strength concrete cylinders, typically reserved for quality assurance testing at a proximate ready-mix concrete facility. These cylinders were basically leftovers from regular batch plant checks on standard-strength concrete mixes sent out for different construction projects. They were carefully shrunk down using a portable crushing device, which made sure the largest diameter was 25 mm, as shown in Fig. 2.

A field emission scanning electron microscope micrograph, shown in Fig. 1, clearly shows the fine details of the RCA's microstructure. Subsequent to the crushing process, the RCA underwent a meticulous mechanical sieving and grading protocol, yielding aggregate fragments spanning sizes between 5 and 12 mm. Nevertheless, despite the methodical preparation process, the RCA's gradation profile showed deviations from the ideal gradation range as set forth by the relevant ASTM standards. This divergence in gradation characteristics was graphically represented and critically examined in Fig. 3, prompting a nuanced consideration of the material's suitability and potential implications for the structural performance of the concrete.

3.1.3 Chemical admixture

Incorporating a high-range water reducer (HRWR) type F and G into the concrete mix is essential as it functions as a superplasticizer, particularly beneficial when utilized alongside high-performance concrete admixtures. The admixture in question comprises a modified polycarboxylate base, predominantly in an aqueous solution form. This specific composition is strategically introduced into the concrete mixes to significantly ameliorate the workability parameters of the concoction. To get the desired improvement in the workability and flow characteristics of the concrete, especially for reinforced reactive powder concrete (RRPC), a precise dosage of 1.5 wt% of the total weight of the cementitious

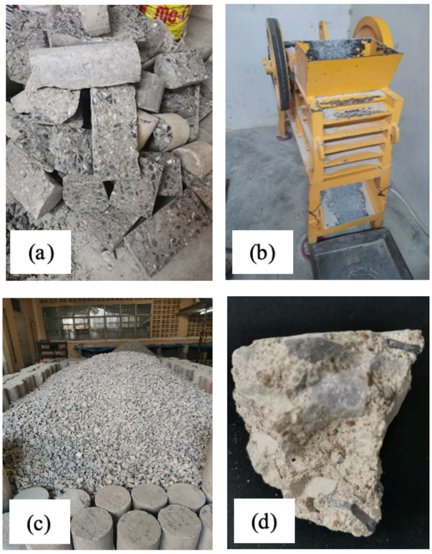


Fig. 2. Grinding of RCA; (a) Concrete waste, (b) Grinding machine, (c) Ground concrete, (d) Nominal size of ground concrete.

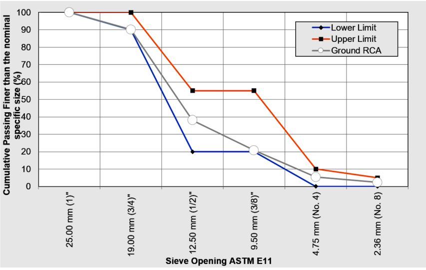


Fig. 3. Gradation of ground RCA.

components is carefully added. This carefully calibrated addition ensures an optimal balance between fluidity and the structural integrity of the RRPC. It is noteworthy that the HRWR employed adheres stringently to the specifications delineated in ASTM C494 [40], underscoring its compliance with industry standards. Additionally, the HRWR has a specific gravity of 1.08, which is another factor that supports the material's suitability and performance within the concrete mixture and helps improve the overall structure and functionality of the RRPC.

3.1.4 Mixing water

In the preparation of the concrete mixture, potable water is employed as a crucial component to facilitate the blending process. The quantity of water introduced is judiciously calibrated to achieve the predetermined slump flow specific to reinforced reactive powder concrete (RRPC). This meticulous adjustment is pivotal in ensuring that the mixture attains the requisite level of flowability, aligning with the prescribed standards. Simultaneously, this careful regulation of water content is instrumental in preserving the intrinsic strength and durability characteristics of the concrete. Such a balanced approach to water content management not only optimizes the workability of the RRPC but also upholds its structural integrity, reflecting a harmonized synthesis of fluid dynamics and material robustness.

3.1.5 Reinforcing bar

In the context of assessing non-steady-state chloride migration in reinforced reactive powder concrete (RRPC), incorporating RCA, FA, and SF, the utilization of reinforcing bar is pivotal. Specifically, deformed bars with a nominal diameter (ϕ) of 25 mm are employed as shown in Fig. 4, providing substantial tensile strength and enhancing the concrete's structural integrity. The distinct surface deformations of these bars facilitate a robust bond with the concrete matrix, crucial for effectively countering tensile stresses and mitigating the risk of structural failure. The incorporation of these deformed bars within the RRPC framework, especially in an environment enriched with industrial by-products like FA and SF and sustainable materials like RCA, ensures a comprehensive evaluation of the concrete's durability and its resistance to chloride-induced corrosion, a critical aspect in extending the lifespan of concrete structures in aggressive environments.

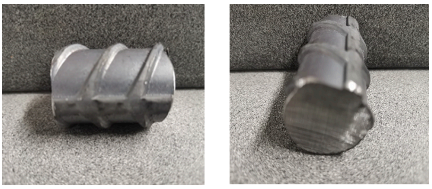


Fig. 4. Deformed bars with a nominal diameter (ϕ) of 25 mm.

3.2 Mixture proportions of RRPC

This experimental study accurately composes a mix design framework encompassing six distinct groups, each meticulously tailored to elucidate the ramifications of varying material compositions and proportions. The core objective is to delineate the impact of specific alterations, notably the substitution of OPC with SF and FA, as well as the integration of RCA. The study also varies the duration for which an electric field is applied in the RCM test, known as the ’power-on duration,’ using three different time periods: 12, 24, and 36 h. In this context, the electric field is applied across the concrete specimens to accelerate chloride ion migration, simulating long-term chloride ingress in a shorter timeframe. This method accelerates chloride ion migration to simulate long-term exposure, based on standardized procedures like NT BUILD 492. These variations provide insights into the chloride resistance and durability of the mixtures [27, 28].

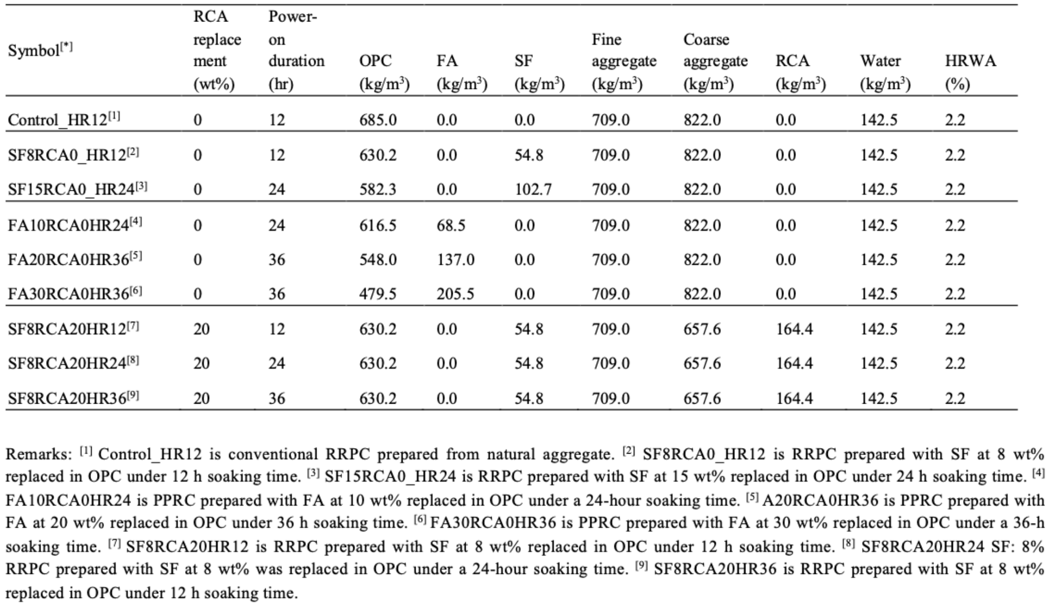
The foundational group in this schema, designated as the control mixture group, establishes the baseline for subsequent comparative analysis. Its constitution comprises OPC, naturally sourced coarse aggregates, fine aggregates, a superplasticizer, and water. This control mix serves as the benchmark to discern the relative impact of material variations introduced in the other groups.

The second group investigates the effect of replacing cement with SF by considering two different replacement ratios: 8% and 15% by weight of the cementitious components. The third group continues this exploration by examining FA substitution at three levels: 10%, 20%, and 30% by weight relative to the cementitious materials. The exploration deepens with the fourth, fifth, and sixth groups, where a more intricate interplay of materials is orchestrated. Here, OPC is concurrently replaced with 8 wt% of SF and 8 wt% of FA, while also integrating RCA as a strategic substitute for the natural coarse aggregates. The incorporation of RCA is varied, with proportions set at 20 wt%, thereby introducing a spectrum of material densities. This structured variation between the six groups, along with the different power-on times for the RCM test, creates a strong matrix for figuring out how SF, FA, RCA, and temporal dynamics affect the non-steady-state chloride migration properties of RRPC. This gives a full picture of how the material acts and behaves in different situations as shown in Fig. 5

3.3 Testing methods

3.3.1 RCM testing

To study how chloride moves in reinforced reactive powder concrete (RRPC) when it’s not in a steady state, cylinder-shaped concrete samples were carefully made to be 50 mm thick all the way around. These samples were vacuum-saturated for 24 h before they were used to measure the chloride migration coefficient. This made sure they were in the best shape possible for the rapid chloride migration (RCM) test. Fig. 6 shows the experimental setup for the RCM test on RRPC. It shows the



Symbol[*]	RCA replacement (wt%)	Power-on duration (hr)	OPC (kg/m³)	FA (kg/m³)	SF (kg/m³)	Fine aggregate (kg/m³)	Coarse aggregate (kg/m³)	RCA (kg/m³)	Water (kg/m³)	HRWA (%)
Control_HR12[1]	0	12	685.0	0.0	0.0	709.0	822.0	0.0	142.5	2.2
SF8RCA0_HR12[2]	0	12	630.2	0.0	54.8	709.0	822.0	0.0	142.5	2.2
SF15RCA0_HR24[3]	0	24	582.3	0.0	102.7	709.0	822.0	0.0	142.5	2.2
FA10RCA0HR24[4]	0	24	616.5	68.5	0.0	709.0	822.0	0.0	142.5	2.2
FA20RCA0HR36[5]	0	36	548.0	137.0	0.0	709.0	822.0	0.0	142.5	2.2
FA30RCA0HR36[6]	0	36	479.5	205.5	0.0	709.0	822.0	0.0	142.5	2.2
SF8RCA20HR12[7]	20	12	630.2	0.0	54.8	709.0	657.6	164.4	142.5	2.2
SF8RCA20HR24[8]	20	24	630.2	0.0	54.8	709.0	657.6	164.4	142.5	2.2
SF8RCA20HR36[9]	20	36	630.2	0.0	54.8	709.0	657.6	164.4	142.5	2.2

Remarks: [1] Control_HR12 is conventional RRPC prepared from natural aggregate. [2] SF8RCA0_HR12 is RRPC prepared with SF at 8 wt% replaced in OPC under 12 h soaking time. [3] SF15RCA0_HR24 is RRPC prepared with SF at 15 wt% replaced in OPC under 24 h soaking time. [4] FA10RCA0HR24 is PPRC prepared with FA at 10 wt% replaced in OPC under a 24-hour soaking time. [5] A20RCA0HR36 is PPRC prepared with FA at 20 wt% replaced in OPC under 36 h soaking time. [6] FA30RCA0HR36 is PPRC prepared with FA at 30 wt% replaced in OPC under a 36-h soaking time. [7] SF8RCA20HR12 is RRPC prepared with SF at 8 wt% replaced in OPC under 12 h soaking time. [8] SF8RCA20HR24 SF: 8% RRPC prepared with SF at 8 wt% was replaced in OPC under a 24-hour soaking time. [9] SF8RCA20HR36 is RRPC prepared with SF at 8 wt% replaced in OPC under 12 h soaking time.

Fig. 5. Mix proportions of RRPC.

setup that was made to measure how chloride penetrates the material. The determination of the chloride migration coefficient, denoted as Dnssm, was anchored in the RCM methodology as delineated by Tang et al. [26], with a comprehensive procedural framework provided in the Nordic standard NT BUILD 492 [27]. The computation of the Dnssm value is facilitated through Eq. (2.3), a critical component in the analytical evaluation of chloride transport within the concrete matrix.

3.3.2 Splitting tensile strength

Testing of the splitting tensile strength was done on cylinders of reinforced reactive powder concrete (RRPC) that were 150 mm in diameter and 300 mm high after being cured for 28 days. Testing intervals were strategically set after power-on durations of 12, 24, and 36 h to evaluate the material's tensile properties under varying conditions. Conducted in alignment with ASTM C496 standards

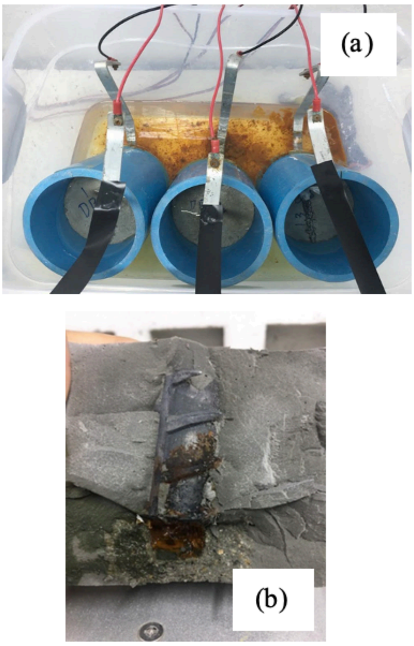


Fig. 6. Testing of chloride migration in a non-steady state for the RRPC facility: (a) Specimens during testing and (b) Split specimen after testing.

[40], the procedure involved applying a diametrical load to the specimens until failure was observed. This method made it easier to get a precise reading of the specimens' splitting tensile strength. This gave us useful information about how long RRPC lasts and how well it works under tensile stress.

3.3.3 Ultrasonic pulse velocity (UPV)

The ultrasonic pulse velocity (UPV) of reinforced reactive powder concrete (RRPC) specimens was measured at power-on durations of 12, 24, and 36 h, following the guidelines specified in ASTM C597 [40]. This test, performed after 28 days of curing, evaluates the quality and uniformity of the specimens by using ultrasonic transducers that generate and detect ultrasonic waves through the concrete. The speed of these pulses is carefully measured and recorded, providing valuable information about the internal coherence and integrity of the RRPC specimens.

4. Results and analysis

4.1 Chloride migration coefficient

Fig. 7 shows the effects of pozzolanic materials and recycled aggregates on chloride migration in RRPC. A control chloride migration coefficient of 14.63 × 10^{-12} m^2/s at 12 h was established by the control mixture. Substituting cement with SF reduced this coefficient by 22.5% for an 8 wt% replacement and even more substantially by 59.9% for a 15 wt% replacement, as observed at 24 h [1,2,5,7,41–43]. This improved resistance to chloride ingress is attributed to the pozzolanic reaction and filler effect of SF, leading to a denser microstructure [8,19,24,38,44].

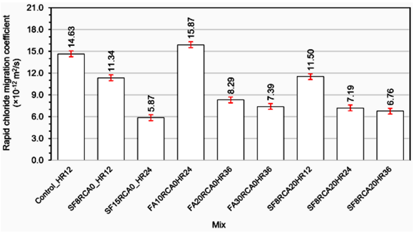


Fig. 7. Chloride migration coefficient.

FA, another pozzolan, when used as a partial cement substitute, initially showed a slight increase in chloride migration coefficient at a 10% replacement level. However, as the percentage of FA replacement increased to 20 and 30 wt%, a notable decrease in chloride migration was observed, especially at 36 h, confirming the material's efficacy in enhancing chloride resistance [1,2,5,8,9,15,19,29,35,38,42–44]. The presence of FA promotes the formation of additional calcium-silicate-hydrate (C-S-H) gel due to the reaction with calcium hydroxide produced during cement hydration, improving the concrete's microstructure [24,25,35].

When the SF content is increased to 15 wt%, the chloride migration coefficient is further reduced, underscoring the efficiency of SF in enhancing the concrete's resistance to chloride ingress. The chart indicates a significant decrease, almost halving the coefficient compared to the control. This dramatic decrease is likely due to an even denser microstructure and lower porosity, as the additional C-S-H fills more space within the concrete matrix and refines the pore structure, leaving less room for chlorides to penetrate [16]. The results for multiple samples with an 8% SF replacement, each with slightly different chloride migration coefficients. These variations could be the result of different aggregate types, water-to-binder ratios, or specific mixing and curing procedures, suggesting that while SF is generally beneficial for reducing chloride permeability, the final outcome can still be influenced by other factors in the concrete mix design [40]. The reduction in chloride migration with the inclusion of SF has significant implications for the service life and maintenance costs of concrete structures, especially those exposed to chloride-rich environments such as marine areas or where deicing salts are used. This study, as represented by the chart, effectively demonstrates the role of SF in improving the durability of concrete, aligning with a broad consensus in the literature on the benefits of pozzolanic materials in concrete technology.

Incorporating RCA in RRPC mixtures generally decreased the chloride migration coefficient, highlighting RCA's beneficial role in enhancing chloride resistance. However, an increase in the migration coefficient was observed in the SF8RCA0_HR12 and SF8RCA20HR12 samples at the 12-hour mark, as shown in Fig. 7. Despite this initial increase, a consistent reduction in the migration coefficient was observed at 24 and 36 hours, affirming the long-term durability benefits of RCA in RRPC [3, 42, 55, 56]. Moreover, the experimental data demonstrate that extended power-on durations during the chloride migration test reduce the coefficient, indicating improved resistance to chloride penetration-a result of the combined pozzolanic effects of SF and FA and the physical characteristics of RCA [13, 17, 42].

The effect of reinforcing bars on non-steady-state chloride migration behavior in concrete is a critical factor to consider in the durability and performance of concrete structures. Several studies have investigated this topic, shedding light on various factors influencing chloride migration and diffusion in concrete. The results confirm that Chen et al. [45] demonstrated the effect of an external electric field on chloride removal in concrete, which also resulted in the migration and aggregation of ions near reinforcing bars. Tang et al. [46] talked about how a longer hydration age lowers the non-steady-state chloride migration coefficient by letting more hydrated products into the pores. Chiang and Yang [47] also came up with an accelerated non-steady-state migration test method to measure chloride diffusivity. They stressed how important penetration depth is for measuring chloride transport. Furthermore, Abro et al. [48] focused on the autogenous healing of cracked mortar and the calculation of the non-steady-state migration coefficient using specific equations. Sanju□n et al. [49] conducted non-steady-state chloride migration tests on concrete samples with ternary cements to estimate service life. Ma et al. [50] studied non-steady-state chloride migration and binding in cracked self-compacting concrete, highlighting the impact of cracks on chloride penetration depth. In addition, Ribeiro et al. [51] underscored the role of chloride ions in causing corrosion of reinforcing steel bars in concrete structures. Moreover, Ortega et al. [52] determined the non-steady-state chloride migration coefficient for mortar durability assessment. Zhang et al. [53] discussed various chloride diffusion coefficients obtained from accelerated tests, including non-steady-state migration coefficients. To sum up, the study of how reinforcing bars affect the non-steady-state chloride migration behavior in concrete is complex and includes things like electric fields from the outside, crack influence, and the ability of chloride to move through the concrete. Understanding these dynamics is crucial for enhancing the durability and longevity of concrete structures.

4.2 Splitting tensile strength and UPV

The splitting tensile strength results are summarized in Fig. 8 for each group after power-on durations of 12, 24, and 36 h. The control mixture exhibited relatively consistent splitting tensile strength values throughout the test duration, measuring 5.53 MPa at 12 h [54].

The introduction of SF as a partial substitute for cement resulted in marginal enhancements in splitting tensile strength. With a replacement level of 8%, the tensile strength increased to 1.7% at 12 h, while at a replacement level of 15 wt%, it further rose to 2.23% at 12 h. However, the substitution of cement with FA yielded varying results in terms of splitting tensile strength. The tensile strengths of RRPC decreased by 1.15, 4.24, and 11.67% at 24 h when replacement levels of 10, 20, and 30 wt% were used. When RCA was incorporated alongside SF and FA, the tensile strength results varied. At a 20% and fully RCA replacement level, the tensile strength values at 12, 24, and 36 h were consistent and increased slightly, indicating that this replacement level did not significantly affect the strength development. Adding pozzolanic materials into RRPC mixtures can cause a chemical reaction with calcium hydroxide, which makes stable compounds. This reaction contributes to the filling of network gaps in the concrete matrix, resulting in greater compactness [19, 41, 44]. It lowers the splitting tensile strength of RCA because old cement mortar connected to the aggregate particles makes coarse aggregates soak up more water [55]. The inclusion of SF at 8% and 15% replacement levels resulted in slight enhancements in tensile strength compared to the control mixture. Conversely, higher levels of FA replacement resulted in a reduction in tensile strength. The presence of RCA at different replacement levels also affected the tensile strength, with higher replacement levels resulting in reduced strength values. This drop in tensile strength suggests that adding more RCA made the interfaces between aggregate particles and matrix less strong [3, 56].

The UPV results presented in Fig. 8 provide insights into the quality and integrity of the RRPC specimens before and after different power-on durations for each group. The control mixture exhibited a slight decrease in UPV values over time. This minor reduction in UPV suggests minimal changes in the concrete's internal structure during the testing period.

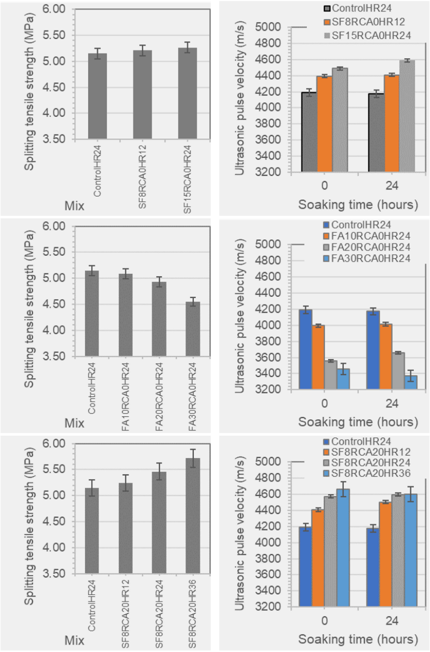


Fig. 8. Splitting tensile strength and ultrasonic pulse velocity of RRPC with different RCA content after power-on duration for 12, 24, and 36 h: (a) RRPC containing SF; (b) RRPC containing FA; and (c) RRPC containing 8 wt% with different 12, 24, and 36-hour soaking times.

When 8 and 15 wt% of the cement

were replaced with SF, the UPV values showed different trends. At an 8% replacement level, the UPV slightly increased to 0.35% at 12 h. This increase in UPV indicates potential changes in the microstructure and internal integrity of the RRPC due to the incorporation of SF. Cement replacement with FA at various levels (10, 20, and 30 wt%) resulted in notable changes in UPV values. At a 10% replacement level, the UPV increased significantly to 20.42% at 24 h. Similarly, at 20 and 30 wt% replacement levels, the UPV values increased from 19.56% and 26.46% after 36 h, respectively. These results indicate that FA incorporation positively influenced the internal structure and improved the integrity of the RRPC [1,2,19,44,54]. Pozzolanic reactions associated with the addition of materials like SF and FA fill voids in the concrete matrix, enhancing compactness, whereas the hygroscopic nature of RCA, owing to residual cement paste, detracts from tensile strength and potentially impairs bond strength. These variations underscore the critical balance needed in composite material design to improve structural performance while maintaining or enhancing material integrity. The research outcomes emphasize the intricate nature of concrete mix design for RRPC and the need for judicious selection of constituents to optimize both mechanical properties and durability.

In the group where SF, FA, and RCA were incorporated, the UPV values exhibited a relatively consistent trend. These results suggest that the addition of RCA at this replacement level had minimal impact on the internal structure and integrity of the RRPC. With a higher RCA replacement level of 50%, the UPV values showed a gradual decrease. These findings indicate that the increased incorporation of RCA resulted in minor changes in the internal structure of the RRPC, potentially affecting the bond between the RCA particles and the matrix. Additionally, a progressive decline in UPV values was seen once RCA completely replaced natural coarse aggregate. RCA with a higher percentage of adhered cement paste has lower stiffness compared to natural stone [55]. This is due to their lesser degree of compactness. The findings indicate that substituting natural coarse aggregate with RCA significantly affected the internal structure and integrity of the RRPC. RCA integration shows a complex relationship with tensile strength, where moderate levels do not compromise strength significantly, but a 50% replacement level reduces it, indicating potential weaknesses at the aggregate-matrix interface. The Ultrasonic Pulse Velocity (UPV) results further substantiate these findings; while slight increases in UPV with low levels of SF replacement suggest a denser concrete matrix, the incorporation of higher levels of FA and RCA, especially at 100 wt% and beyond, points to internal structural changes that could compromise the RRPC's integrity.

The accompanying analysis reflects a detailed investigation into the material properties of RRPC with varying compositions. Splitting tensile strength tests, summarized in Fig. 8, indicate that the control mixture maintains consistent strength over time, affirming the benefits of extended curing on material performance. Substitution of cement with SF at 8 and 15 wt% leads to slight improvements in tensile strength, where FA replacement presents a decrease, notably at higher percentages. These outcomes suggest that while SF enhances the concrete matrix, excessive FA may undermine tensile strength, potentially due to its influence on the microstructure.

Ultimately, the data reveal that the inclusion of SF leads to slight improvements in tensile strength and varying impacts on UPV, indicative of changes in concrete microstructure. On the other hand, FA reduces tensile strength while generally enhancing UPV, and the use of RCA can lead to reductions in both tensile strength and UPV, especially at higher replacement levels. These findings underscore the intricate balance between improving concrete's resistance to chloride penetration and maintaining its mechanical properties, highlighting the need for caution.

5. Discussion

This comprehensive study delves into the multifaceted effects of reinforcing bar and various composite components on the properties and performance of reinforced reactive powder concrete (RRPC), with a particular emphasis on the interplay between power-on duration and the fundamental characteristics of concrete. One interesting thing about this study is that it found a strong link between the length of power-on and the properties of RRPC. This is similar to what Liu et al. [17] found, which is that there is a link between the movement of chloride ions and the length of power-on time. It's interesting that the study shows that chloride ions are initially drawn to the anode by the electric field. This causes a change in the chloride migration coefficient, which is a way to measure how resistant the concrete is to chloride ions penetrating it. At first, this coefficient goes up as the power stays on, which means that the material is more permeable. However, it strangely goes down over time, which could mean that the concrete matrix has a self-healing mechanism that stops chloride from getting through.

The incorporation of RCA introduces another layer of complexity to the study, revealing an inverse relationship between the chloride migration coefficient and RCA content. This means that RCA, which has special properties from being used concrete, helps to make the concrete matrix denser, which makes it less likely for chloride ions to move through it. This phenomenon is attributed to the alteration of the pore structure within the concrete, which not only reduces permeability but also acts as a barrier to chloride ions. The study also looks at how the length of power-on affects RCA content, giving a more complete picture of how these two factors affect chloride migration together. At the 12-h mark, an increase in RCA content correlates with a decreased chloride migration coefficient, whereas, at extended durations of 24 and 36 h, this trend becomes less pronounced. This observation suggests that the initial stages of power-on duration are critical for activating the concrete's self-healing and sealing capabilities, which are subsequently influenced by the presence of RCA.

The complicated connection between the length of time the power is on, the amount of RCA present, and the chloride resistance of RRPC shows how important it is to design the mix specifically for each application. For scenarios demanding rapid construction with immediate chloride resistance, shorter power-on durations may be preferred. Conversely, longer power-on durations could be advantageous for enhancing the long-term durability and self-healing properties of RRPC, contributing to its overall resilience against chloride penetration. The study reveals that the self-healing mechanism in RRPC, indicated by the initially increasing and then decreasing chloride migration coefficient with prolonged power-on duration, is likely enhanced by the inclusion of SF and FA. Both materials refine the concrete's microstructure and promote additional calcium silicate hydrate (C-S-H) gel formation. The pozzolanic reactions of SF and FA help fill microcracks and pores, thereby improving resistance to chloride ingress. Not only does this study support earlier research that RCA makes concrete last longer and be more resistant to chlorides, it also makes the field better by explaining how power-on duration affects how well RCA works in RRPC. These kinds of insights are very helpful for making concrete more environmentally friendly, encouraging the use of recycled materials, and planning future research on how to improve the performance and strength of RRPC when it is exposed to chloride. The research makes a big contribution to the ongoing discussion on sustainable building materials by carefully looking at these factors. It also opens the door for more research into the long-term durability and environmental resilience of RRPC formulations that include RCA.

6. Conclusion

This research provides novel insights into the behavior of chloride migration in RRPC utilizing RCA, FA, and SF under non-steady-state conditions. The findings distinctly highlight the impact of incorporating RCA and varying the power-on duration on the chloride migration coefficient. A noteworthy observation from the study is the initially increasing and subsequently decreasing trend in the chloride migration coefficient with prolonged power-on duration. This phenomenon suggests the activation of a self-healing mechanism within the concrete matrix over time, which enhances its resistance to chloride ingress. Furthermore, the incorporation of RCA not only contributed to a reduction in the chloride migration coefficient but also demonstrated that increasing RCA content enhances the concrete's durability and resistance to chloride penetration. However, it was observed that the influence of RCA content on chloride resistance was particularly prominent in shorter time frames but diminished as the duration increased. These findings underscore the beneficial role of RCA and SF in enhancing the long-term performance and sustainability of RRPC.

By integrating RCA, FA, and SF into the concrete mixtures, the study explores the synergistic effects of these materials on the chloride resistance of RRPC. The experimental results underscore the complexity of chloride ion transport and highlight the significant influence of material composition and power-on duration on the chloride migration coefficient. This intricate relationship indicates the possibility of optimizing RRPC mix designs for specific environmental exposures and durability requirements. The study's approach to modeling chloride transport, grounded in non-steady-state conditions, reflects a more realistic representation of environmental exposures, thus providing a robust basis for predicting the long-term performance and durability of RRPC structures.

The inclusion of reinforcing bars in RRPC plays a pivotal role in influencing the Non-Steady-State Chloride Migration Behaviors, as evidenced by the research findings. The presence of reinforcing bars is found to significantly affect the chloride migration dynamics, likely by altering the electrical field distribution within the concrete matrix and providing physical barriers to ion movement. This interaction suggests a complex interplay between the physical reinforcement structure and the chloride ions' path, potentially enhancing the concrete's resistance to chloride ingress. The reinforcing bars, therefore, not only contribute to the mechanical strength of RRPC but also its durability against chloride-induced corrosion, underscoring the importance of considering the reinforcement layout and characteristics in the mix design to optimize both structural performance and longevity in chloride-rich environments.

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